THE INDUSTRIAL APPLICATIONS OF GASFILLED TRIODES

THE INDUSTRIAL APPLICATIONS OF GASFILLED TRIODES

(*THYRATRONS*)

By
R. C. WALKER
B.Sc. (Lond.), A.M.I.Mech.E.
A.M.I.E.E.

LONDON
CHAPMAN & HALL LTD
37 ESSEX STREET W.C.2
1950

First published 1950

Catalogue No. 385/4

PRINTED IN GREAT BRITAIN BY STRANGEWAYS PRESS LTD., LONDON
Bound by G. & J. Kitcat, Ltd., London, *Flexiback Binding*

PREFACE

THE grid controlled gasfilled triode, under one of its proprietary names, is by no means a newcomer to the family of thermionic discharge tubes. It is referred to in all books on electronics and in many dealing with other subjects. As distinct from other thermionic devices there are, however, few works devoted exclusively to a discussion of its utility in industry.

This book is intended to fill this gap, to treat the tube in its proper perspective with respect to other thermionic devices, and not least, to provide a representative, if incomplete collection of references of the investigations which have been carried out on the performance of the tube and its utility in commerce.

Acknowledgements are due to the editors of *Electronics*, *Electronic Industries*, *Journal of the Institution of Electrical Engineers*, *Journal of Scientific Instruments*, and other journals for permission to use material which has priority of publication and to all the firms whose names are mentioned hereafter for their kind co-operation in supplying information about proprietary apparatus and industrial installations.

I am greatly indebted to my friend the late Mr. G. Windred for many helpful suggestions and constructive criticism and for his undertaking to read the manuscript, a task regrettably interrupted by his untimely passing.

Reading, 1948. R. C. W.

CONTENTS

CHAPTER I

Fundamental Characteristics of the Hot Cathode Gasfilled Valve 1

Introduction. The vacuum diode. The gasfilled rectifier. Cathode temperature. Gas pressure. Thermal efficiency of the cathode. The addition of a control grid. Grid control ratio. Constructional features. Current in the grid circuit. Extinction of the discharge. Gas pressure. Deionisation time. Arc voltage drop. Rating of a gasfilled triode (maximum peak forward voltage, maximum peak reverse voltage, maximum peak anode current, maximum permissible mean anode current grid control ratio, deionisation time). Some practical considerations. References.

CHAPTER 2

The Gasfilled Tetrode or Shield Grid Thyratron 44

Limitations of the triode. Design of the grid in a gasfilled tetrode. Grid resistance. Electrode potentials. Means of varying the control characteristics. Typical gasfilled tetrodes.

CHAPTER 3

Methods of Applying Gasfilled Triodes—Basic Circuits 55

Extinction of the anode discharge. Relay switching. Condenser discharge. Alternating anode voltage. Grid control curve. Alternating anode voltage, with steady grid bias. Alternating grid voltage. Phase change and its effect on the mean anode current. Alternating grid and steady anode voltage. Variation of grid voltage amplitude. Superposition of an alternating voltage on a steady grid bias. Peaked voltage firing impulses. Biphase connection of triodes. Parallel operation. Inverse parallel. Methods of producing phase change in the grid circuit. Inductive loads. Some practical considerations. Switching heater and anode circuits. Protection against overload.

Merits of the gasfilled triode as a switching device. Further considerations. Some basic circuits. Switching by condenser discharge. Signal pre-amplification. Differentiating relay circuits. Overload relay. Cathode ray time-base circuits. The gasfilled triode as a fly-back switch. Linear time base and amplifier. Other forms of scanning circuit. Means of stabilisation. Velocity modulated sweeps. Frequency division. Switching selector for double-trace screen recording. Temperature control. Printing and wrapping machinery. Register control. High-speed counters. Multiplier circuits. Cascade connection. Other modifications. Frequency measurement. Measurement of short time intervals.

A direct-current amplifier using gasfilled triodes. Timing circuits. Applications to electric welding. Automatic synchronisation. Servo mechanisms. Frequency stabilisation. Frequency comparison. Measurement of transient voltages. The hot cathode gasfilled valve as a stroboscope. Voltage displacement of neutral point in a three-phase network.

Stabilisation of generator voltage. Methods of application. Automatic control of generator frequency. Generator field supplied entirely through gasfilled triodes. Alternative modifications. Voltage control on a lamp circuit. Control of electric motors. The problem of speed variation for A.C. motors. Advantages secured by electronic control. A simpler form of speed control with reversal for a small motor. Auxiliary circuits for closer speed control. Correction for supply voltage variation. Variation of load. Speed variation by field control. Limitation of armature current. Thymotrol system. Applications. Current control by reactors. Compensating reactor voltage drop. Voltage pulse generators. Square wave single or multiple voltage pulses. Peaked voltage generators.

Current rectification. Filter circuits. Harmonics. The grid circuit-phase displacement. Arrangement of heater circuit. Compounding. Misfires and backfires, etc. Inverters-parallel type. Automatic switching. D.C. conversion. Series type of inverter. Voltage regulation. Large inverters. Practical applications. D.C. transmission. Commutator-less D.C. motors.

The ignitron. The distinction from the mercury arc rectifier. The starter or igniter electrode. Water-cooling. Applications. Welding. Non-synchronous current control. Methods of current adjustment. Dual timing circuits for seam welding. Stored energy circuits. Magnetically controlled valves. Advantages. Pulse modulators. Cold cathode tubes. The diode. The triode life. Nomenclature. The cold cathode tube as a relay. Methods of operation. Merits and disadvantages. Rectification. Relaxation oscillators. Timing circuits. Voltage stabilisers. Stabilovolt. Short-period illuminants. The stroboscope. The strobotron discharge tube. Modern forms. Neostron. Kodatron. Circuits for operation, etc.

CHAPTER I

Fundamental Characteristics of the Hot Cathode Gasfilled Valve

Introduction. The vacuum diode. The gasfilled rectifier. Cathode temperature. Gas pressure. Thermal efficiency of the cathode. The addition of a control grid. Grid control ratio. Constructional features. Current in the grid circuit. Extinction of the discharge. Gas pressure. Deionisation time. Arc voltage drop. Rating of a gasfilled triode (maximum peak forward voltage, maximum peak reverse voltage, maximum peak anode current, maximum permissible mean anode current, grid control ratio, deionisation time). Some practical considerations. References.

Introduction

THE hot cathode grid controlled gasfilled rectifier has properties which differ considerably from those of the hard vacuum thermionic valve, as a result of which the fields of application of the two in industry are markedly distinct. Though primarily designed as a sensitive electronic relay, the grid controlled gasfilled rectifier has many commercial applications in which it does not function as a relay, so that the term gasfilled relay, though established by usage, is, as a descriptive term, hardly adequate to embrace all its numerous and increasing uses in industry. As triodes and tetrodes these devices are perhaps better known by the proprietary name of thyratron, a term which is general in America and which has some justifiable claim for correct and appropriate association with this type of valve.

Though the adoption of gasfilled triodes and tetrodes for industrial use is relatively recent, the basic properties of the grid-controlled gasfilled valve have been known for more than thirty years. Valves of this type were described by Reisz,[1.1] and patent literature of the same period[1.2] reveals the fact that the basis of their operation was well understood. Langmuir had a patent on the subject in 1913. In the following decade much of the development work on this type of valve was carried out by Hull, Winter, Kingdon and Langmuir in America.[1.3, 1.4, 1.5]

The gasfilled triode comprises an electrode assembly which includes a cathode, usually though not essentially indirectly heated, an anode, a control electrode or grid, and in the case of the tetrode a shield grid, the whole electrode system being mounted in a glass or metal bulb. After being evacuated of air, the bulb is filled at very low pressure with mercury vapour or one of the inert gases such as argon, neon, xenon or helium, or a mixture of these gases, the characteristics of the valve being to some extent influenced by the particular gasfilling.

Since it contains the same elemental electrode system as the vacuum valve, it is not surprising that, in the smaller sizes at any rate, the two bear considerable resemblance in external appearance. The following description will, however, indicate that there are distinctive differences in design and construction of the electrode system in the gasfilled valve, notably in the heater and the grid, so that the gasfilled triode is in no way, apart from its special electrical characteristics, a simple modification of the vacuum valve. The distinctive properties which result from gasfilling are best understood by first comparing the gasfilled diode with the corresponding hard vacuum valve.

The Vacuum Diode

The cathode of a hard vacuum valve when heated, either by the passage of an electic current through it or by radiation from an independently heated circuit, is the source of electrons or elemental negative charges of electricity whose passage through the gas space between cathode and anode constitutes the current through the valve. It is hardly necessary to discuss here the theory of the nature of atomic structure. Suffice it to say that there are present in all electrical conductors a certain number of "free" electrons. The heat developed in the cathode is partly transferred to these free electrons and serves to increase their kinetic energy of motion. Within the interior of the cathode electrons are influenced on all sides by the electric fields due to other electrons and the forces are balanced; but near the surface the electrons are not equally surrounded on all sides by the same medium, and such forces are asymmetrical, so that sufficient thermal energy may be transferred to some of the surface electrons to enable them to overcome the restraining forces tending to pull them back into the interior and they are projected into the surrounding gas space. This is true for any heated surface, though in the case of pure metals the electron emission is very small. The cathode of a valve, therefore, needs to be one having a specially prepared surface which facilitates the escape of electrons in order that this property of thermionic emission may be usefully employed.

In the absence of any external forces, most of the electrons emitted from the cathode of a valve in this way will return again to its surface. Only a very few will have sufficient kinetic energy to enable them to pass across to the anode when the latter is not connected to any electrical source.

If, however, the anode or plate is connected to some source of electrical energy so that it is at a potential positive to the cathode, this positive field will exert an attractive force on emitted electrons. The electrons leaving the cathode surface are then subjected to two opposing forces, one due to the attraction of the anode and another in the opposite direction due to the restraining surface forces and the repulsive effect of all the electrons then present in the gas space. As a result, a cloud of electrons known as the space charge is formed at a short distance in front of the cathode and is held in equilibrium by these opposing forces.

Only those electrons which leave the cathode surface with sufficient kinetic energy to penetrate the space charge will be able to reach the anode. If the positive anode voltage is raised, the attractive force of the anode field is increased so that the number of electrons which are able to pass through the space charge will, within certain limits, also be increased. Above a certain value of anode voltage, depending on the design of the valve and the temperature of the cathode, practically all the electrons leaving the cathode will pass across to the anode and the rate of current increase with increase of anode voltage will thereafter be small, since approximate saturation of current results. For certain reasons, however, a true saturation is not secured with modern types of coated cathode.

If the anode potential is made negative to the cathode, the anode field will assist the space charge in repelling the electron emission and the number of electrons reaching the anode will be reduced or even cut off completely. An alternating voltage applied to the anode, therefore, results in the passage of current through the valve when this voltage is positive, but not when it is negative to the cathode, and the valve becomes a device for obtaining a unidirectional current from an alternating supply. The fact that no current can pass through the valve when the anode potential is negative to the cathode presupposes that the anode itself is incapable of acting as a source of electrons. Such is the case under all normal conditions of working when the potential between the electrodes is not excessive. The electron emission from cold cathodes is always very low and special preparation of the surface and design of the electrode system is necessary to secure any appreciable emission of electrons. Nevertheless, if the voltage across the valve is high enough, some electrons may be drawn out of the anode and pass to the cathode in the reverse of the normal direction when the anode and cathode potentials are reversed. If conditions are such that this can take place, the function of the valve as a rectifier ceases. An upper limit is therefore placed on the alternating voltage which can be applied to the anode of any valve.

To distinguish this condition from that of normal operation, the positive voltage applied to the anode is termed the "forward" voltage. Under conditions where the anode becomes negative to the cathode, the potential difference is known as the "inverse" voltage.

The current through a hard vacuum valve is always relatively small—for half-wave rectifiers usually something less than 0·25 amps. The impedance of the hard vacuum diode is consequently high and the voltage drop across the electrodes relatively large.

The Gasfilled Diode

Now consider the effect of the presence of an inert gas at low pressure in the bulb. If the anode potential is only a few volts, the existence of the gas has little effect. The gas molecules in the inter-electrode space may to some extent impede the passage of electrons from cathode to anode, but the relation between current and voltage under these conditions is of very little importance. When the voltage reaches a certain value known as the ionising potential some ions are produced, though the process of recombination is also taking place in the reverse direction so that the number of ions at first produced is relatively small. The effect of the ions produced is twofold: (1) the negative ions pass to the anode and reinforce the cathode emission; (2) the positive ions tend to reduce the space charge by neutralisation. The effect of (1) is practically negligible, but the reduction of the space charge means that the current curve rises more steeply when gas is present up to the voltage at which saturation of the cathode emission occurs. At saturation the current is sensibly the same whether gas is present or not. Prior to saturation, the difference between the two cases at very low voltages is not, therefore, one of any great practical importance, because it represents conditions under which the gasfilled valve is never operated and in consequence need not be further considered.

When the anode voltage is raised above that which would in the vacuum valve produce current saturation a marked increase in current takes place in the gas diode. Sufficient energy is then communicated to the electrons emitted from the cathode to enable an appreciable number of them to make collisions with the gas particles of sufficient violence to disrupt the gas atoms and split them into electrons and positive ions. The exact value of anode voltage at which this process of ionisation starts, or rather becomes appreciable, depends on several factors, notably the nature of the gas, and its pressure, but in the case of the gasfilled valves under consideration it is in the range of 15-25 volts.

Ionisation is always accompanied by a process in the reverse direction by which ions are lost through recombination and drift to the walls of the enclosure.

Positive ions produced by this process of disruptive collision tend to neutralise the electrons in the space charge, so that if they are produced at a rate greatly exceeding the rate of recombination the current-limiting effect of the space charge is removed and the current through the valve rises enormously. The valve is then said to break down, strike or fire. When the discharge passes, the impedance of the valve falls to a low value, and the voltage between cathode and anode thereafter is practically independent of the current. The discharge assumes the nature of a small arc and becomes visible as a glow in the bulb characteristic of the particular gas involved. The voltage drop across the valve is then practically constant (15-25 volts) and the current must be restricted in magnitude by a resistance in the external circuit or by some other limiting device, otherwise it will rise to a high value and possibly destroy the active cathode surface. The distinctive differences in behaviour between a hard vacuum and a gasfilled diode as the anode-cathode voltage is raised is shown in the two curves to different current scales in Fig. 1.1.

The permissible current which passes through the valve is large compared with that in a vacuum valve. Small gas tubes may pass peak currents of several amperes, whereas a vacuum triode with a current rating of 200 ma. is a large valve of its type.

The positive ions formed in the gas are of much greater mass and move much more slowly than the electrons, and they play little part in the transfer of current through the valve, which is due almost entirely to the electrons. The maximum current is, therefore, determined solely by the supply of electrons which the cathode is able to furnish or the emissivity of its surface.

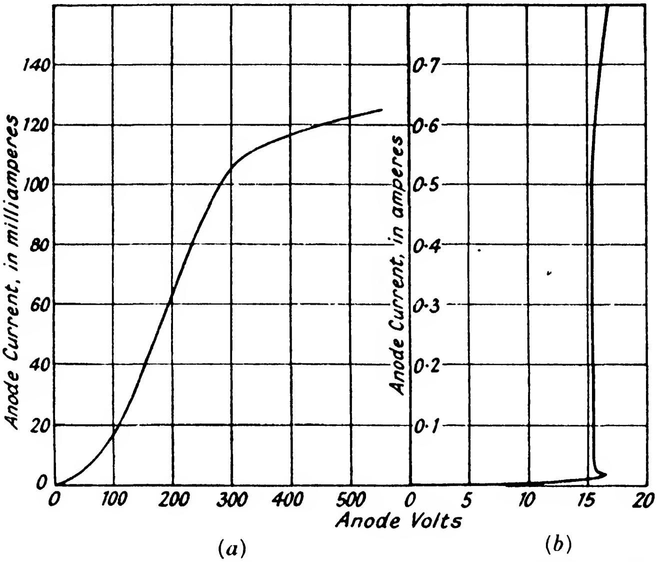


Fig. 1.1.—Typical anode voltage/anode current curves for (*a*) High vacuum thermionic valve rectifier; (*b*) Mercury vapour rectifier under conditions producing ionisation.

When the valve fires, the distribution of potential between cathode and anode changes considerably, practically the whole voltage drop occurring over a short space in front of the cathode (Fig. 1.2). Curve 1 of Fig. 1.2 shows the potential distribution between two flat plates in a vacuum with a potential difference between them, and curve 2 indicates the distribution of potential between the electrodes of a hot-cathode gas discharge valve after the current has been established.

To avoid the complication which the curvature of the electrodes would produce in the external field, Fig. 1.2 is drawn for parallel plate electrodes and is therefore hypothetical, but will serve to indicate the general trend of the potential distribution between the cathode and anode of a gasfilled valve.

Practically all the ionisation takes place within a space a short distance from the cathode and almost the whole voltage drop takes place over the region AB.

This space is generally referred to as the cathode sheath, the rest of the space which practically fills the whole tube being known as the plasma. The low potential gradient of the plasma indicates the existence in it of both positive and negative ions. In this region the few positive ions which are produced serve to maintain the number lost by either recombination or drift to the walls of the bulb.

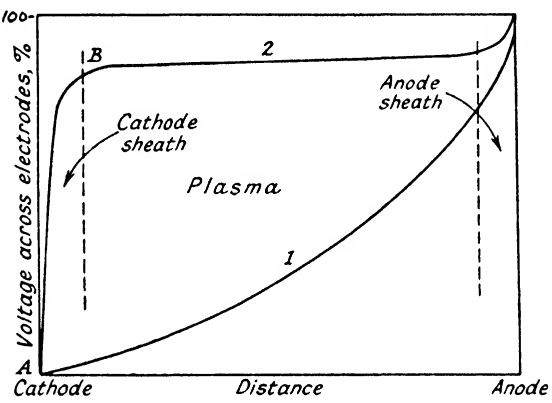


Fig. 1.2.—Voltage distribution across a simple diode for (1) vacuum, (2) gasfilling.

The space surrounding the anode is also a region of steeper potential gradient, though much less so than the cathode sheath. These regions, which represent a small portion of the interelectrode space, are areas to or from which a greater number of electrons enter or leave the plasma. Near the anode, conditions may be such that the passage of electrons to the anode surface leaves the plasma more positive in potential, so that the anode may actually be slightly negative to the space immediately adjacent to it.

Disintegrating Voltage

If the impedance of the external circuit is low enough to make the current passing through the valve higher than the saturated emission of the cathode, the voltage between the cathode and anode will rise and will accelerate positive ions towards the cathode with increasing energy of impact. Owing to the steep potential gradient in front of the cathode all the positive ions which bombard this surface do so with kinetic energy corresponding to almost the full voltage drop across the tube. Consequently there is a critical voltage drop characteristic of the particular gas in the valve below which it is safe to operate the valve. This difference in potential is known as the disintegrating voltage. It varies from about 22 volts with mercury vapour to 27 volts with neon, and represents the limiting value of voltage across the valve above which the impact of positive ions on the cathode is violent enough to destroy its emissive properties. Bombardment of the cathode in this way results in disintegration or sputtering of the activated surface. With coated cathodes, portions of the active material may be torn off and in severe cases of overload are visible as bright scintillations while the discharge is passing. With smaller overload the destruction of the cathode, though not visible, will nevertheless be progressive and will result in short life of the valve, usually with blackening of the bulb. Failure of the valve due to such a cause may eventually occur either through direct loss of cathode emission or by the deposit of a conducting film on the electrode supports. Intermittent sparking takes place along this film, resulting in ionisation of the gas and conduction during what should be the non-conducting period of the valve. With thoriated cathodes the effect of current overload will depend on the rate at which thorium can be diffused from the interior to replace the active material lost by bombardment. With cathodes directly heated by D.C. the cathode is no longer an equipotential surface and voltage drop across the valve is greater at one end of the cathode than at the other. Consequently the voltage difference between the anode and the negative end of the cathode must not exceed the disintegration voltage.[1.6]

These facts will emphasise the importance of ensuring that during use both the peak and the mean currents through a gasfilled valve do not exceed the values for which it is designed.

Cathode Temperature

Since the emissivity of the cathode depends on its temperature, it will be clear that the damage to the active surface just referred to will take place if any attempt is made to load a gasfilled valve even to its normal rating before the cathode has reached its working temperature. Gasfilled diodes (and triodes and tetrodes) almost always have indirectly heated thoriated or oxide coated cathodes, so that unless the current loading is very small the cathode must have attained a sufficiently high temperature, and the heater circuit must therefore be switched on some time before the anode circuit of the valve is completed. This preheating time of the cathode varies from 30 secs. to about 15 mins. according to the size of the valve, and in the case of mercury filling it depends also on the time which has elapsed since the valve was last fired. For the same reason the heater circuit must not be switched off before the anode circuit is opened, though the two may be switched off simultaneously. No attempt must ever be made to secure circuit adjustment by resistance included in the heater circuit. The heater circuit will usually stand a slight overload, but underheating is fatal and results in the cathode disintegration previously referred to.

Thermal delay switches of various designs are available to enable the switching operations to be carried out automatically, and circuits incorporating such components are referred to later.

The necessity for preheating the cathode is the chief and unavoidable disadvantage of all gasfilled valves with thermionic cathodes, and one which is more in evidence in equipment which is used intermittently where it is undesirable to keep the heater permanently switched on.

The question of cathode protection does not arise in the case of large rectifiers having mercury pool cathodes. Such units are capable of withstanding heavy overloads. The electron emission takes place at a hot spot in the mercury surface, and as this is constantly renewed no damage results from positive ion bombardment.

Gas Pressure

The life and performance of a gasfilled rectifier is dependent on another factor, and one over which the user has no control. The concentration of gas in the bulb has two effects: (1) it restrains the rate of cathode evaporation (*cf.*, gasfilled lamp); (2) it affects the breakdown voltage both in the forward and the inverse direction. With mercury filling the gas pressure is in the range of 0·001-0·1 mm. and is established by introducing during manufacture a small globule of the metal into the bulb. When the cathode is heated, a low pressure atmosphere of mercury vapour is formed in the bulb. The mercury vapour pressure increases rapidly with the temperature and is therefore determined by the temperature of the coolest part of the bulb where the mercury condenses. As a result, there is a minimum operating temperature for any mercury-filled valve below which there will be a high voltage drop across the electrodes. In practice the minimum condensation temperature is about 40° C., which corresponds to a vapour pressure of 0·006 mm. Hg. On the other hand, above 75° C. a mercury-filled bulb can withstand less than half the peak inverse voltage possible at normal atmosphere temperature.

Since the vapour pressure determines the performance of the valve, mercury vapour fillings are to some extent at a disadvantage in the case of triodes, where operation under conditions of varying ambient temperature is involved.

The use of the inert gases in place of mercury overcomes this disadvantage. Except in some special high-current, low-voltage diodes the use of inert gasfilling is confined to triodes, though the chief characteristic would apply equally well to diodes and is therefore referred to here.

For inert gasfilling the pressure is higher than in the case of a mercury-filled valve—*e.g.*, for argon of the order of 0·15 mm. Successive firing of a gasfilled diode (or triode) necessitates the maintenance of the gas pressure within a specific range applicable to the gas in question.

If the pressure is made too low in an attempt to increase the peak inverse voltage which the valve will stand, the rate of ionisation is reduced and the maximum permissible current must also be reduced to avoid positive ion bombardment of the cathode. The current rating is thus restricted.

On the other hand, if the pressure is made too high, the rate of cathode evaporation is reduced so that it becomes possible to operate it at a higher temperature with greater thermal efficiency. This is offset by a greater disadvantage that the peak inverse breakdown voltage is considerably reduced and the valve is more likely to fire when a reverse voltage is applied to the anode. Valves with high gas pressure can therefore be used only at relatively low anode voltages.

The Tungar rectifier is an example of a high-pressure gasfilled diode rectifier valve used largely for battery charging equipment. The gas pressure is of the order of 5 mm. Hg and the high cathode temperature results in a very efficient form of converter. There is, however, some tendency for the discharge to become localised at certain points of the cathode, to overheat by forming hot-spots and burn out.

With low-pressure rectifiers having inert gasfilling—*e.g.*, argon, helium, neon, krypton or xenon—the effect of temperature is very small and the gas pressure changes little over the normal working temperature range. There is, however, another factor—viz., tendency for the gas pressure to decrease gradually during life due to "clean-up" of the gas which becomes adsorbed on the bulb and electrodes. In valves designed to work at high voltages the gas pressure must be maintained within close limits, otherwise the life of the valve may be reduced.

In consequence, this clean-up of the gas cannot be tolerated and inert gasfilling is not used in such cases, but is restricted to valves operated at more moderate voltages where the maintenance of the gas within close limits is not so essential. A partial corrective for gas clean-up is to ensure that the bulb originally contains sufficient gas to provide for the adsorption which takes place during life.[1.7]

Thermal Efficiency of the Cathode

The neutralisation of the space charge by positive ions which results in the increased current-carrying capacity of a gasfilled valve also makes possible a considerable modification in cathode design so as to secure a marked increase in thermal efficiency on the electron emitting surface. In the hard vacuum diode (or triode) an enclosure or semi-enclosure of the cathode surface has to be rigidly avoided because recesses or cavities result in the formation of a local space charge which is intense enough to prevent any emitted electrons from escaping without the aid of an excessively high anode voltage (Fig. 1.3). The loss of heat by radiation, particularly in the case of an oxide-coated filament, by reason of the extended radiating surface area which the foregoing condition involves, is, therefore, relatively high and the thermal efficiency low—viz., about 0·1 amp. peak per watt.

With the neutralisation of the space charge in the case of a gasfilled valve the necessity for an extended cathode surface no longer exists, and the cathode design can be modified so as to concentrate a relatively large amount of emitting material in a small space. It is thus possible to conserve power in the heater circuit by surrounding the cathode by an enclosure of heat-reflecting surfaces or in the case of a directly heated cathode by adopting a spiral or re-entrant formation by including folds in the surface or other artifices which would not be possible in the vacuum tube. Various forms of corrugation or serration of the cathode surface have been adopted to secure the same results.[1.8] Heat-shielded cathodes were developed originally in America by A. W. Hull. An early form of indirectly heated shielded cathode is shown in Fig. 1.4 (iii), wire housed in the centre of a cylindrical cathode which has a number of radial vanes circumscribed by an outer nickel cylinder. The cathode surface is coated with a paste of alkaline oxides to form the electron emitting surface. The outside of the cylinder is polished and several further polished nickel cylinders of increasing radii are mounted concentrically to it and act as successive reflecting surfaces to return radiated heat back to the centre. By utilising a construction of this kind the thermal efficiency may be increased to about 3 amps. per watt of heat energy. For a given cathode temperature the power consumption of the heater is therefore correspondingly reduced. Other forms of construction which have been adopted to conserve the heat are shown in Fig. 1.4.

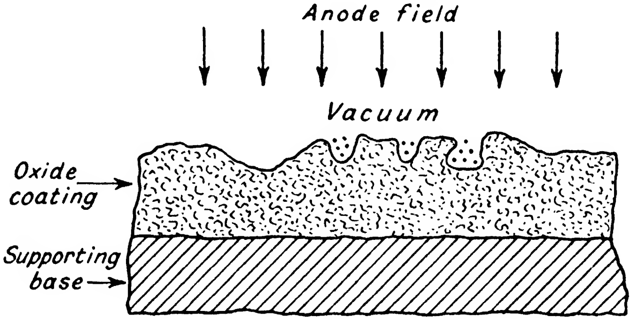
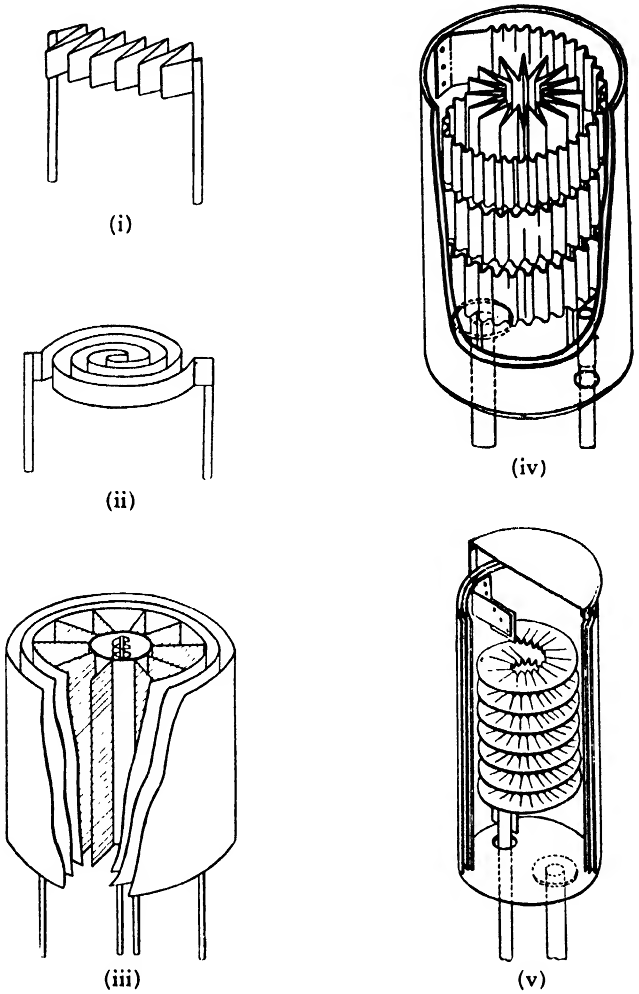


Fig. 1.3.—Incomplete saturation in emission from an irregular coated surface in a vacuum due to local space charge.

In the case of directly heated cathodes the cathode strip, if wound in the form of a spiral, may have the outer turns uncoated and polished, this again resulting in a reduction of heater current required to produce a given cathode temperature. Some idea of the effect of heat shielding can be formed from the rating of a large tube such as the G.E. type, FG 53, which has an emission current of about 600 amps., with a heater rating of 80 amps. 5 volts, representing an efficiency of about 1,500 ma. per watt.



(i) (ii) (iii) (iv) (v)

Fig. 1.4.—Typical forms of cathode construction for heat conservation as applicable to gasfilled valves. (i) and (ii) Re-entrant shapes to reduce heat radiation. (iii) Heater and cathode enclosed by shields. (iv) Spiralled heater. (v) Cathode surrounded by filament and indirectly heated by it. (*Electronics*).

The Addition of a Control Grid[1.9]

The foregoing characteristics of a gasfilled diode apply equally to a gasfilled triode or tetrode, with which we are more closely concerned. The introduction of a third electrode or grid between the cathode and the anode enables the conditions under which the discharge will start to be modified at the expense of very small power consumption in the grid circuit.

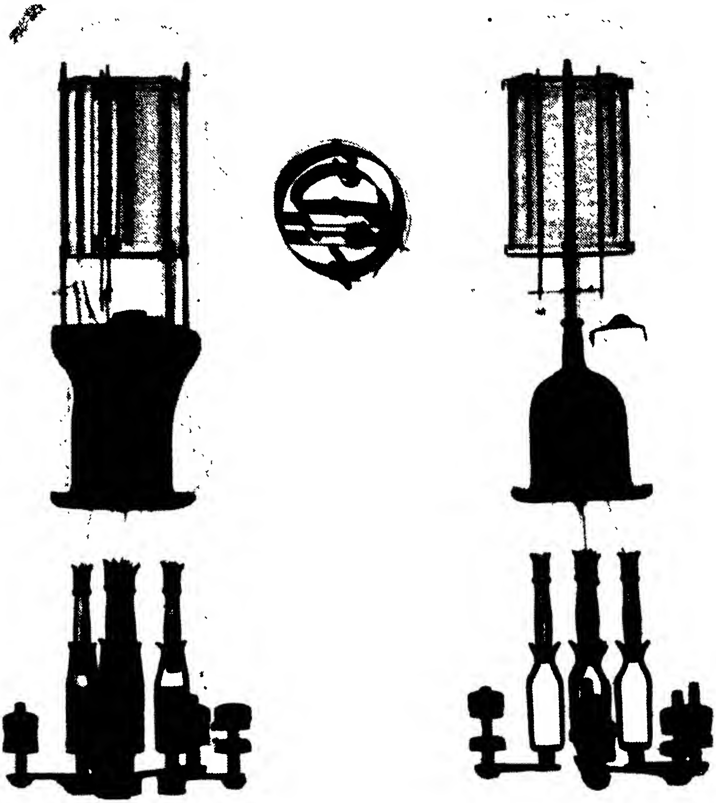


Fig. 1.5A.—X-ray photograph of Osram GT1C. *Left and right.*—Side views of electrode system. *Centre.*—End view ditto.

Since multi-electrode tubes may contain several auxiliary electrodes which may be referred to as grids, it is usual to refer to the electrode by means of which an external signal controls the anode current as the control or signal grid.

Fundamental Characteristics of the Hot Cathode Gasfilled Valve

Before a gasfilled triode fires[1.10, 1.11] it behaves in a manner similar to that of a vacuum triode—*e.g.*, the small current to the anode can be varied in magnitude by changing the control grid potential relative to the cathode. Increasing the negative value of the control grid voltage reduces the number of electrons passing from cathode to anode and vice versa. After the discharge is established and the valve has fired, the necessary conditions for which are the subject of the following discussion, the signal grid ceases to have any further control over the anode and the valve behaves as a diode rectifier and all resemblance to the vacuum triode disappears.

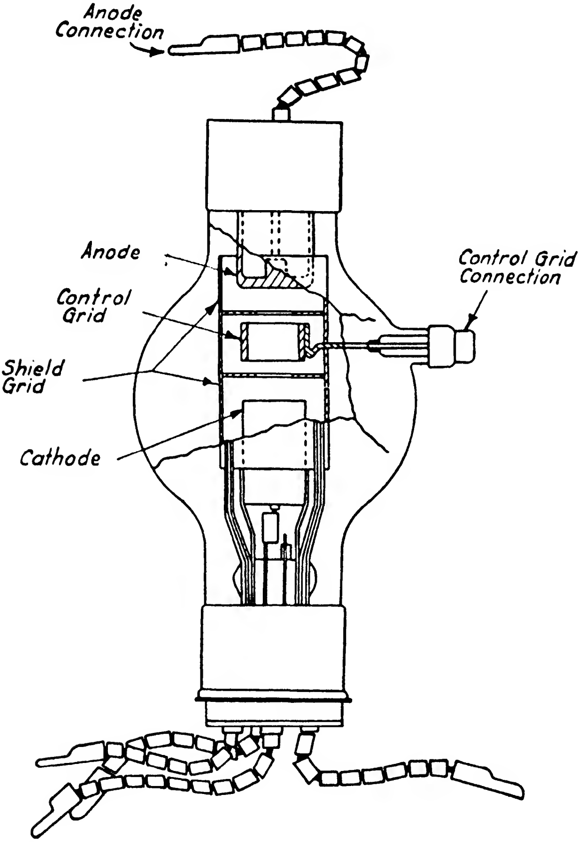


Fig. 1.5B.—Diagrammatic representation of shield grid thyratron Type BT 27.

(B.T.H.)

It has already been explained that in the case of the gasfilled diode the valve fires at a point where the anode voltage is about 15 volts positive to the cathode. If, however, before the anode discharge starts a voltage negative to the cathode is applied to the control grid, it will exert a restraining action on the starting of the discharge and a higher anode voltage will be required to cause the valve to fire. There is, in fact, for every value of control grid voltage V_g a corresponding minimum positive voltage V_a which will just cause the valve to fire.[1.12] The sudden increase of the anode current from a negligible value to its full maximum resulting from a relatively small increase in the ratio of anode voltage to grid voltage is the characteristic feature of the gasfilled triode, and shows a marked difference from the vacuum triode.

The corresponding hydraulic analogies of both diodes and triodes are shown in Fig. 1.6. Alternatively, the vacuum triode can be con-

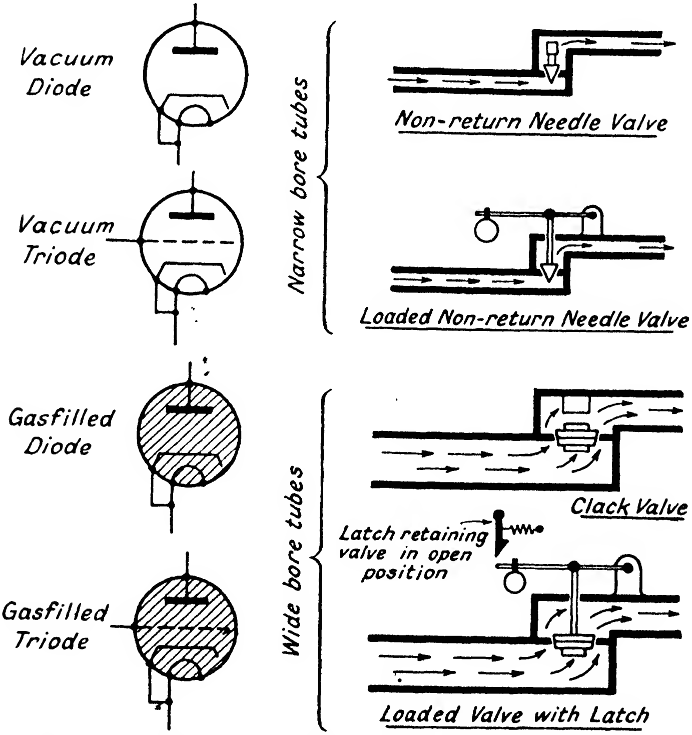


Fig. 1.6 —Hydraulic analogies of vacuum and gasfilled valves.

sidered as the analogy of a variable resistance adjustable in magnitude by the grid potential, while the gasfilled triode resembles a snap action switch.

Fig. 1.7A (*a*), (*b*) and (*c*) shows the usual British nomenclature for small gasfilled valves in circuit diagrams, the shading serving to indicate gasfilling. Fig. 1.7A (*d*) indicates the circuit representation frequently adopted in American literature, the dot in the circle indicating gasfilling.

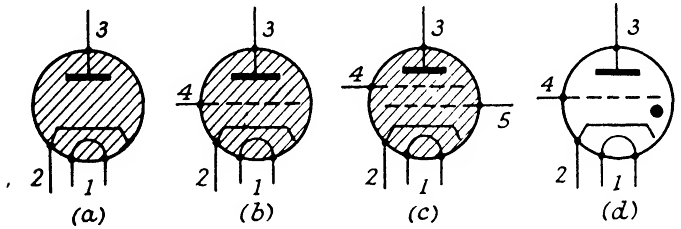


Fig. 1.7A.—Conventional representation of gasfilled valves. (*a*) Diode, (*b*) triode, (*c*) tetrode or shield grid valve, and (*d*) alternative representation of gasfilled (American) valve. 1. Heater 2. Cathode. 3. Anode. 4. Control signal grid. 5. Shield grid.

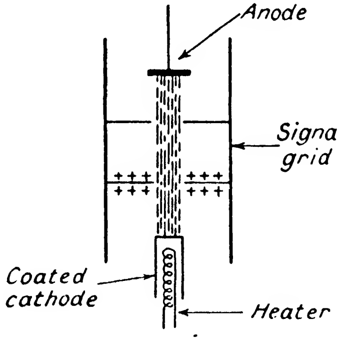


Fig. 1.7B.—Diagrammatic representation of the functions of the electrodes.

Valves with Negative or Positive Grid Control Voltage

The critical grid voltage may be positive or negative according to the design of the valve electrode system. It may be partly in both regions or wholly in either in the same valve under different conditions of operation. Such occurs in the tetrode (*q.v.*), in which variation of the shield voltage moves the range of the critical grid control voltage.

In most small triodes the critical grid voltage is negative, but in large power triodes used for motor speed control, etc., it is a distinct advantage to have valves with positive grid control. With positive grid valves, zero grid voltage corresponds to the condition in which the discharge is restrained.

This condition is desirable where it is required to ensure safety against inadvertent firing of the valve through a possible fault or open circuit in the grid bias voltage, which condition is not provided for in valves having negative grid control which require a separate grid bias voltage.

Grid Control Ratio[1.13, 1.14]

In the case of negative grid gasfilled triodes the ratio $V_a/-V_g$, where V_a is the anode voltage and $-V_g$ the grid bias voltage applied to the valve at the same instant and under conditions where the valve is just on the point of firing, is termed the grid control ratio. In most cases V_a is proportional to V_g over a considerable range, so that this ratio is then a constant. A typical grid control ~~radio~~ ratio curve for a small thyratron is shown in Fig. 1.8A.

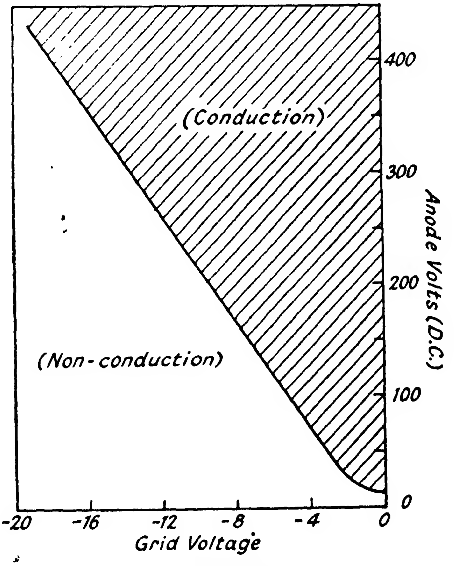


Fig. 1.8A.—Grid control ratio of a gasfilled triode (=25 over the linear position of the curve).

The grid control ratio is a characteristic of the particular type of triode and is settled by the electrode geometry, the gas pressure, etc. In a triode the user has no means of varying this factor.

Fig. 1.8B shows the corresponding relation between anode voltage and grid voltage at different temperatures for a large gasfilled triode having positive grid control. The distinction between the two sets of curves should be noted, due regard being made to the scales and potential ranges covered in the two cases.

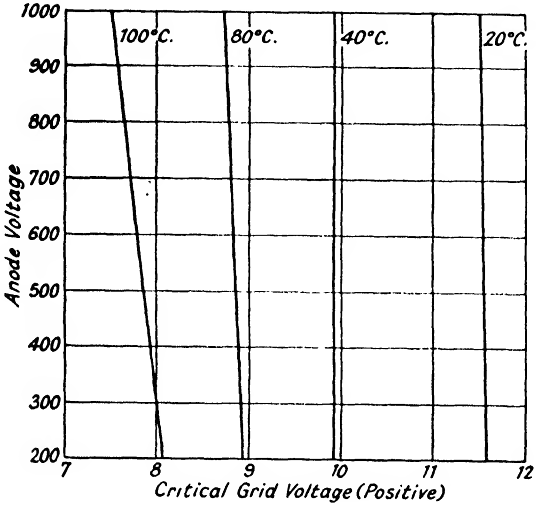


Fig. 1.8B.—Positive grid tubes. Typical characteristic curves.

While obviously the definition of grid control ratio as applied to a negative grid control valve cannot be made applicable to a positive grid valve, there is in both cases a range of linearity in the control characteristics. It will be noted that in the case of Fig. 1.8B at 20° C., with a grid voltage of 11, the valve will not fire at any anode voltage in the range shown, whereas if the grid voltage is raised to 12 it will be impossible to prevent the valve firing at any anode voltage. Compared with a negative grid control valve, therefore, the transition from the non-conducting to the conducting state is much more clearly determinable in a positive control valve by a change in grid voltage than by a change in anode voltage.

Energy required to Fire the Valve

Since the change in grid voltage required to fire the valve is very small and the current passing in the grid circuit in the non-conducting state is only of the order of a microampere, the energy required to fire the valve is minute. Consequently the term "gasfilled relay" adequately expresses the ability of the device to control large power with the expenditure of a very small amount of energy. Where the signal circuit is a high impedance one—viz., an emission type of photocell—it will be shown later that the tetrode is preferable to the triode. Even the large types of valve require only a power of a few microwatts in the grid circuit.

Though the energy required to fire the valve is so small, it does not follow that the work done in bringing about this change is also of the same order. For instance, if the grid voltage change is brought about by an induction regulator or resistance under conditions which will be discussed later, the friction of the drive may be large compared with the energy change in the grid circuit.

Referring to Fig. 1.8A, it will be clear that for any given valve at a fixed temperature the shaded area represents the condition of conduction, so that if a point representing the operating conditions of the valve is moved towards the shaded area the valve fires when the point passes across the curve.

The terms "mutual conductance" and "plate impedance," as applied to vacuum triodes, are meaningless in the case of a gasfilled triode, since the grid controls the anode current quantitatively only when the anode current is very small.

The grid control ratio, however, is sometimes considered as the analogue of the amplification factor of a vacuum triode.

Immediately the valve fires, the anode current rises at once to a value determined by the supply voltage and the external circuit resistance, and thereafter the control grid potential has no further effect on it.

The time which elapses between the instant at which the ratio of anode voltage to control grid potential exceeds the critical value and the establishment of the anode current is known as the ionisation time and is of the order of microseconds. For many practical purposes it is sufficient to say that this time lag is negligible and that the response of the valve is instantaneous.

The control grid can, therefore, if sufficiently negative, withhold the discharge, but cannot vary it or stop it once it has been started.

The usual explanation given for the inability of the control grid to vary the discharge after the valve has fired is that increasing negative grid voltage merely serves to attract more positive ions to it, producing an increased grid current and a sheath of positive ions around it, a process which continues until the positive ion sheath is in electrical equilibrium with the potential of the grid. The external field on this assumption is, therefore, very small, and has no effect on the discharge, so that since the thickness of the ion sheath is small compared with the grid spacing, the main discharge between cathode and anode through the plasma continues practically unaffected by the grid voltage.

The complete explanation appears to be more involved than this and will not be discussed here,[1.15, 1.16] but there are indications that the positive ion sheath around the grid is due not to the attraction of positive ions by the negatively charged grid, but to the repulsion of electrons which thus leaves an area in which there is an excess of positive ions. The positive ions in the sheath which come in contact with the grid lose their charge to the grid and are replaced by others which are brought into the neighbourhood of the sheath by their movements in the discharge and not by electrostatic attraction of the grid.

There is no doubt, however, that, compared with the neutralisation of positive and negative ions which takes place in the main discharge, the number of positive ions removed by conduction to the control grid is very small, so that it produces practically no effect on the magnitude of the discharge.[1.17]

Since the grid potential at which the valve fires is critical, the gasfilled valve behaves as a trigger device, the discharge being immediately established if the grid control ratio is exceeded either by increasing the anode voltage with a constant grid voltage or making the grid more positive with a constant anode voltage, or varying both potentials simultaneously.

Constructional Features [1.18]

As the anode current in a gasfilled triode is, for valves of comparable size, so much larger than that of a vacuum triode, the electrode system is of more ample dimensions. Small gasfilled rectifiers have cathodes of nickel with a sheathing of barium or strontium carbonate, forming a unipotential emissive surface of an alkaline earth sleeve with an independent electrically heated element, though both thoriated and directly heated cathodes have been used.

The anode is generally in the form of a plain disc or cylinder and constituted of a substance such as carbonised nickel or graphite from which surface electrons are extracted only with considerable difficulty. This characteristic property minimises secondary emission and enables the permissible peak voltage which can be applied to the anode to be increased. As the voltage drop across the valve is small when current is passing, the plate dissipation is low, so that the anode area can be relatively small (Fig. 1.7B).

In small valves a single-ended construction is employed with the electrode assembly mounted on a glass pinch, but with larger valves the anode may be taken to a separate cap often at the opposite end to the supporting base.

The characteristics of the valve are largely determined by its grid design and disposition.[1.19] The grid no longer controls the average flow of electrons once the valve has fired, but initiates the discharge by enabling ionisation to be established. The region of control is the area between cathode and anode, where the potential gradient due to space charge was highest before ionisation. As distinct from the mesh construction of the high vacuum valve, the grid is nearly always a solid cylindrical electrode surrounding the cathode and anode and separating them by a diaphragm perforated with one or more holes through which the discharge passes. Negative grid control valves usually have a single large perforation in the diaphragm. Positive grid control is secured by increasing the number of grid baffles or reducing the size of the holes in these baffles so that the grid-cathode region is screened from the anode field. A number of holes in the diaphragm are used in some valves with positive grid control. In any case, the apertures must be large enough not to be bridged by the positive ion sheath which forms around the grid when the discharge starts. Positive grid control valves are useful at higher operating frequencies, as they exhibit rapid deionisation for resetting.

The cylindrical grid construction assists in conserving the cathode temperature and shields both cathode and anode from any electric fields due to charges on the wall of the bulb, so that any influence they might have in producing irregularities in the starting characteristics is obviated.

Electron emission from the grid must be minimised by using a substance of low emissivity or one treated to secure this condition, since grid emission can produce ionisation and give rise to erratic firing. Carbonised nickel, nichrome and graphite of large area to ensure low temperature are among the substances employed. Coating sputtered from cathode to grid may also give rise to grid emission.

A shield grid (*q.v.*) between cathode and control grid in the tetrode form of valve still further modifies the performance and reduces the value of the starting grid current (*q.v.*)

Ionisation Time[1.20, 1.28, 1.42]

The period required to establish the discharge after the grid voltage has been reduced below the critical value has been the subject of special investigation, which appears to show that this period may vary over a wide range from a fraction of a microsecond to several hundred microseconds. The conditions most favourable to a short ionisation time in any given tube appear to be the incidence of a positive pulse on the grid at the instant the anode voltage, if alternating, is at its positive peak. The ionisation time is, over a certain range, practically inversely proportional to the grid over-voltage—viz., the amount by which the applied grid voltage in the positive direction exceeds the critical control voltage.

In the case of moderate-sized tubes the ionisation time shows a rapid decrease, as the grid over-voltage is increased until V_g is about +40, after which further increase in grid voltage produces a much less rapid rate of decrease in the ionisation time.

The period depends largely on the design of electrode system, on the particular gas used and on its pressure. Fig. 1.9 shows the general trend of the curves relating ionisation time with grid over-voltage for an FG57 tube. Harrison has shown[1.20] that the ionisation time as indicated by oscillograph records shows two separate stages, a relatively long time lag indicated in Fig. 1.10 by t_1, an initial delay during which little change in anode voltage occurs, followed by a much shorter period t_2 in which the breakdown of the gas discharge path takes place. t_2 remains practically constant for variation of grid over voltage, but t_1 and t_2 both become smaller as the anode voltage is increased.

Webster[1.41] more recently has confirmed these deductions by applying positive rectangular impulses of known amplitude to the grid, obtained by discharging a condenser through a resistance voltage divider. The impulse was initiated by the spark over of a gap in the time sweep circuit of a cathode ray tube and delayed

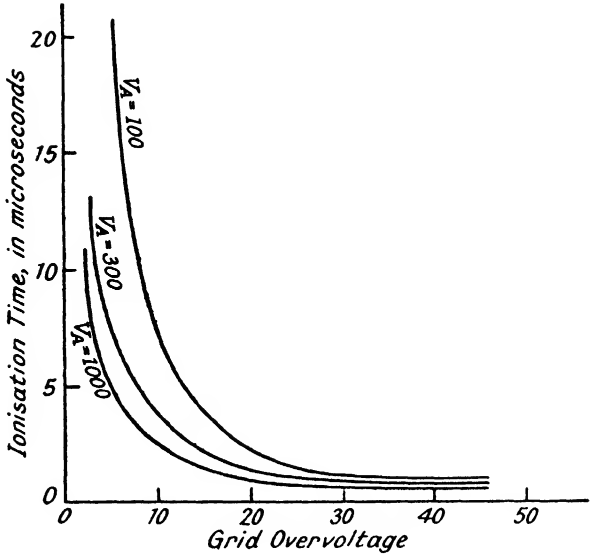


Fig. 1.9.—Effect of anode and grid bias voltages on the ionisation time of an FG57 thyratron under specified conditions.

slightly by a short length of cable so that the leading edge of the impulse was known to strike the grid ·06 microseconds after the start of the screen trace.

It would appear that with large grid over voltages, some ions are produced in the grid-cathode space and drift back to the cathode, where they tend to neutralise the space charge in front of the cathode. Their time of transit is approximately t_1. With small grid over voltages, ions are produced only in the grid-anode space, and tend to be withdrawn by the grid which becomes covered with an ion

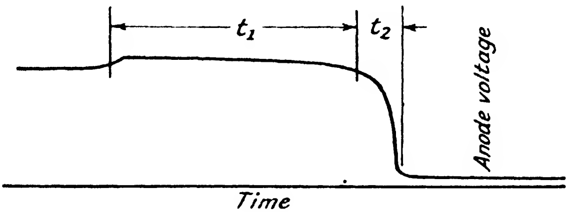


Fig. 1.10.—Nature of the breakdown in an FG57 thyratron t_1 = time lag; t_2 = breakdown period, $t_1 + t_2$ = ionisation time.

sheath. Subsequently, ions return to the cathode and progressively remove the negative potential barrier outside it. The combined effects of the grid and the smaller grid-cathode field cause a longer initial delay. t_2 is the time required to remove the electron space charge and build up the ion space charge which constitutes the cathode fall of potential in an arc discharge.

Current in the Grid Circuit

In valves having negative grid control the current in the grid circuit is many times greater when the valve is in the conducting than when it is in the non-conducting state. The direction and magnitude of the grid current are influenced by the grid potential. Representative curves in Fig. 1.11 (non-conduction) and Fig. 1.12 (conduction) show conditions which may be expected in a small gasfilled triode.

Before ionisation under conditions where the anode potential is negative, zero or low positive with respect to the cathode, a small negative grid current—*i.e.*, passage of electrons to the grid—of the order of 1 or 2 microamperes passes for values of negative grid

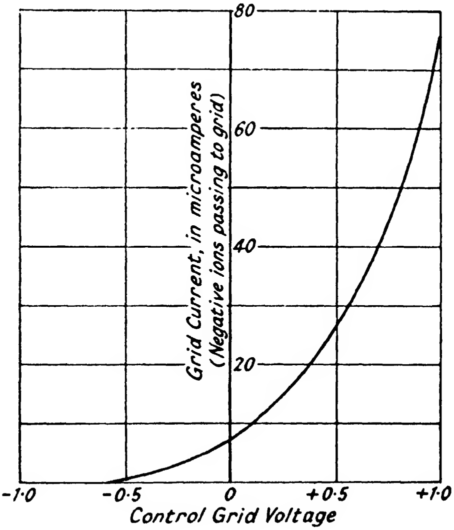


Fig. 1.11.—Relation between grid current and voltage before the anode discharge passes. Current is represented by the passage of negative ions to the grid.

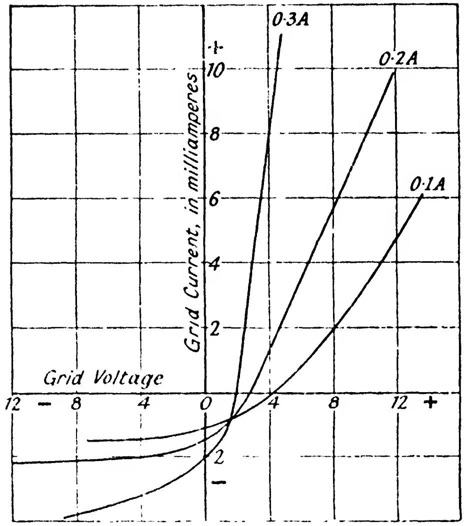


Fig. 1.12.—Current in the control grid circuit during the discharge for varying values of anode current in a small grid controlled gasfilled triode.

voltage up to about −8 volts in the case of the Osram GTIC, before which the bias is sufficient to cut off all electron flow to the grid. Incidentally, most makers impose a maximum value of the negative voltage which should be applied to the grid. As the grid is made more positive, the grid current increases and may be as high as 50-100 microamperes at $V_g=0$. These conditions approximate closely to the performance of a hard vacuum valve. After the anode discharge passes there will be a relatively large positive ion current to the grid of the order of several milliamperes, so that the current in the grid circuit changes direction when the valve fires. This grid current will be reduced in the neighbourhood where V_g is zero or slightly positive and will then rise again rapidly in the reverse direction (Fig. 1.12) with increasing positive voltage on the control grid. If the grid is thereafter made highly positive, it may approach the potential of the plasma and reach the ionising voltage. Under these conditions the positive ion sheath disappears and a discharge may pass to the grid, which will thus take over the function of the anode. To prevent this occurrence a high resistance, frequently as high as 1 megohm in small valves, is included as a current stopper in the grid circuit. When the supply is alternating, the grid may be alternately positive and negative with respect to the anode according to the phase relationship, so that the prediction of grid current becomes much more involved.

There is in the case of triodes a maximum value of resistance which may be included in the grid circuit. If this resistance is too high, the voltage drop across it due to the starting grid current may give rise to inadvertent firing and unreliable operation. The relatively large grid current which is established after the main discharge starts also causes a voltage drop which may appreciably modify the grid voltage curve. It does not affect the anode current wave form, since it occurs under conditions where the grid voltage no longer influences the anode current.[1.21, 1.22]

The optimum value of grid resistance is generally lower the larger the valve. For triodes with a mean anode current of 10 or 12 amps. it may be as low as 10,000 ohms.

Positive grid valves have high grid current both before and after firing, so that more power is required in the grid circuit.

In shield grid valves (*q.v.*) the magnitude of the grid current is greatly reduced, so that this type of valve is preferable for any application involving high grid resistance or coupling to a high impedance circuit such as an emission type photocell.

Extinction of the Discharge

Since the control grid normally exerts no influence over the anode discharge once this has been established, the circuit can be reset and the arc extinguished only by reducing the anode voltage to a value below the ionising potential for a period long enough to enable the ions in the plasma to recombine or drift to the walls of the valve or the electrode surfaces, so that the grid may regain control when the positive anode voltage is again applied. This process of resetting can be performed by (1) opening the anode circuit, (2) injecting into the anode circuit a reverse voltage which reduces the anode potential, (3) by some additional circuit arrangement which secures either of these conditions—*e.g.*, normally maintaining the anode voltage from a charged condenser which is suddenly discharged when the valve fires and produces the required voltage drop on the anode.

Under certain conditions of very low anode current, high negative control grid voltage, and low gas pressure in the valve there are exceptions to the general rule that the control grid cannot interrupt the anode current. The necessary modifications in design to secure such characteristics can be obtained by surrounding the anode by a very fine meshed grid, by spacing the grid and anode so that the distance of separation is not greater than the mean free path of an electron in the gas, and by locating these electrodes in a position in the tube where the ionisation is not intense. Under such conditions with a high negative grid voltage and low current through the plasma the sheaths of positive ions round the grid wires can be made to overlap and cut off the discharge. Such tubes are, however, of small practical importance and may be considered as exceptions to the performance of the thyratron as a type. In the case of shield grid valves, conditions may arise in which a positive control grid voltage may be required to restrain the discharge.[1.23, 1.24]

The Anode Current

Heating effects set the limit to the maximum current which the valve can pass continuously consistent with an economical life. Excessive current may give rise to hot spots on the anode, with consequent tendency to failure by arc back. Current overload may cause evolution of gas from the bulb or the electrodes, or loss of control by the grid, through the production of grid emission. Local heating of the lead-in wires or expansion resulting from the conduction of internal heat may cause mechanical fracture or insulation breakdown in the pinch.

Since the thermal capacity of the system introduces a time lag in the heat developed, a gasfilled valve can carry for short periods current loads considerably in excess of the normal continuous rating, so that it is usual to specify a continuous and a short-term rating.

Peak and Mean Anode Current

The importance of the mean and peak anode current ratings of a gasfilled triode warrant a closer examination of the precise meaning of these terms.

Over a given period the mean value of a variable current implies the magnitude of a steady current which would produce the same indication on the instrument used for measuring it. Though the meaning of the term is, in general, well understood, it should be remembered that the term "average" or "mean" is capable of more than one interpretation. Suppose, for the purpose of illustration, we take a case where the current varies over a given period as in

Fig. 1.13. Assume that this cycle is recurrent and takes place so quickly that the measuring instrument is unable to follow the current fluctuations. Then, if the whole period is divided up into a large number of small intervals, a moving-coil instrument will indicate one type of average—viz., arithmetical means of all the current values during the short intervals. If, on the other hand, the measuring device is, say, a hot-wire instrument, the reading will be that of a steady current which represents the same power consumption, and since the power consumption is proportional to the square of the current, the "average" in this case will be the square root of the mean square of all the current values during the short intervals, or, as it is more concisely expressed, the root mean square or R.M.S. value. This type of "average" is something referred to as the effective or virtual value of the current, and is a factor which in most engineering calculations is of much greater importance than the arithmetical mean value. In the case of a gasfilled triode the anode current only flows during the whole or part of the positive anode voltage half-cycle. If we assume that the current passes during the whole of this half-cycle, the current-time outline will be like that of Fig. 1.14. In this case the mean or average value as shown on a moving-coil instrument is I/π, where I is the peak value. The R.M.S. value is I/2. The ratio $\frac{\text{R.M.S.}}{\text{mean}} = \frac{\pi}{2} = 1{\cdot}57$, so that the R.M.S. value is nearly 60 per cent. greater than the arithmetical mean value.

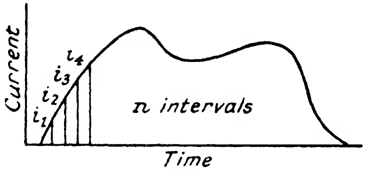


Fig. 1.13. Mean value of a variable = $\frac{1}{n}[i_1 + i_2 \dots \text{to } n \text{ terms}]$

R.M.S. value = $\sqrt{\frac{(i_1^2 + i_2^2 + i_3^2 \dots \text{to } n \text{ terms})}{n}}$

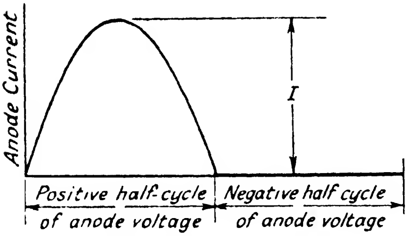


Fig. 1.14.—"Average" values of anode current in a gasfilled triode. Arithmetical mean of anode current = I/π. R.M.S. or virtual value of anode current = I/2.

Now, the arc drop across the triode in the conducting state is constant, consequently the resistance of the arc must decrease as the current increases (V=RI). This fact will probably have been made self-evident from the necessity of including a current limiting resistance to stabilise the discharge. Since the discharge path does not behave as an ohmic resistance, the heating in the valve is no longer proportional to the mean square current, but to the square of the arithmetic mean value. While the external loading may be determined by the R.M.S. value, the internal conduction is limited by the mean value. It is well to be clear on the distinction of the implication of the mean value in the two cases.

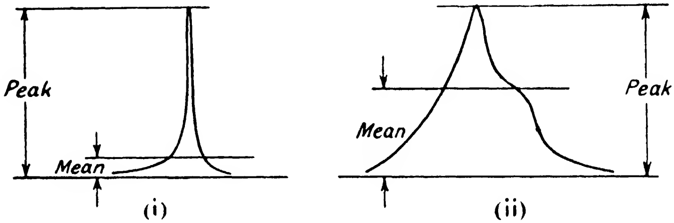


Fig. 1.15.—Effect of transient current on mean current rating of a gasfilled triode.

The instantaneous peak rating is even more important, since by reason of its transient nature it may be determinable with much less accuracy and, without special measuring devices, may escape detection entirely.

The peak value implies the maximum point to which the current rises and from which it immediately falls, and is indicated by a cusp in the time-current curve. While the time element does not enter into the specification of the peak current value, the gradient of the transient obviously affects the mean current value. For instance, the two transients in Fig. 1.15 both have the same peak value, but the mean current is much greater in one case than the other. The two ratings, peak and mean current, are not, therefore, independent, since both the magnitude and frequency of recurrence of the peaks affect the mean value.

Although, therefore, an overload in the peak value is in general more destructive to a thermal cathode than a similar overload in mean current, it is most important that during service these current limits shall be both restricted simultaneously. The peak current rating implies the maximum transient current without restriction on its frequency of recurrence, always provided the mean value is not exceeded.

The surge-rating or short-circuit current which represents the maximum permissible current at very infrequent intervals is generally somewhat in excess of the peak recurrent rating, though the makers do not usually specify this figure as a separate rating.

In the case of small valves it is usually possible to limit the surge or short-circuit current to a safe figure by suitable design of the anode transformer to secure sufficient circuit reactance, but with large valves additional chokes are included in the anode circuit to secure this condition.[1·25]

The Gases used in Triodes

The effect of varying the gas pressure already referred to in the case of a diode applies also in the triode, with the additional factor of its effect on the starting characteristic. Greater gas concentration involves a reduction in the mean free path, so that the plasma will be formed at lower electron currents and a more negative voltage on the control grid will be required to restrain the discharge. This is illustrated in Fig. 1.16, where the higher temperatures correspond to greater gas pressures. Since in the case of each of these curves the region of current conduction lies on the right-hand side of the curve, a reduction in gas pressure—*i.e.*, lower temperature—requires an increase in anode voltage to maintain the discharge. Thus the point A represents a condition of conduction at 45° C., but one of non-conduction at 25° C., and

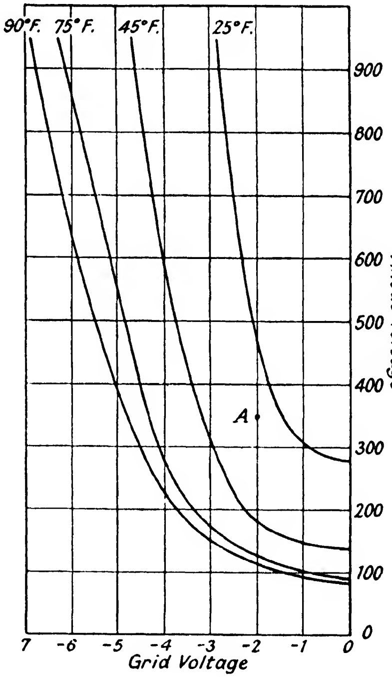


Fig. 1.16.—Variation of control ratio at different temperatures in a mercury vapour triode.

an increase in voltage from about 350 to about 475 is required to establish conduction at the lower temperature. In a mercury-filled triode, therefore, if the starting voltage is required to be critical, some means of controlling the temperature must be available, and, on account of the variation in starting voltage which temperature changes produce, mercury vapour triodes in small sizes have to a large extent been superseded by those having inert fillings in spite of the lower current rating. Also if clean-up of the gas occurs with an inert filling, the progressive decrease in pressure necessitates a more positive grid voltage as a limiting potential in restraining the discharge.[1.26]

Argon, neon, xenon and helium, at pressures varying from about four to ten times that common in mercury vapour triodes, have been used for inert gasfillings. Argon is chiefly used in this country and helium is common in valves of American manufacture. Xenon has been used in some American valves (R.C.A. 2050). It has the merits of low anode voltage drop and reduced tendency to clean up. In operation, inert gasfilling is recognised by the characteristic colour of the discharge as distinct from the bright blue colour of the mercury discharge. Hydrogen has been used in valves of special design for war applications.

Deionisation Time

The non-conducting state of the valve is not immediately restored when the anode voltage is reduced to less than the ionisation potential. A short but finite time is required for the plasma to disperse and for the positive ions to disappear by recombination or drift to the walls of the bulb, and if the anode voltage is again applied before this takes place the discharge will again be established even though the control grid is highly negative. The control grid cannot restrain the discharge as long as the plasma exists and positive ions are present.[1.27]

There is, however, a distinction between the time required for the grid to regain control if sufficiently negative and the time necessary for the ions to so disperse as to produce the same conditions in the bulb as existed before the valve fired. While this distinction exists, whether these times will be appreciably different or substantially the same will depend on the conditions under which the valve is being operated.

The period between the instant at which the anode potential is reduced below the ionisation voltage and the instant at which the control grid, if sufficiently negative, can restrain the discharge is known as the deionisation time. In many practical applications it is a most important factor, because it sets the limit to the rate at which the discharge can be recurrently stopped and started. Compared with the time required to establish ionisation[1.28] for the purpose of initiating the discharge, the deionisation time is long. It can hardly be considered as a constant even under fixed conditions of use, since, as the frequency of the firing cycle is increased, it begins to be apparent as intermittent firing which passes into a state of continuous uninterrupted discharge as the frequency is further increased. Both the design of the valve and the conditions of use affect the deionisation time. Normally this period is of the order of 10 to 1,000 microseconds. Some idea of the difficulty of specifying the deionisation time except within rather wide limits may be gathered from the fact that practically all the features of the valve have some influence on this period. The design and disposition of the electrodes influence its extent. A large grid surface, preferably with a number of small holes rather than a few large ones, favours a short deionisation time. The time is greater the higher the anode current prior to resetting, since under such conditions the ionisation during the conduction period is more intense (see Fig. 1.17). Recombination of ions takes place more readily at low gas pressure and is favoured by a high negative grid voltage, both of which tend to reduce the deionisation time. The rate of increase of voltage between anode and grid which takes place after the discharge has been interrupted is a contributory factor in determining the deionisation time.

In mercury vapour filled valves the increase in vapour pressure which occurs with rising temperature is accompanied by a marked increase in the deionisation time. The presence of external magnetic fields and the interelectrode capacitance of the electrode system also have an influence on this characteristic. Since the deionising time is less the higher the negative grid voltage, the performance of a gasfilled triode in a high-frequency switching circuit can be extended if the grid circuit provides the necessary high negative impulses through a low impedance path, so that the grid can assist the anode in cleaning up residual ions after conduction ceases.[1.29] Under favourable conditions of wave form and circuit constants, gasfilled triodes can be operated at switching frequencies of several hundred kilocycles. The deionisation of the valve under these conditions may be incomplete, but normal switching performance can be secured.[1.30]

It should be noted that even at low frequencies the duration of the whole of the negative voltage half-cycle is only available for resetting if the load is resistive and if the anode voltage and grid voltage are suitably phased. If the load is not resistive, the anode current may be extended into a portion of the negative voltage half-cycle; and if the grid voltage is alternating and a phase change method of control is employed, the resetting may be retarded and the deionisation time increased by the fact that the grid voltage may be more positive than the critical value during part of the time the anode voltage is reversed.

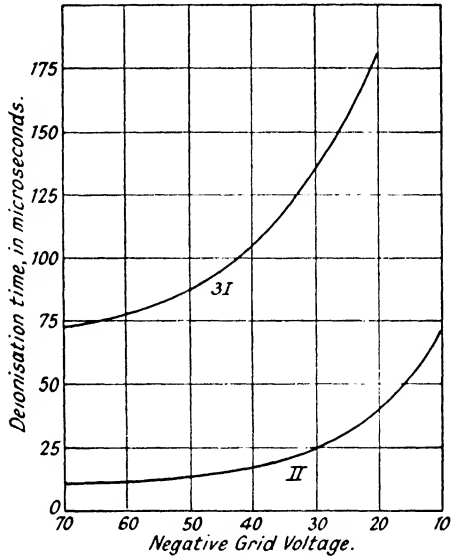


Fig. 1.17.—Deionisation time as a function of applied negative grid voltage.

The most favourable conditions for extinguishing the discharge and for producing the shortest deionisation time exist when both anode and grid become highly negative simultaneously at the instant the discharge is interrupted. If f is then the cyclic frequency, the whole period $1/2f$ sec. is available for resetting.

It is thus obvious that it may be possible by the arrangement of the circuit to secure conditions which tend to promote rapid deionisation and thereby increase the possible repetition frequency of switching (*cf.* p. 272). For instance, in the case of the parallel inverter (*q.v.*)

high negative impulses derived from the voltage across the commutating condenser are employed to reset the valve at the instant of current transfer. With all these facts in mind, it is easily understood why most makers do not specify any figure at all for the deionisation time, or do so only in the broadest terms[1.31, 1.32, 1.33]

Arc Voltage Drop [1.34]

The voltage across the valve, which is equal to the supply voltage in the non-conducting state, falls to a low value when the valve fires, and is then almost independent of the anode current. The lower limit of this voltage is the potential required to maintain ionisation; the permissible upper limit is the disintegration voltage of the cathode (or heating effect in the valve). Temperature variation affects the arc drop much more with mercury-filled valves than with those having inert filling. Fig 1.18 shows the test results on a small gasfilled triode with a mean current of 0·3 amp., the lower curve relating to a valve immediately after completion of the cathode preheating time, and the lower one to the same valve when it had previously been passing a current of 0·2 amp. for one hour.

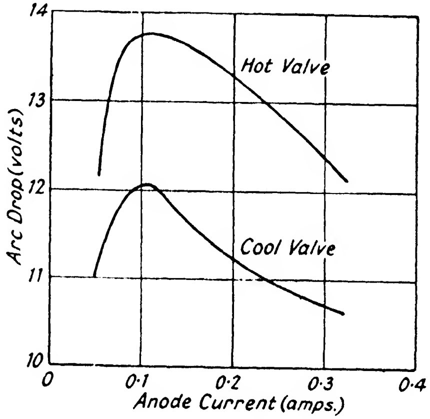


Fig. 1.18.—Arc voltage drop in a small gasfilled triode.

The arc drop is a function of the temperature and gas pressure and depends on the precise gas involved. In the case of valves having mercury pool cathodes, with which we are not here concerned in detail, the arc drop changes suddenly when a second hot spot forms on the cathode and results in the existence of a region of discontinuity in valves where adjustment of the mean anode current is secure by phase control (see Chapter VII.).

Rating of a Gasfilled Triode

Summarising the foregoing discussion, it will be evident that before such a valve is put into service the maker's rating under the following headings must be known and the circuit in which it is included must not impose more arduous conditions upon it, otherwise the valve may be damaged or only a short useful life secured from it. The important ratings are:

(i.) *Maximum Peak Forward Voltage.*—The maximum peak forward voltage is the highest permissible instantaneous positive voltage which may be applied to the anode without endangering the functions of the valve. In practice, the maximum voltage applied will, in the case of A.C., be the peak value of the voltage wave, though unsuspected transients may introduce a much higher peak voltage. In any given case the maximum forward voltage will be set by the gas pressure and electrode geometry, which should be designed to avoid sharp corners and projections which give rise to high-potential gradients. The gas pressure plays an important part in fixing the permissible forward voltage, particularly in mercury vapour valves, where a rapid increase in pressure occurs with rise of temperature. The proximity, in the pinch or base, of wires having a large difference of potential may cause trouble, even if the valve as a discharge device is capable of operating at much higher voltages.

Beyond a certain value of anode voltage the valve will fire irrespective of the magnitude of the negative grid voltage and all control will be lost. Consequently the working voltage ever likely to be applied to the anode must be well below this figure. There is also a limit of potential difference between anode and control grid, since, if a cold cathode discharge is established, sufficient ionisation may be produced to enable a positive ion sheath to form round the grid and no longer enable it to restrain the discharge.

In mercury-filled valves the maximum permissible forward voltage is generally greatly in excess of the voltages at which they are called upon to operate; but this is not so with inert gases, where the voltage limit set by breakdown of the gas is of a much lower order.

(ii.) *Maximum Peak Reverse Voltage.*[1.35, 1.36]—The highest reverse voltage (*i.e.*, anode negative) which can be applied safely without back firing. If the anode supply is A.C., the peak inverse voltage actually applied will be usually taken as the same as the peak forward voltage, so that it is customary to quote similar figures for both. Conditions may easily occur, however, due to the existence of capacity or inductance in the circuit under which transient voltages greatly in excess of the peak supply potential appear, and which may only be detectable by oscillographic recording. In a grid-controlled half-wave rectifier the reverse voltage is twice the forward voltage, and in an inverter (*q.v.*) a reverse voltage occurs momentarily at the instant of commutation.

It is usual to allow a large margin between the rated permissible reverse voltage and the arc-back voltage, usually of the order of 50 per cent. Both are influenced in exactly the same way as the permissible peak forward voltage by the electrode construction and disposition, the gas employed and its pressure, etc. The arc-back voltage decreases with increase of temperature, though much less so with inert gases than with mercury vapour.

Since, as already mentioned, the deionisation time is affected by this, among other factors, the conditions under which ionisation took place in the previous firing cycle may, for recurrent operation, limit the peak permissible inverse voltage due to the effect of ionisation remaining from the previous conducting half-cycle. With a valve having an inert gasfilling the possible clean-up of gas is met by an initial higher gas pressure. With inductive loads—*e.g.*, polyphase rectifiers—the period of conduction may persist into the negative half-voltage cycle and cease when the anode voltage has reached a relatively high negative value and while many positive ions exist in the discharge path. This produces increased tendency to arc-back and the need for operation well within the rated voltage limits is obvious.[1.37, 1.38.]

(iii.) *Maximum Peak Anode Current.*—The highest permissible instantaneous current which can pass through the valve recurrently, always provided the mean rating is not exceeded. Contributory limitations to the peak value are set by the possible evolution of gas from the electrodes, ion emission from the grid, mechanical stresses in the seal due to expansion, tendency to arc-back or formation of hot spots on the cathode. The peak current is an important factor where there are condensers which may charge or discharge through the valve. If accidental overload is possible, an instantaneous overload circuit breaker must be included in circuit to operate at not more than the peak current rating. Fuses are insufficiently rapid in action to afford protection.

Transient voltages and currents are delineated most satisfactorily by means of the cathode ray tube. For such purposes, electrostatically deflected tubes are generally employed. As these are voltage-operated instruments, the measurement of current is most easily carried out by recording the voltage produced by the current across a known resistance. If the deflectional sensitivity of the tube is not known, it will need to be calibrated by the application of known direct voltages to the plates. Where the firing of the triode is a regular cyclic process, a linear or spiral recurrent time base can be roughly adjusted to the circuit frequency and finally synchronised with the firing impulse. In such cases a stationary outline may be delineated and the existence of transients located and measured. Evaluation of peak currents in this way presupposes no discontinuity in the curve since this may indicate a peak off the screen, in which case it will be necessary to reduce the input voltage to the tube, and possibly increase the spot-brightness if the movement near the peak is too rapid to give a readable trace.

If the conditions of use of the triode do not permit of recurrent screen traces, and only a single traverse is possible, it may be necessary to resort to photographic recording to determine peaks of transients.[1.39]

(iv.) *Permissible Mean Anode Current.*—Usually expressed as a true arithmetic mean measured by a moving coil instrument, this rating is fixed by the emissivity of the cathode. Usually makers specify the permissible mean value of the order of one-third to one-fifth of the permissible peak current rating, but often this value is conservative and may be as much as 50 per cent. of the safe peak current.

Closely associated with the anode current is the heater rating. Triodes and tetrodes are almost invariably voltage rated for the heater circuit. This means that the voltage specified by the makers must exist across the heater terminals when the heater circuit is completed. The current is specified as a nominal rating, since it is necessary to know this for the purpose of calculating the winding for the transformer supplying the heater current.

The danger to the life of the valve by operating at insufficiently high cathode temperature through low voltage at the heater terminals has already been referred to and cannot be over-stressed. To ensure maximum life the heater voltage should be maintained within ±5 per cent. of the rated value. Change from no load to full load on the transformer frequently results in a greater voltage change than this, and the mains voltage may show fluctuations of as much as ±10 per cent.

The importance of close control on cathode temperature will be appreciated when it is stated that a reduction of 10 per cent. in heater voltage may increase the arc drop and starting voltage by about 40 per cent. Insufficiently high cathode temperature results in increased positive ion bombardment due to the higher arc drop, and the emission, instead of being distributed, becomes concentrated in localised arc spots at which the temperature and current density is high enough to tear off portions of the oxide coating.

Over-voltage at the cathode terminals produces increased cathode evaporation resulting from the higher surface temperature. This results in reduced life, with the possibility of deposition of active material on the anode and grid, causing a tendency to arc-back and loss of grid control as the life of the valve progresses.[1.40]

(v.) *Grid Control Ratio.*—This factor corresponds to the slope of the anode voltage /critical grid voltage curve, and is obviously constant only over the linear portion of that curve—usually a fairly wide range in negative grid control valves. In such valves it decreases at quite low anode voltages, so that towards the lower end of the curve the critical voltage may be positive. There is little to indicate what the optimum value of grid control ratio ought to be apart from the fact that from practical considerations based on the likely values of anode voltage it should lie between about 20 and 100, and if any choice is available the higher values are suitable for high voltages and vice versa.

(vi.) *Deionisation Time.*—Since this is a factor dependent on so many circuit variables, and not merely a characteristic of the valve alone, it is usually the one which can be specified with least precision, in spite of its importance as the limiting factor for rapid recurrent firing.

Of all these factors, possibly the peak current is the most important to watch in any circuit under proposal. Many cases of short or inadequate life in circuits which perform a repeated cycle of functions are due to the existence of such unsuspected current transients, and not to any fault in the valve to which user may be inclined to attribute them.

Some Practical Considerations

Although the value of the grid voltage at which a gasfilled triode fires is critical and the discharge can be established by a grid impulse of only a few microseconds duration, many voltage surges and disturbances of this duration and of considerable amplitude, which for most other practical purposes would pass unnoticed, are met with in industrial circuits; it is essential that precautions are taken to prevent such transients gaining access to the control grid, where they will produce erratic and spontaneous firing of the valve.

Since efficient earth screening will prevent the pick-up of direct electrostatic or electromagnetic interference, such disturbances are most liable to find their way into the valve through the only remaining path—*i.e.*, via the power supply.

The incoming leads should therefore be provided with condenser shunts on D.C. circuits. The existence of fairly large capacity condensers in gasfilled triode circuits in positions where they apparently play no essential part at all is thus explained.

A large difference of potential between heater and cathode is an undesirable feature, hence the practice of connecting one side of the heater to cathode. Though the maximum permissible potential difference between heater and cathode depends on the electrode design, in general the permissible difference is greater when the heater is negative to the cathode than when this polarity is reversed.

In a small valve a voltage difference of 30 with the heater positive to the cathode may cause loss of control and possibly a disruptive discharge.

In some instances it may be necessary to provide electrostatic shielding between the windings of any transformer feeding the grid circuit. A small condenser between grid and cathode in addition to the usual grid resistor is preferably included as a means of preventing precipitate operation.

For similar reasons the magnitude of both the negative restraining grid voltage and the triggering voltage should be larger than theoretical considerations indicate, so as to secure reliable operation.

The necessity for adequate grid voltage amplitude when the valve is operated by a phase change on A.C. supply is referred to later in Chapter II.

The past twenty years have seen the development of numerous electronic devices, many of which have indicated promise of practical utility, and the gasfilled triode among them has shared a place in the vast amount of patent and technical literature which has been published. As with any relatively new device, there has been some tendency to over-optimism of the possible scope of application of the gasfilled triode, and while the following pages indicate its importance in its proper sphere, there are many instances where it could be used, but for very good reasons has not been used. Some of the promising applications have not been commercially exploited, though this in no way detracts from the technical interest in the uses of the valve which it is the object of this book to describe.

It is desirable, therefore, to view the practical utility of the gasfilled valve in its true perspective, before an unbiased assessment of its merits can be secured.

The higher current rating as compared with a hard valve of comparable size may not necessarily be such an advantage as to justify the higher cost of the gasfilled valve. The following pages will indicate that many simple relay circuits can be actuated equally effectively either with a hard valve or a gasfilled triode, in which case the former will score on first and replacement costs.

Valve replacement after a specified life is inevitable, so that an additional operating cost will be debited against either type of valve if an adequate alternative solution by mechanical means is possible.

The question, therefore, which must always be foremost in the prospective user's mind is not whether any mechanical method as an alternative solution can be evolved, but whether the gasfilled triode can provide a more satisfactory solution, and, if so, are the replacement and running charges involved worth the advantages secured.

Since almost every application uses gasfilled triodes under different conditions, a definite life guarantee is difficult to specify, and in view of the diversity of conditions of use, the maker's rated life is often a conservative figure. In general the expectation of life may be extended by operating the valve at anode currents below the maker's rating.

The preheating time of the cathode is certainly a drawback and one which is unavoidable. If the valve is to be operated only at infrequent intervals, the continuous power consumption of the heater becomes of greater concern as the size of the valve increases.

The cathode needs protection against heavy peak currents due to surges, short circuits, etc., which can be very destructive, so that the inclusion of automatic cut-outs may be called for, since the time lag of fuses affords insufficient protection against damage.

There is little evidence that the gasfilled valve is any less robust than its vacuum prototype. Where the inherent characteristics of the gasfilled valve are essential, the particular type of gasfilled valve to be used may be determined by what is commercially available. On the other hand, the user has the alternatives of a mercury vapour valve with the necessity for temperature control for stable operation or one with inert gasfilling with lower voltage and current rating but little restriction on the ambient temperature.

CHAPTER REFERENCES

1.1. *Elektrot. Zeits.*, 34 (1913), p. 1356.

1.2. U.S. Patents 1,112,655, 1,087,180, 1,112,549, 1,450,749, 1,364,129, 1,408,118, 1,369,457 and others.

1.3. Hull and Winter, *Phys. Rev.*, 21 (1923), p. 211.

1.4. Kingdon and Langmuir, *ibid.*, 22 (1923), p. 148.

1.5. Hull, *Trans. Am.I.E.E.*, 47 (1928), p. 153.

1.6. Found, A new method of investigating thermionic cathodes, *Phy. Rev.*, 45 (1934), p. 524.

1.7. Steiner, Gable and Maser, Engineering features of gasfilled tubes, *Electrical Engineering*, 51 (1932), p. 313.

1.8. Hull, *Trans. Am.I.E.E.*, 47 (1928), p. 798.

1.9. Hull and Langmuir, Control of an arc discharge by means of a grid, *Proc. Nat. Acad. Science*, March, 1929.

1.10. Mahla, Predischarge current measurement with two grids, *Zeits. f. tech. Phys.*, Vol. 17, No. 1, pp. 19-35, and No. 2, pp. 36-44 (1936).

1.11. Wheatcroft and Hammerton, Pre-striking condition in a thyratron, *Phil. Mag.*, Vol. 26 (1938), p. 684.

1.12. Glaser, Physical basis of grid control of gas discharges, *Zeits. f. tech. Phys.*, Vol. 13, No. 11 (1932), pp. 549-50.

1.13. French, Operating characteristics of small grid-controlled hot cathode arcs or thyratrons, *Journ. Franklin Inst.*, Vol. 221 (1936), pp. 83-102.

1.14. Hull, Hot cathode thyratrons, *G.E. Rev.*, Vol. 32 (1929), p. 219.

1.15. Tonks and Langmuir, General theory of the plasma of an arc, *Phy. Rev.*, Vol. 34 (1929), pp. 876-922.

1.16. Hughes, Grid-controlled rectifiers, *Electrician*, 116 (March 6, 1936), p. 313.

1.17. Wehner, Periodic extinction and control of a mercury vapour arc with plasma-surrounded grid, *Zeits. f. tech. Phys.*, 21, 3, (1940), pp. 53-63.

1.18. Nottingham, Characteristics of small grid-controlled hot cathode mercury arcs or thyratrons, *Journ. Frank. Inst.*, Vol. 211 (1931), pp. 271-301.

1.19. Fairbrother, Dependence of thyratron characteristics on electrode spacing and design, *Wireless Engineer*, 14 (April, 1937), pp. 196-8.

1.20. Harrison, Ionisation time of thyratrons, *Trans. Am.I.E.E.*, 59, pp. 747-50.

1.21. Kirchstein, The ignition characteristics of rectifiers and the influence of grid resistance thereon, *Wiss. Veroff. a.d. Siemens Werken*, 18, 3, (1939), pp. 82-93.

1.22. Selitzky and Shevki, Grid and plate currents in a grid-controlled mercury vapour rectifier, *Journ. Frank. Inst.*, 215 (March, 1933), pp. 299-326.

1.23. White, Deionisation, *Electrician*, 116 (March 27, 1936), p. 407.

1.24. Hermann, Deionisation and reignition in grid-controlled discharge tubes, *Arch. f. Elektrot.*, 30 (September 8, 1936), pp. 555-80.

1.25. Hellmund, Current ratings of electronic devices for intermittent service, *Trans. Am.I.E.E.*, 61 (August, 1942), p. 569.

1.26. Kobel, Vapour pressure and voltage drop in mercury arc rectifiers, *E.T.Z.*, 53 (September 15, 1932), pp. 881-3.

1.27. Gaudenzi and Kobel, The effect of residual ionisation on grid control of mercury vapour arc rectifiers, *Congrès International d'Electricité*, Paris, Sec. 3 (1932), Rapport 22.

1.28. Snoddy, Ionisation time of thyratrons, *Physics*, Vol. 4 (October, 1933), pp. 366-71.

1.29. Morack, Voltage impulses for thyratron grid control, *G.E. Rev.*, 37, (1934), p. 288.

1.30. Shepherd, Deionisation considerations in a harmonic generator employing a gas-tube switch, *Proc. I.R.E.* (N.Y.), 31 (February, 1943), pp. 66-74.

1.31. Watanabe and Nakamura, Reignition voltage characteristics of grid-controlled discharge tubes, *Electrochemical Journal* (Tokyo), 3, (November, 1939), pp. 243-6.

1.32. Hermann, Deionisation and restriking of grid-controlled gas discharge tubes, *Arch. f. Elektrot.*, 30 (September 8, 1936), p. 555.

1.33. Wittenberg, Frequency performance of thyratrons, *Trans. Am.I.E.E.*, 65 (December, 1946), pp. 843-7.

1.34. Reinhardt, Measurement of arc drop in mercury vapour rectifiers, *Elektrot. u. Maschinenbau*, 57 (October 13, 1939), pp. 497-501.

1.35. Watanabe and Takahasi, Methods of measuring backfire voltage, *Electrochemical Journal* (Tokyo), Vol. 3 (March, 1939), pp. 56-9.

1.36. Kingdon and Lawton, The relation of residual ionisation to arc-back in thyratrons, *G.E. Rev.*, 42 (November, 1939), pp. 474-8.

1.37. Hull and Elder, Phase of arc-back, *J. App. Phys.*, 13 (March, 1942), pp. 171-8.

1.38. White, A new approach to the study of arc-back, *J. App. Phys.*, 13 (April, 1942), pp. 265-73.

1.39. Wilson, The cathode ray tube in industry (Chapman and Hall).

1.40. Jenks, Filament control and its tube life effect, *Communications*, 22 (December, 1942), p. 12.

1.41. Webster, Note on the ionisation time of an argon-filled relay, *Journ. Sci. Instr.*, Vol. 24 (November, 1947), pp. 299-301.

1.42. Cance, Note on the ionisation and deionisation times of gasfilled thyratrons, *Journ. Sci. Instr.*, Vol. 23 (March, 1946), p. 50.

CHAPTER 2

The Gasfilled Tetrode or Shield Grid Thyratron

Limitations of the triode. Design of the grid in a gasfilled tetrode. Grid resistance. Electrode potentials. Means of varying the control characteristics. Typical gasfilled tetrodes.

Limitations of the Triode

THE addition of a second grid to a gasfilled triode forming a tetrode considerably extends the ways in which the grid-controlled gasfilled rectifier can be used, and results in a device which has a number of advantages over its simpler prototype.

Reference has already been made to the fact that although the triggering voltage on the grid of a triode is critical, it is not always possible to secure positive and reliable operation if the change in voltage on the grid intended to fire the valve is too small. Small changes in the characteristics of the valve or short-period surges in the electric supply may provide sufficient change on the grid to initiate the discharge if the bias in the quiescent state is set too close to the critical value. Moreover, the grid current rises to a relatively large value after the discharge starts. Although this is not directly disadvantageous from the point of view of firing the valve, since it occurs after the grid has ceased to exercise control, it may have undesirable effects in particular cases.

For instance, the distortion of the signal voltage which results from high grid current may upset the sequence of firing of other valves associated with the circuit. If the grid circuit includes a transformer, a condition of semi-saturation may be produced in the magnetic circuit which persists after the discharge should have ceased and when the grid is trying to regain control.

More important than this is the limitation which grid current imposes on the value of the resistance between grid and cathode before the discharge takes place. Unless the starting grid current is very small, it gives rise to a voltage drop across this resistance, reducing the input signal voltage and tending to make the point of firing less dependent on the signal voltage. The grid resistance of a small triode

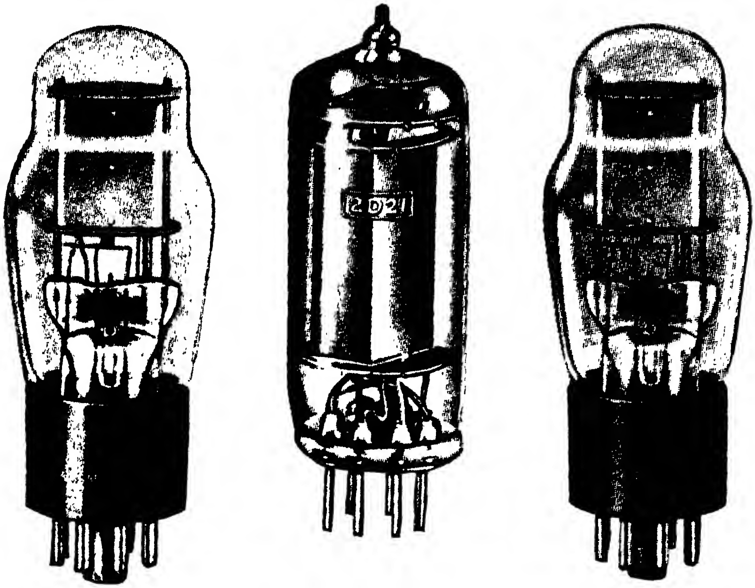


Fig. 2.1A.—Some typical shield grid thyratrons.

is, therefore, limited to about a megohm, with the result that if connected to a high impedance signal circuit such as an emission type of photocell, the combination is relatively insensitive except to large light changes.

The effect which the grid current of a gasfilled triode has on the performance of the circuit when the grid resistance is high is not difficult to demonstrate. With an alternating anode voltage of constant peak value and a suitable milliammeter in the anode lead to indicate when the valve fires, a circuit can be connected up with an adjustable direct negative voltage applied to the grid. If the negative grid bias is gradually increased from a low value, a point will be reached when its value is, say, E_1, at which the valve just ceases to fire. The test is then repeated with a high resistance, say

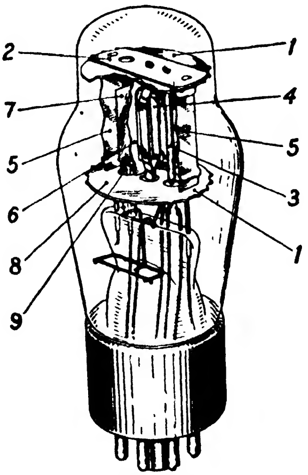


Fig. 2.1B.—Exploded view of the electrode system of the R.C.A. type 2050.

5-10 megohms in series with the grid bias. In this case the negative grid voltage, say E_2, which is just sufficient to restrain the discharge, is much higher than E_1, possibly eight to ten times as great. Though the value of the factor $\frac{E_2-E_1}{R}$, where R is the grid resistance, may be some rough indication of the magnitude of the grid current, it is of little practical use for comparative tests, because it does not distinguish any of the several contributory causes of grid current.

In the case of a mercury vapour valve the grid current will change as the valve warms up, with a corresponding change in voltage across the grid resistor, so that the point of firing may be uncertain until steady conditions have been attained.

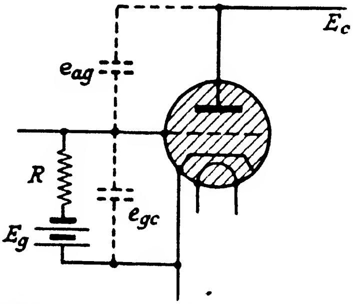


Fig. 2.2.—Feed back in a gasfilled triode through inter-electrode capacitance.

In some cases where the anode voltage increases with a steep wave front, the anode-grid capacitance in a triode may be sufficient to communicate this voltage change to the grid, which thus tends to follow the anode voltage change. This is opposed by the grid bias voltage, but if the grid resistance is high the bias battery may not be able to offset instantaneously the voltage fed back from the anode, with the result that the grid may momentarily assume a potential which enables the valve to fire (see Fig. 2.2).

A condenser between grid and cathode will improve the stability in such cases, and can be included if the grid power is not too limited; but if the signal input is too small to permit the inclusion of such a condenser, then a smaller grid resistance must be used or the triode abandoned in favour of a tetrode.

Design of the Grid in a Tetrode

The design of a tetrode results in a grid current which is many times smaller than in the case of a triode (Fig. 2.3). In a gasfilled triode the signal grid is relatively large in order to exercise control over all the possible electron paths between cathode and anode and to screen the discharge path from any electrostatic charges which may collect on the walls of the glass bulb. In the tetrode the shield grid performs the latter function, and the control grid can then be reduced in size so as only to be large enough to cover the openings in the baffles of the screen through which the discharge will pass.

The reduction in the size of the control grid results in a greatly reduced ion current both before and after the discharge passes. In addition, the shield screens the control grid from any active surface material which may be evaporated or sputtered from the cathode surface and which would tend to increase grid emission. It also forms a heat shield to cut off direct heat radiation from cathode to control grid.

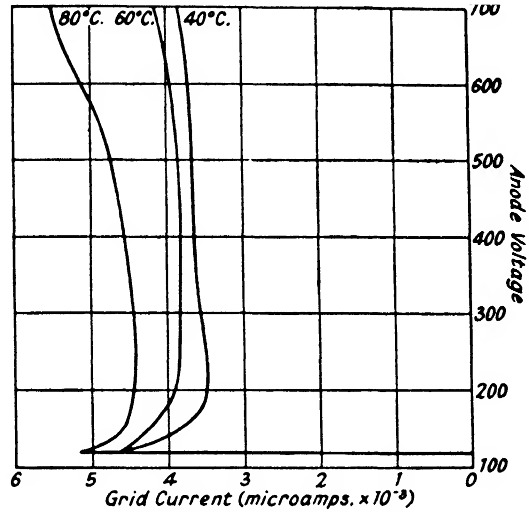


Fig. 2.3.—Grid current in a typical shield grid thyratron. Shield grid connected to cathode. Signal voltage 50v A.C.

It will be clear from the disposition of the electrodes in a tetrode shown diagrammatically in Fig. 2.4 that the electrostatic capacitance of the signal grid to anode or cathode is greatly reduced and its charging current small, due both to this cause and to its small physical dimensions.

One result of this construction is that circuits operated by phase change between anode and grid can be made highly sensitive to small changes in capacitance.

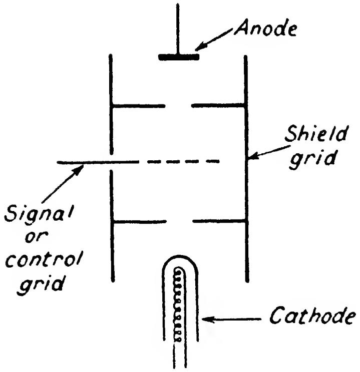


Fig. 2.4A.—Diagrammatic representation of the electrode system of shield grid or tetrode thyratron.

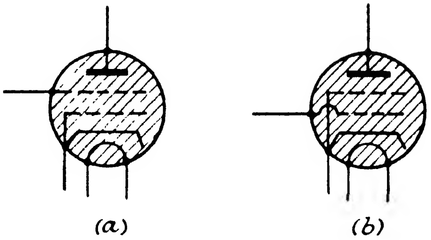


Fig. 2.4B.—Alternative methods of representing screen grid gas-filled valves (shield at cathode potential).

Grid Resistance

Such modifications in design enable much higher grid resistances to be used with tetrodes than are permissible with triodes. In nearly all cases where triodes are employed tetrodes could equally well be used, and with advantage in the case of high impedance signal circuits.

Electrode Potentials

Means of Varying the Control Characteristics.—The existence of the second or outer grid introduces the possibility of an independent variable which widely extends the possible conditions under which the valve can be operated, and enables a unit with either positive or negative control grid voltage to be secured. The precise effect of varying the shield voltage will, of course, depend on the design of the particular electrode system, but in general for steady shield grid bias voltages the more negative the bias on the shield grid the less negative the critical control grid voltage, so that with a sufficiently negative shield voltage positive grid control is secured.

As has been previously mentioned, positive grid control valves are advantageous in some applications, since the discharge is in such valves restrained at zero grid voltage. If for the purpose of safety it is desirable to ensure that the discharge is shut off if any fault occurs in the grid circuit, the positive grid control clearly secures this condition, but negative grid control tubes do not.

With a fixed negative shield voltage the critical control voltage becomes more negative as the anode voltage is increased, in this respect following the general trend of the triode characteristics.

With a specified anode voltage the initiation of the discharge depends on the resultant potential applied to the signal and shield grids, and in consequence the control of the valve can be made conditional upon two voltages which may be dependent or independent of each other.

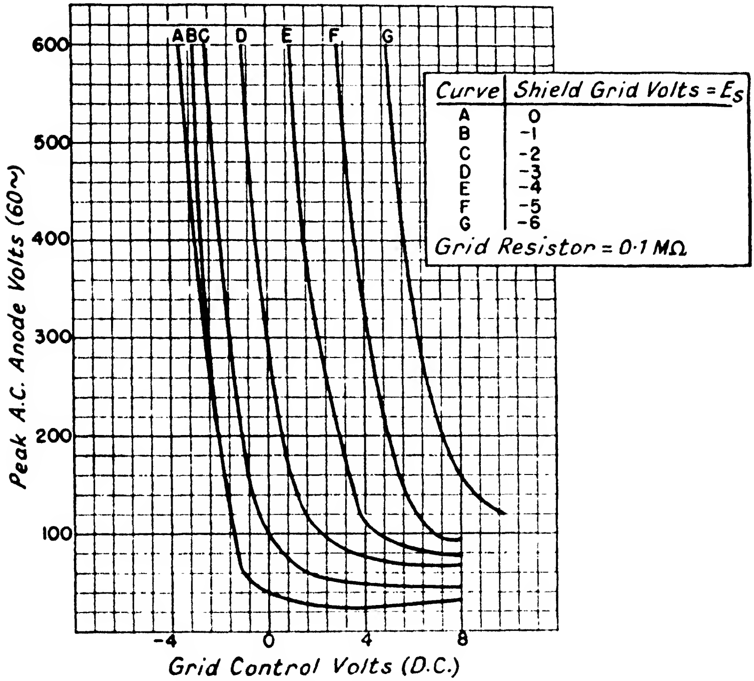


Fig. 2.5.—Grid control characteristics of the Westinghouse WL2050 shield grid thyratron.

Fig. 2.5 shows a set of grid control curves for a typical shield grid thyratron, indicating their general trend for various values of potential on the two grids. As the shield grid is made more negative with respect to the cathode, the curves are displaced in the direction of positive signal grid control, the effect being that for a fixed signal grid restraining bias the anode voltage required to fire the valve is increased. For instance, in the case of curve C, Fig. 2.5, with -2 volts shield grid voltage, a signal grid bias of -1 volt requires an anode voltage of about 200 to fire the valve. Maintaining the same signal grid voltage and increasing the shield grid potential to -3 volts requires an anode voltage of about 600 to fire the valve. Making the shield grid less negative has the opposite effect—viz., the anode voltage required to establish the discharge is reduced. It will be clear, therefore, that a small change in shield grid voltage has a relatively large effect on the anode voltage required to start the discharge, and that the region of positive voltage control on the signal grid is easily secured by applying a bias of a few volts negative to the shield grid.

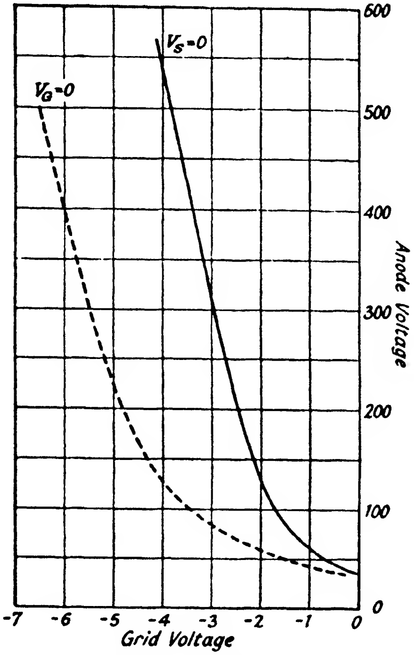


Fig. 2.6.—Curves showing the effective control exercised by the two grids in a typical shield grid thyratron.

From the curve shown in Fig. 2.5 it is possible to plot further characteristics which indicate more clearly the relative functions played by each grid if used independently as the controlling medium. In Fig. 2.5 curve A shows the relation between anode voltage and signal grid voltage when the shield grid voltage is zero. Another curve can be drawn whose abscissæ are the values of the points at which the curves of Fig. 2.5 cut the vertical co-ordinate axis corresponding to $E_g=0$, with the corresponding anode voltages as ordinates.

Carrying out this construction with the curves of Fig. 2.5 does not depict the result very clearly, since only three of the curves intersect the vertical axis of co-ordinates. Fig. 2.6 shows the general trend of such a pair of curves for another type of shield grid thyratron of rather different construction. Here the full curve shows the conditions under which the valve will fire when the shield grid voltage is zero; the dotted curve indicates the conditions obtaining when the signal grid is maintained at cathode potential and the shield grid voltage varied to control the discharge. The first of these curves, being of steeper slope, indicates a higher grid control ratio than with the second curve, and shows that potential variations on the signal grid are more effective in controlling the discharge than when the normal functions of shield grid and signal grid are reversed—a result which might be anticipated.

A further set of curves can be plotted from Fig. 2.5 by drawing lines parallel to the horizontal co-ordinate axis, each such line representing a condition of constant anode voltage and recording the points at which each such line cuts the curves A . . . G. If the points of intersection are then plotted with co-ordinates as the corresponding values of signal grid and shield grid voltage, a set of curves is obtained indicating signal grid and shield grid voltages as independent variables with constant anode voltage.

All these curves indicate the possibilities of using either grid as the controlling medium for steady input voltages. The effect of varying the grid resistance is indicated by the curves of Fig. 2.7.

If the screen grid voltage is fluctuating, it is possible to secure

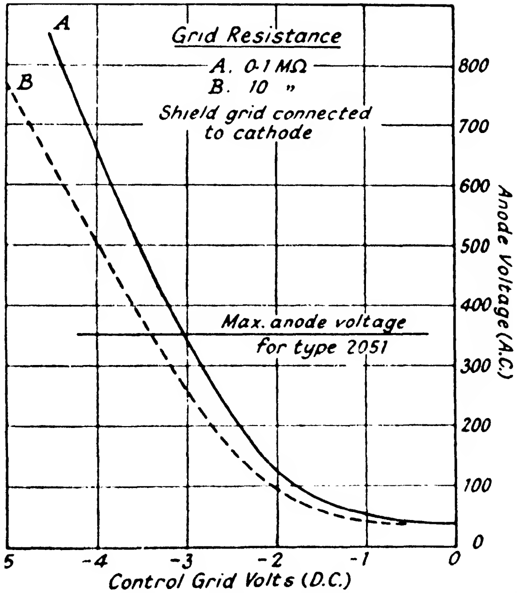


Fig. 2.7.—Average control curves of hot-cathode gasfilled tetrodes, R.C.A. types 2050 and 2051.

characteristics in which the control voltage is positive over some parts of the curve and negative over others. Further interesting cases arise when both signal grid and shield grid voltages are alternating and variable in phase and magnitude, or when one is alternating and the other steady. The point of firing and the mean anode current will then depend on the relation between the two voltages, and the mean anode current then becomes a function of two independent signals.

Numerous possibilities are thus available for the conditions under which a shield grid thyratron can operate and a variety of grid control characteristics become feasible with a single valve.

As far as the author is aware, such varied conditions of use, though of considerable interest, have not been put to any extensive practical use, and the industrial applications of the shield grid thyratron are almost confined to cases where the shield grid is given a constant steady voltage for the purpose of securing greater stability and protection against spurious firing impulses, and for the utility of this type of valve for direct control from a high impedance circuit made possible by the reduced grid current which the electrode construction secures.

Representation.—The shield grid thyratron is found represented in published literature, as shown either in Fig. 2.4B (*a*) or (*b*). Since the shield screens both cathode and anode, either according to the usual method of valve representation would appear to be justified, though the former is most usual, possibly from the established practice of representing the hard vacuum tetrode in this way. It is the one adopted throughout this book.

Typical Gasfilled Tetrodes

Examples of the way in which the structural design ensures a low grid current in the gasfilled tetrode by confining the electron paths between cathode and anode to as short excursions as possible are those of the R.C.A. 2050 and 2051 (Fig. 2.1B).

These valves have steep control characteristics independent of the ambient temperature over a wide range and are fitted with standard octal bases. The cathode is oxide coated, indirectly heated, and of 6·3-volt 0-3 amp. rating, and shown at (3) in Fig. 2.1B at one side of the stem. In practice the cathode is preferably connected to the midpoint of the heater, and although the cathode may be made positive to the heater, the voltage between the two must be as small as possible. The cathode should never be made negative to the heater. The anode (7), which is on the other side, is a small flat plate mounted on a heavy-gauge wire support surrounded by a glass sleeve (8) extending through the mica, insulating it from all other points of the electrode assembly, so that leakage of the gas discharge between the anode and any other part of the electrode system is prevented and a high insulation resistance maintained between control grid and anode. The metal shield (5) surrounds the anode and cathode, which are separated from one another by a slot aperture (6) dividing the shield into two compartments. This design ensures that practically all the field lines from the cathode terminate at the surface of the shield or on the mica plates (1) which close the end of the shield. As the number of ionising collisions which can occur in this region is small, the gas leakage current is reduced to a low value.

The small size of the control grid minimises its tendency to collect ions and reduces its electrostatic capacity. By transposing the lead-in wires so that the cathode wire passes through the point between those of the anode and the grid, the grid-anode capacitance is reduced.

The shield micas at the top and bottom of the mount are coated with a conducting deposit to complete the shielding, and this is connected to shields 5 and 6. The shield also affords protection to the control grid against radiant heat from the cathode. These micas do not support the cathode and grid, this function being carried out by insulating micas (2), one above the top shield mica and another below the bottom one. The shield micas effectively prevent material sputtered or evaporated from the cathode being deposited on the insulating supports to form leakage paths between either of the electrôdes. They also space and align the components so that only small tolerances exist in the characteristics of individual valves. Although the performance of the valve is not appreciably affected by line surges, when a high valve grid resistance is used the grid-anode capacitance should be kept as low as possible by placing the resister at the socket terminals and keeping the base clean and dry.

The makers recommend that a high grid resistance should not be used when the shield grid voltage is more positive than -1 volt. As the shield grid is made more negative, the signal grid-firing voltage is made more positive, and at $V_s = -4$ the control grid characteristic is entirely in the positive region.

Type 2051 is argon filled, while with type 2050 the filling is xenon, for which the ionising potential is lower. This results in some difference in characteristics between the two types, the 2050 having nearly twice the permissible peak forward and reverse anode voltages and more than 30 per cent. higher mean anode current than the 2051.

Oscillograph tests on the control characteristics to investigate the uniformity of the firing voltage have shown that the changes which occur are small. With the valve under continuous operation at maximum rated anode voltage the rate and extent of the change is greater the greater the load. As the change in characteristics can be restored by keeping the heater in circuit for a period with a high negative voltage on the signal grid to prevent the discharge passing, such changes as do occur have been attributed to localised reduction in cathode emission at points opposite the grid aperture due to bombardment of the emitting surface by positive ions during the formation of the discharge, and to changes in contact potential between the grid and a surface layer formed on it by bombardment and heating of the grid by the discharge. The effect is to require a reduced negative control grid voltage.

Most of the change occurs in the first 200 to 500 hours of life, after which remarkable constancy is observed until the time approaches when the useful life terminates by loss of cathode emission. The maximum change in grid control voltage observed was 0·8 to 1·0 volt in the 2051 and 0·3 to 0·4 volt in the 2050.

REFERENCES

1. Windred, The gasfilled tetrode, *Electronics, Television and Short Wave World* (August, 1940), p. 359.
2. Livingston and Maser, Shield grid thyratrons, *Electronics* (April, 1934), p. 114.
3. Bahls and Thomas, New sensitive and inexpensive gas control tubes, *Electronics* (September, 1941), pp. 33-5.

CHAPTER 3

Methods of Applying Gasfilled Triodes— Basic Circuits

Extinction of the anode discharge. Relay switching. Condenser discharge. Alternating anode voltage. Grid control curve. Alternating anode voltage. Steady grid bias. Alternating grid voltage. Phase change and its effect on the mean anode current. Alternating grid and steady anode voltage. Variation of grid voltage amplitude. Superposition of an alternating voltage on a steady grid bias. Peaked voltage firing impulses. Biphase connection of triodes. Parallel operation. Inverse parallel. Methods of producing phase change in the grid circuit. Inductive loads. Some practical considerations. Switching heater and anode circuits. Protection against overload.

Extinction of the Anode Discharge

ALTHOUGH, as mentioned in the previous chapter, it is possible to design a grid-controlled thermionic gasfilled valve in which the application of a high negative grid voltage will extinguish the discharge, this means of control is limited to cases where the anode current is small and considerable power is required in the grid circuit to disperse the sheath of positive ions surrounding the grid. Valves operating under such conditions are exceptional and of little practical importance, and do not come within the purview of the present discussion.

Normally it may be assumed that the discharge, when once established, can be extinguished only by reducing the anode voltage below the ionising potential of the gas in the valve and for a period exceeding the deionisation time.

This is most simply carried out by opening the anode circuit, which may in some cases permit of the manual operation of a switch in the anode lead. In the case of a relay actuated circuit this operation can in certain circumstances be performed automatically by the relay itself, which after closing the contacts of the controlled circuit also breaks the anode circuit. This means that without some further attachment the relay is de-energised almost immediately it is excited. In order to ensure that the controlled circuit is closed long enough for the indicator or other device included in it to be fully operated, one or both of the following modifications may be included in the relay: (*a*) The relay may be provided with a copper slug around the iron circuit at a point remote from the pole face. This constitutes a single short-circuited turn of wire of very low resistance and high inductance, and has little or no effect on the operating time of the relay; but when the exciting coil circuit is opened, the inductance of the slug tends to maintain the magnetic flux, which dies away less rapidly, giving a delayed opening to the contacts. A delayed release up to about 400 milliseconds can be obtained in this way, so that the make contacts of the circuit-controlled will be able to close positively before the relay releases due to the opening of the anode circuit. A relay with a slug attachment for obtaining a delayed release is represented diagrammatically by the partly shaded rectangle, as shown in Fig. 3.1. (*b*) Another modification which can be included in the relay is a make-before-break change-over set of contacts. In Fig. 3.1 the contacts *ab* close before *bc* open, so that the indicator 2 is operated before the anode circuit of the valve is broken. In some cases the time interval obtained by this method will be insufficient, but it can be used to supplement the action of a slugged relay.

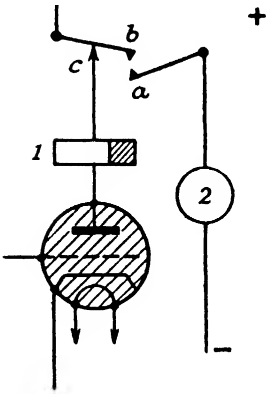


Fig. 3.1.—Extinction of the anode discharge by relay operation.

Where the time delay in both cases is insufficient it will be necessary to add a separate delayed-action switch.

It should be noted that this arrangement is operative in giving a single impulse in the indicator circuit only if the cyclic period of the relay circuit is greater than the duration of the signal impulse. If the grid of the valve is reduced below the critical negative value for a time greater than that required by the relay to complete its operation, the excitation of the relay will repeat and give a double indication, and in fact will continue to do so as long as the anode current through the valve persists.

The suppression of the discharge by means of an injected reverse voltage which may be communicated to the anode circuit through a transformer, one winding of which forms part of the anode circuit, is another and obvious method of resetting the circuit, but it is one which is not always easy to apply and hardly needs further elaboration.

A third method, and one of some importance, is the use of a condenser discharge. Two cases in which this may be applied are illustrated in the circuits of Fig. 3.2. In Fig. 3.2 (*a*) the anode circuit includes a high resistance 3 (20,000 ohms or so), which is too high to pass the mean anode current of the valve, but which enables condenser 4 to charge up to the full supply potential when the valve is negatively biased on the control grid to a value which would normally prevent the valve from firing. On the arrival of an impulse which reduces the negative bias on the control grid below the critical value the valve "fires" and the condenser discharge passes through the relay 1 as a short-duration discharge of relatively high peak value. The condenser voltage immediately falls to a low value, since resistance 3 is too high to maintain the discharge through the supply and the discharge is extinguished. Resistance 2 is included in the relay circuit to prevent the peak value of the current rising above its rated value if the resistance of the relay is insufficient to ensure this condition. After the condenser has discharged it starts immediately to charge up again through resistance 3, ready to repeat the process outlined as soon as the control grid is again reduced below its critical value. As in the case of the circuit of Fig. 3.1, where the electromagnetic relay interrupts its own circuit, the relay 1 in Fig. 3.2 (*a*) will

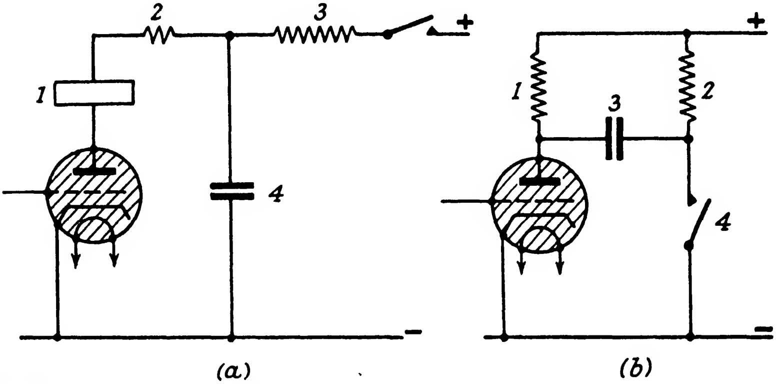


Fig. 3.2.—Extinction of the anode current by means of a condenser discharge, (*a*) automatically by the valve as soon as it fires; (*b*) independently by a separate switch.

be excited a second time if the signal impulse on the control grid is sustained, and will repeatedly operate at a frequency determined by the time constant of the resistance 3 and condenser 4. The circuit is a very useful one for detecting signal impulses of short duration and secures an independent reset. Since the peak value of the current through relay 1 can be increased up to the maximum rating for the valve by increasing the value of the condenser 4, a fairly large electromechanical movement can be operated by means of a small valve.

A second method of resetting the anode circuit after the valve has fired is shown in Fig. 3.2 (*b*). After the anode discharge has been established condenser 4 will become charged through resistance 2 by the potential difference which exists across the terminals of the load resistance 1, which is equal to the supply voltage less the drop across the valve—*i.e.*, about V − 15 volts. As soon as the switch 3 is closed the condenser 4 is applied directly across the anode and cathode of the valve, the condenser voltage opposing that of the supply. The anode current is therefore interrupted and a reverse current may flow during that period of the condenser discharge in which there is any residual ionisation remaining in the valve. In consequence, if the condenser is large enough to permit deionisation to take place sufficiently during the period of its discharge the grid will regain control, and if sufficiently negative will prevent the anode current starting again.

One of several factors affecting the deionisation time in order that the anode current shall be interrupted is the value of the capacitance of the condenser, and there is a minimum capacitance for any given set of circuit conditions. Fig. 3.3 shows the characteristic relation between the anode current grid voltage and condenser capacity for a typical small gasfilled triode. If current has been passing through the valve continuously for some time, a larger condenser may be necessary, especially at high currents, where the capacity may be much larger than that indicated by the curves of Fig. 3.3. The reason for this is probably the heating effect of the current on the electrodes.

Though it might at first appear that the circuit of Fig. 3.2 (*b*), where resetting is carried by means of a switch operating in conjunction with a charged condenser, might just as well be performed by a mechanically operated switch as in Fig. 3.1 without any condenser at all, the principle involved is important because the function of switch 4 (Fig. 3.2 [*b*]) can be performed by a second and similar gasfilled triode. Successive impulses on the common grid circuit of two valves connected in this way result in the anode discharge being transferred from one valve to the other in turn. This type of circuit finds application in inverters and multivibrators.[3.1]

It should be noted also in connection with condensers across the valve that if the discharge is passing it may in certain cases be possible to extinguish it by the sudden connection of an uncharged condenser between cathode and anode. The effect of this will depend on the

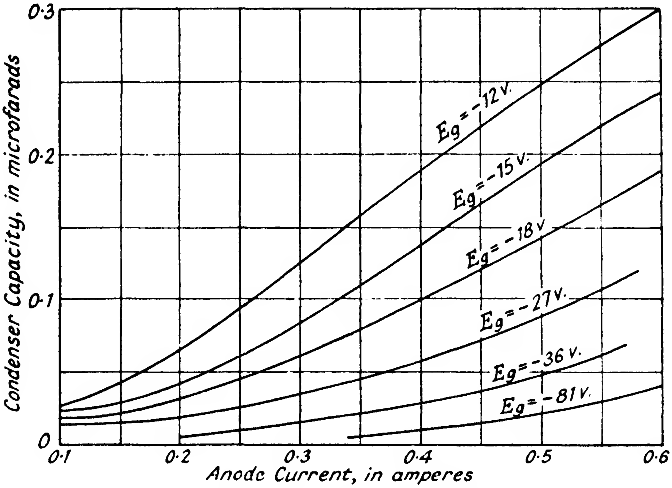


Fig. 3.3.—Relation between anode current and minimum condenser capacity required to extinguish the anode discharge in a small grid controlled gasfilled valve for various values of applied grid bias.

regulation of the voltage supply, and only in some cases will the momentary drop be sufficient to reduce the anode voltage below the striking point. If during this process the grid is sufficiently negative, whether the discharge will restart will depend on the rate of change of voltage on the condenser and the deionisation period under the conditions existing. As in most cases the switching of such a condenser will cause only a small and often unappreciable momentary voltage drop, this method of resetting is not of general application.

In all these cases the condenser used may be relatively large in capacitance. It is essential, therefore, to ensure that its inclusion does not result in transient currents through the valve in excess of the maximum peak rating.

Alternating Anode Voltage

So far only the case where a steady anode voltage of polarity positive to cathode exists has been considered. The use of alternating anode voltage introduces further possibilities through the variables of amplitude, frequency and phase in the anode circuit. Fundamentally the same conditions have to exist to restrain the anode discharge as with constant anode voltage, but since the alternating potential on the valve anode will pass from a positive value through zero once every cycle of the supply voltage, the anode current will be automatically extinguished near the end of each positive voltage half-cycle. As in the case of a steady positive anode voltage, there exists, over the linear portion of the control characteristic, a constant ratio between the instantaneous values of anode voltage and negative grid bias voltage at the threshold point where the discharge is just restrained (*cf.* Fig. 1.8A, page 18). If the valve fires at any point in the positive half-cycle of the anode voltage, the anode current will continue till the end of that half-cycle, and will, of course, be completely suppressed during the following half-cycle when the anode is negative to the cathode.

If the circuit conditions remain unchanged, what happens in one positive half-cycle will be repeated in succeeding positive half-cycles, so that the discharge through the valve will consist of pulses of unidirectional current separated from each other in time by 0·02 sec. on a 50-cycle supply. By the addition of a smoothing circuit a steady current can be obtained.

If, therefore, the load in the anode circuit is purely resistive, the instantaneous value of the current depends on the instantaneous value of the anode voltage and the total resistance in circuit; but the mean anode current depends on the point at which the valve fires in each positive half-cycle of anode voltage. The use of an alternating anode voltage, therefore, enables some quantitative relation between grid voltage and mean anode current to be secured under certain conditions. (See Appendix A.)

In the case of reactive loads the instantaneous value of the anode current is again determined by the instant of firing, but its duration may be prolonged into the negative half-cycle of the anode voltage and for a time depending on the magnitude of the reactive component of the load. (See Appendix B.)

The valve has the whole of the time of the negative half of the anode voltage cycle in which to reset when the load is resistive unless this period is comparable with the deionisation time. When this condition is approached intermittent firing and resetting of the valve will at first occur, and finally the discharge will be permanently established as the frequency of the alternating voltage is raised still further. The limiting frequency is generally within the range 5,000 to 10,000 cycles per sec. On 50-cycle industrial supply voltages, since the duration of the negative half-cycle is 0·01 sec., the question of frequency limitation with resistive loads does not arise.

Grid Control Curve

If the grid control characteristic of the valve is linear, as it usually is over a large portion of the working range of the valve, the grid control voltage for an A.C. anode voltage can be represented as a curve on the opposite side of the time co-ordinates of the anode voltage wave form, and this can be done merely by reducing all the ordinates of the anode voltage in a given ratio, since at any point in time the ratio of the instantaneous value of the anode voltage to the corresponding critical grid voltage is constant. If, however, the grid control characteristic is not linear, then the graphical method of construction shown in Fig. 3.4 can be adopted. Here the grid control characteristic is shown on the left-hand side of OY axis and the anode voltage on the right-hand side. Ordinates at points A_1 B_1 C_1 etc., on the grid control characteristic are drawn to meet the OX axis, and values of the grid voltages represented by the points a, b, c_1 etc., are projected on to the ordinates through the corresponding points A_2, B_2, C_2 on the anode voltage curve, so that $x_1a_2=oa_1$, $x_2b_2=ob_1$ and so on. The points a_2, b_2, c_2, etc., so found lie on a curve which represents the grid control voltage throughout the positive anode half-cycle. This curve is usually shown dotted, and in Fig. 3.4 the scale of drawing is increased to make the construction clear. In most cases the grid control characteristic departs from linearity at the lower end and does not pass through zero. As a result, zero grid voltage is the critical value corresponding to a definite positive value of anode voltage, and a positive control grid voltage is required at low values of anode voltage down to the minimum striking value. It will be noted that in Fig. 3.4 the grid control voltage curve intersects the anode voltage curve above the time axis. Most makers of these valves do not issue very much information about the lower portion of the grid control characteristic, possibly for the very good reason that in practice this part of the curve is not of great importance. For most applications it is sufficiently accurate to assume that only the linear portion of the curve is used and consider that the grid control curve is a reduced replica of the anode voltage curve. For instance, if the anode voltage contains harmonics, any peaks or troughs due to such will be reflected in the shape of the critical grid voltage curve, and the ratio of the instantaneous values under such conditions will still be the grid control ratio. The method of constructing the curve shown in Fig. 3.4 is, of course, applicable to any wave form and shape of grid control characteristic, though the precise outline varies a good deal according to the type of valve, and indeed between different specimens of the same type.

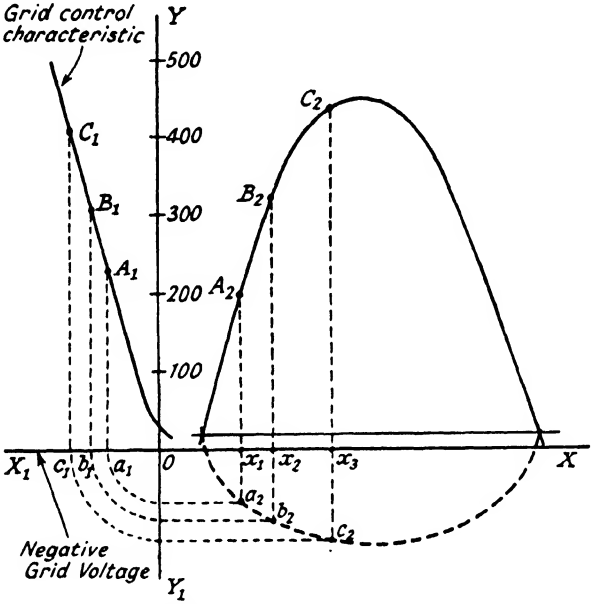


Fig. 3.4.—Graphical method of determining the critical grid voltage curve for an alternating anode voltage.

Alternating Anode Voltage—Steady Grid Bias

Assuming a linear relation between anode voltage and negative grid control voltage, the curve of the latter for alternating anode voltage can be represented as in Fig. 3.5. If a negative steady bias voltage represented in magnitude by the ordinate Og_1 (Fig. 3.5[*a*]) is applied to the grid it can be portrayed as a horizontal straight line parallel to the time axis and will cut the critical grid voltage curve at the point "*a*" and at a similar point in each succeeding half-cycle.

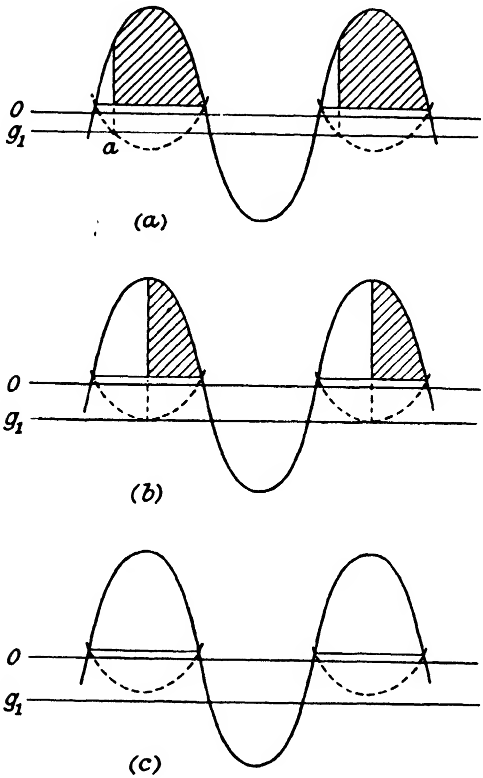


Fig. 3.5.—Alternating anode voltage—steady grid voltage.

The anode current will, therefore, start at this point, and its initial value will be fixed by the instantaneous value of the anode voltage and the total resistance in circuit. Assuming a resistance load in the anode circuit, the discharge then continues to a point near the end of the positive half-cycle when the anode voltage is below about 15, and since at any instant after the discharge has started the current is proportional to the voltage, the current pulse can be conveniently represented to a suitable scale by the shaded portion of the voltage curve. It will be clear from Fig. 3.4 and the considerations of the previous paragraph that to secure the earliest firing during the positive half-cycles the grid must be slightly positive.

In Fig. 3.5 (*b*), the applied negative grid bias has been increased so that it becomes tangential to the critical control voltage curve, and the discharge in consequence starts at the mid-point of the positive anode voltage half-cycle. By increasing the negative bias still further (Fig. 3.5[*c*]) the two curves do not intersect at all, so that the valve never fires.

Since the negative bias voltage line must, in these cases, intersect the critical control voltage curve during the first half of the anode voltage half-cycle or not at all, the anode current can be made to vary over a range of maximum represented by the current flowing during the whole of the positive half-cycle to half maximum, as represented by the condition shown in Fig. 3.5 (*b*), and quantitative control of the mean value of the current over this range can be secured by adjusting the value of the steady negative grid bias. When the point of half-maximum is reached, further increase in grid bias prevents the valve from firing at all. Owing to the small angle at which the two lines intersect near the point where they become tangential, a small change in the control characteristic may produce a relatively large change in the mean anode current and the performance may become inconsistent. Since such small changes may occur due to temperature variation in mercury vapour valves or due to gas clean-up in valves filled with inert gases, this method of current control, apart from its restricted range, is not very satisfactory, and phase adjustment of the grid voltage described in the next section is to be preferred.

This discussion assumes the wave form of the anode voltage to be free from surges and ripples the existence of which may cause premature firing of the valve, and therefore an apparent departure from the behaviour outlined. In addition, if the current is inductive the rise of current will be delayed and the peak anode currents retarded with respect to the peak anode voltage. During the conductive periods, energy is stored in the inductive circuit and set free later when the anode voltage passes through zero or even becomes negative.

The starting point of the current will be more clearly defined at higher anode voltages, since the relative slopes of the applied and critical voltage curves are more widely different, and effects such as temperature changes are reduced. These remarks apply also to the following paragraphs.

Alternating Grid Voltage

Quantitative control of the mean anode current is also possible by means of alternating grid voltage, which permits of two different circuit arrangements:

(1) Feeding the grid circuit with alternating voltage of constant amplitude and varying, with suitable circuit components, the phase angle between the anode and grid circuits.[3.2]

(2) Maintaining the phase angle between these circuits constant and varying the amplitude of the alternating grid voltage. Both these conditions can, of course, take place simultaneously. A further case arises where an alternating voltage is superimposed on a steady grid bias and either is made variable in magnitude.

Fig. 3.6A shows the voltage relationship between the grid and anode circuits when these are both fed from the same alternating supply, and in which the phase angle between them is varied by one of several means hereafter described. In Fig. 3.6A (i) the phase angle is 180° and the grid voltage fails to intersect the critical control voltage curve at all, so that the discharge is completely restrained and the current zero. It should be noted that here the lower part of the critical grid voltage curve is important because its precise configuration will determine exactly what happens when the phase angle is near opposition. In Fig. 3.6A (ii) the angle is reduced to 150°, the anode voltage leading the grid volts, and the grid voltage curve then intersects the critical voltage curve towards the end of the positive half-cycle of the anode voltage. Similarly, in Fig. 3.6A (iii) and 3.6A (iv) the lag of the grid voltage is still further reduced, the magnitude of the current pulse in each half-cycle increasing with reduced angle of lag of grid voltage until it becomes a maximum when the grid and anode circuits are in phase.

It will be noted that, as distinct from the case where a variable direct bias is given to the control grid, phase variation provides a means of varying the magnitude of the mean current over the whole range of zero to maximum by gradually shifting the phase angle away from the position of phase opposition.

A phase shift of the grid voltage from 180° in the opposite direction will produce an entirely different result (see Fig. 3.6B), a small phase shift of over a few degrees being sufficient to establish the discharge to its full value. Since the grid voltage is then always more positive than the critical value at the beginning of the positive anode half-voltage cycle, no quantitive control therefore is possible in this case.

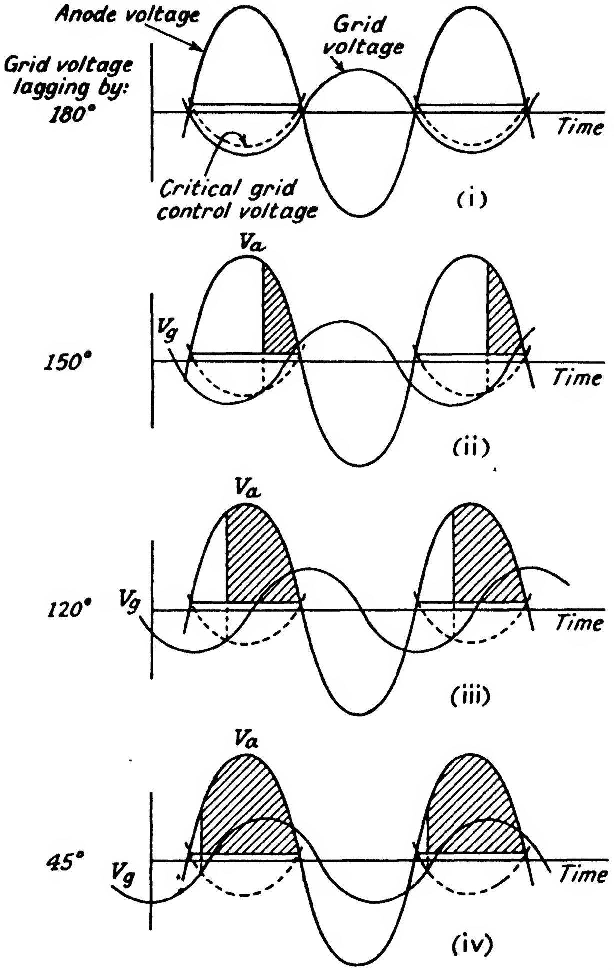


Fig. 3.6A.—Progressive increase in mean anode current as the grid voltage is advanced from phase opposition.

Provided the negative peak alternating grid voltage exceeds the maximum critical control value, the condition of phase opposition always corresponds to zero anode current. A phase shift of the grid voltage in one direction gives a graded increase in mean anode current, while a shift in the opposite direction gives a trigger action with a simple on and off control. These two cases are illustrated in the diagram of Fig. 3.7. It is important to distinguish these two

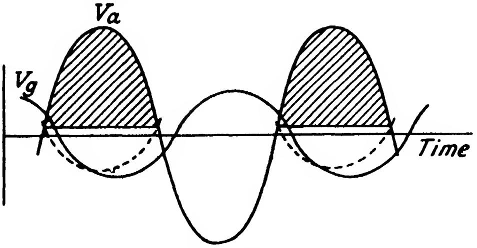


Fig. 3.6B.—Sudden increase of the anode current to a maximum as the grid is slightly retarded from phase opposition.

cases clearly because it is easy, in applying the principle of phase shift to practical problems, to obtain the opposite effect to that required merely because the phase shift of the grid voltage takes place in the wrong direction.

Fig. 3.8 shows examples of basic circuits in which phase control of the grid voltage is employed. In Fig. 3.8 (*a*) the mean anode current increases as the resistance is increased, while in Fig. 3.8 (*b*) the reverse action takes place—*i.e.*, increasing the variable resistance gives a progressive decrease in anode current. These two circuits apply the conditions shown in Fig. 3.6A. In the circuit of Fig. 3.8 (*c*) the anode current is either a maximium or zero with no intermediate condition according to whether the resistance is made greater or less than a certain value. This corresponds to the conditions shown in Fig. 3.6B and to the left-hand side of Fig. 3.7. It will be noted that the distinction between the two cases is made clear in the three vector diagrams of Fig. 3.8. In Fig. 3.8 (*c*), where no quantitive control of

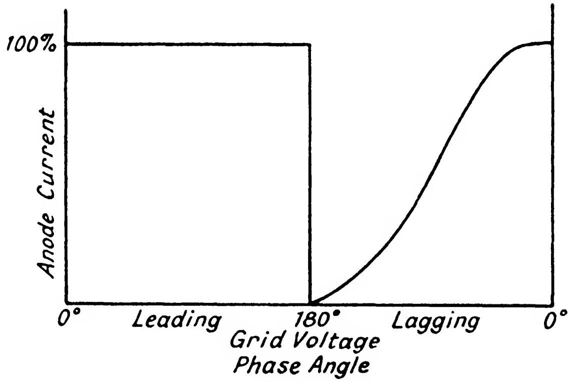


Fig. 3.7.—Effect of direction of phase displacement of grid voltage.

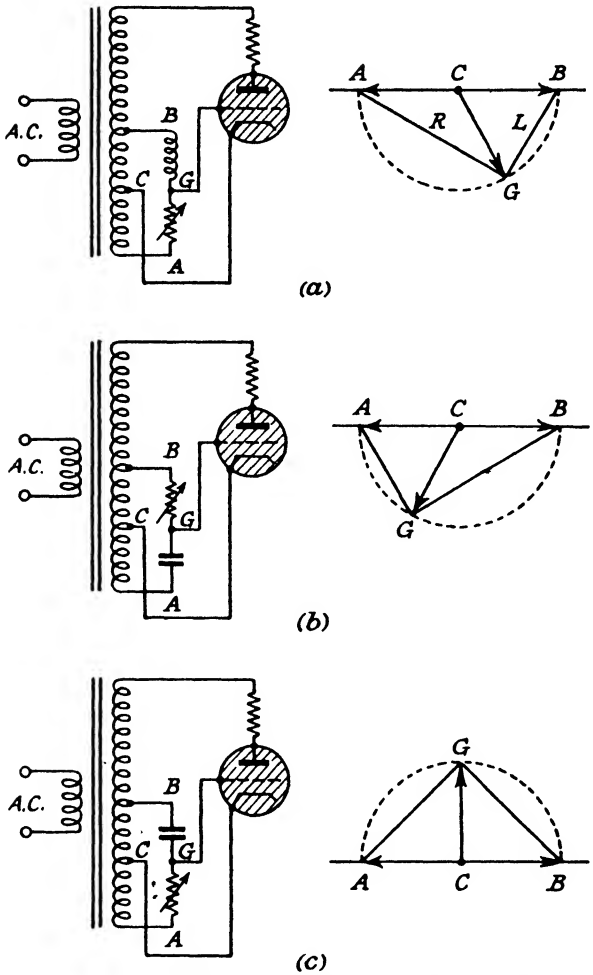


Fig. 3.8.—Applications of phase displacement.

the mean anode current is possible, the grid voltage vector is wholly on the positive side of the axis and is therefore always less negative than the critical value. Other methods of applying phase change will be referred to in connection with specific applications.[3.3, 3.4, 3.5, 3.15]

Alternating Grid and Steady Anode Voltage

There is a further case to which only passing reference need be made, since it is one of unusual occurrence and of little importance

—viz., steady anode voltage with alternating grid supply. The alternating voltage either does or does not exceed the (constant in this case) critical value, so that the discharge is either cut off or fully established. The only exception arises in the case where the anode voltage is switched on separately, in which case the grid voltage may at that instant be less than the critical value, so that, although the discharge is fully established, this condition is delayed by a period which may be anything up to ½ cycle of the supply. For all practical purposes this is of no account, since the time displacement of the switching will be a matter of pure chance, and unless intervals comparable with supply cycle are involved in the control circuit, the discharge can be considered as being established at once. We will revert, therefore, to further consideration of the more general cases.

Variation of Grid Voltage Amplitude

Some control of the anode discharge may also be secured under certain conditions by varying the amplitude of the alternating grid potential while maintaining its phase angle constant. If the A.C. grid voltage is exactly 180° out of phase with the anode voltage, one of two conditions will exist: either the anode current will be wholly cut off or will be fully established at its maximum value, according to the amplitude of the grid voltage. This condition is shown in Fig. 3.9, where the grid voltage amplitude is shown decreasing in successive voltage cycles from left to right until a condition is reached where the valve fires at the beginning of each positive half-voltage cycle. No quantitive control is thus possible under these conditions, the anode current being either a maximum or zero.

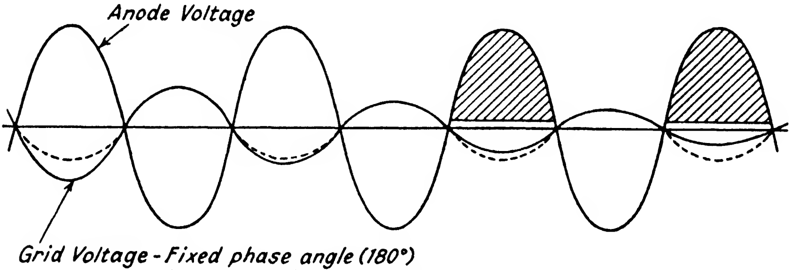


Fig. 3.9.—Anode and grid voltages in phase opposition. Amplitude variation of grid voltage gives on and off control only.

If, however, the phase of the grid voltage is slightly advanced from phase opposition by a small angle, say 30°, as shown in Fig. 3.10, the previous conditions no longer exist and some control of the value of the anode current becomes possible. Similarly, by repeating the construction of Fig. 3.9 for different values of the phase angle it can be shown that quantitive control is still possible at other phase angles. There is, however, another point which needs consideration. It will be noted that in some of these cases a relatively large change in amplitude of grid voltage produces only a small excursion of the point of intersection with the critical grid voltage curve along the time axis; for instance, in Fig. 3.11 a large change in grid voltage amplitude is required to cause the point of firing to move through less than one-quarter of a complete cycle of alternating voltage represented by the successive points *a*, *b*, *c*, *d* (Fig. 3.11). This would indicate that adjustment of alternating grid voltage as a means of varying the magnitude of the anode current results in a much narrower range of control than phase variation, and is therefore a much less satisfactory means of adjustment. In practice, a rather wider range of control is obtained than would be indicated from Fig. 3.11 because in most cases of amplitude variation some change in phase also occurs simultaneously, so that the control is made by a mixture of the two. This arises from the fact that in a phase shift network with a resistance used as one component for securing phase displacement a change in the value of this resistance varies the voltage

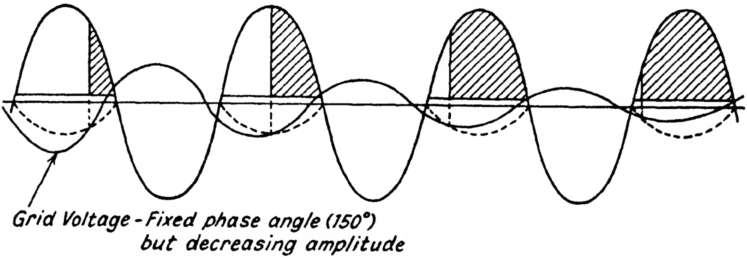


Fig. 3.10.—Quantitive control of anode current by grid voltage amplitude variation.

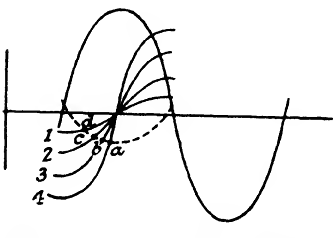


Fig. 3.11.—A.C. grid voltage of variable amplitude but constant phase angle.

component in phase with the current; in order, therefore, to make the variation of the resistance independent of the phase angle, a further compensating circuit must be included.

Superposition of Alternating Voltage on a Steady Grid Bias

Particular instances—*e.g.*, cases where one fixed phase angle is chosen, where an alternating voltage is superposed on a steady grid voltage—are shown in Fig. 3.12A. If the amplitude of the alternating grid voltage is comparable with the steady bias, the effect of superposition being additive will mean that the axis of the A.C. grid voltage is displaced in the ordinate direction by a distance equal to the steady bias without altering its outline. Thus in Fig. 3.12A (*a*) the simultaneous application to the grid of an alternating voltage and a steady positive bias of magnitude Og_1 means that the resultant grid voltage curve G_1 is the same as that of the alternating grid potential component displaced vertically and is no longer symmetrical about the horizontal co-ordinate axis. The effect of this is that the resultant curve G_1 intersects the anode voltage early in the positive half-cycle. In another case, Fig. 3.12A (*b*), the steady bias is a negative one

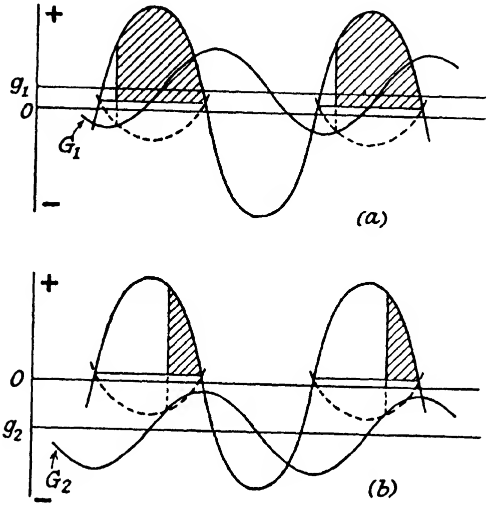


Fig. 3.12A.—A.C. grid voltage with constant amplitude and phase angle but variable superposed D.C. bias.

of magnitude Og_2, the alternating component voltage having the same phase angle as before. In this case the resultant grid voltage G_2, is displaced in the direction of negative voltage ordinates and the curve does not intersect the critical voltage curve till late in the cycle. By varying the steady bias alone, therefore, adjustment of the mean anode current can be made throughout the whole range of zero to a maximum.

The degree of control over the mean anode current which is possible by using a grid control voltage having superposed D.C. and A.C. components depends on the relative magnitudes of these voltages and the phase angle of the A.C. component. Any specified conditions can be investigated most simply by applying the graphical construction illustrated in the previous examples.

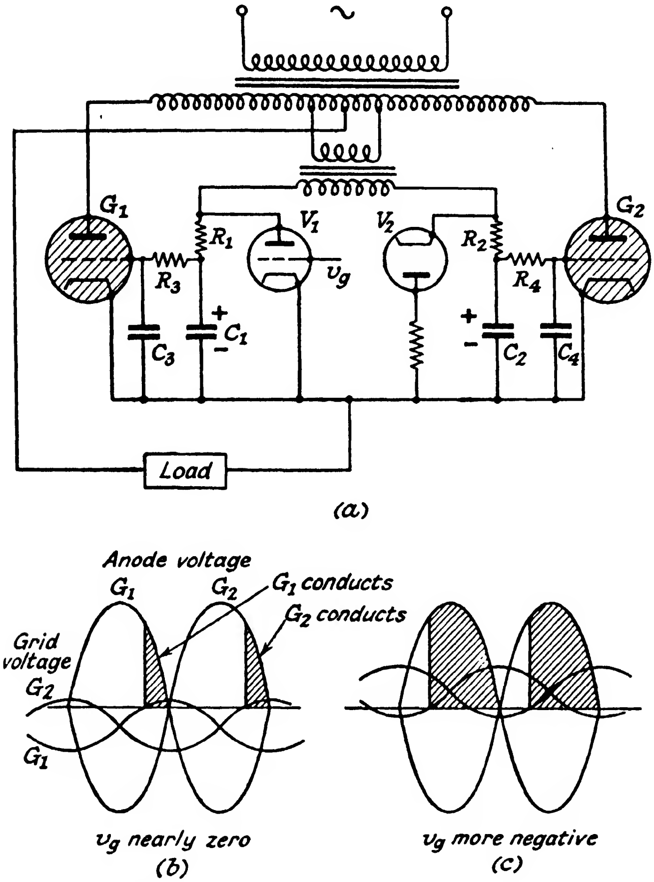
Possibly the most useful case is that in which the D.C. component is adjustable in magnitude up to the peak value of the A.C. component in both positive and negative directions and the A.C. component lags the anode voltage by 90 degrees.

Graphical construction along the lines previously carried out will show that adjustment of the D.C. voltage over its whole range enables smooth control of the mean anode current to be secured over the full 180 degrees of anode voltage.

This has been applied to motor control (*q.v.*) in a manner basically similar to other forms of thyratron regulation described later, but its chief interest lies in the circuit by which the two component voltages are obtained, and the means adopted for smooth adjustment of the D.C. component, the principle of which is shown in Fig. 3.12B.[3.16]

Here an auxiliary transformer applies a small alternating voltage across condensers C1 and C2, lagging on the voltages applied to the anodes of the gasfilled triodes G1 and G2 by nearly 90 degrees. V2 is a diode which conducts on alternate half-cycles and during its conduction passes electrons to the lower plates of C1 and C2 so that the grids of G1 and G2 each receive a positive steady bias as shown in Fig. 3.12B. V1 is a triode whose conduction can be quantitatively controlled by its grid voltage and which through its opposite phase connection tends to charge C1 and C2 to the reverse polarity. The resultant magnitude and polarity of the steady voltage component on the grids of G1 and G2 depend, therefore, on the relative periods of conduction of V1 and V2.

By increasing the negative voltage on the grid of V1 the steady



(a)

vg nearly zero
(b)

vg more negative
(c)

Fig. 3.12B.—(*a*) Method of securing 180° control of anode current with A.C. and D.C. superposed grid voltages. (*b*) and (*c*) Effect of increasing negative grid voltage vg.

voltage component on the grids of G1 and G2 can be varied from a negative value equal to the peak of the A.C. component to a positive value of the same magnitude and the mean anode current of G1 and G2 varied from zero to a maximum.

In Fig. 3.12B condensers C3 and C4 are of small capacity to by-pass transient voltages introduced through the interelectrode capacity of the corresponding triode.

It will be clear that if the steady negative grid voltage component is made large compared with the amplitude of the alternating component the two curves will not intersect at all, and conditions will be the same as if the alternating component were not present and no quantitive control of switching is possible. It would also be true that if the steady grid voltage were highly positive it would completely swamp any effect of the alternating component and the discharge would always start at the beginning of the cycle; but as the condition of positive grid bias is not, for other reasons, desirable, this case is not a practical one.

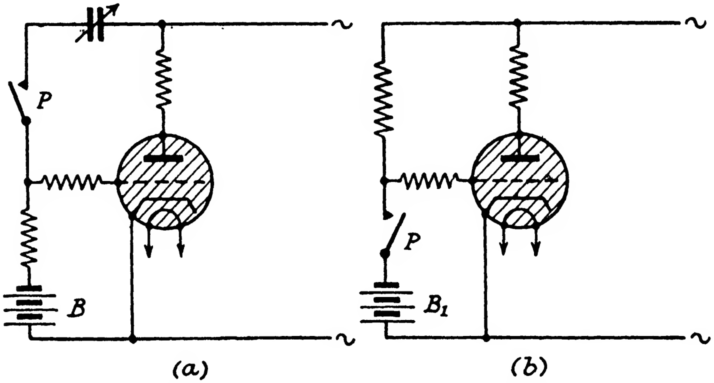


Fig. 3.13.—Case of superposed D.C. bias with A.C. grid voltage. (*a*) Closing switch P causes load current to rise to maximum. (*b*) Closing P cuts off anode current.

It is clear, therefore, that quantitive control of the mean anode current in such cases only becomes possible when the steady component is of the same order of magnitude as the amplitude of the A.C. voltage.

As an example of the use of this form of control, the circuit of Fig. 3.13 (*a*) with the switch P open has the grid of the gasfilled triode negatively biased by battery B, so that the discharge is restrained. Closing switch P superposes on the steady grid bias an alternating component which establishes the discharge through the valve immediately, the mean current value being determined by the phase angle imposed by the coupling condenser. In Fig. 3.13 (*b*), with the switch P open, current passes through the gasfilled triode. If battery B_1 is of sufficiently high voltage, closing the switch P secures the reverse result to that of Fig. 3.13 (*a*). A high negative bias is applied to the grid, and since the anode voltage is alternating, the discharge is suppressed at the instant following the closure of P at which the anode voltage passes through zero. During the negative half-cycle of the anode voltage the bias battery B_1 receives charging current.

The principle of superposing an alternating voltage on a steady grid bias as a means of securing a change in the value of the mean anode current is useful in the case where it is required to stabilise a fairly high direct voltage. This voltage source may be connected in opposition to another stabilised steady reference voltage of comparable magnitude, so the variable component has a low mean value but relatively large amplitude of variation about either side of zero, which is then applied to the grid simultaneously with an alternating voltage of comparable amplitude. This principle has been applied to motor speed control. The motor armature is supplied by the anode current of a gasfilled triode or triodes. The motor whose speed is required to be maintained constant drives a small pilot generator mounted on the same shaft, and the voltage output of this pilot motor is fed in opposition to the fixed reference voltage. Small variations in speed of the motor therefore produce a resultant voltage which varies in magnitude and polarity. The superposition of the A.C. voltage then reproduces conditions similar to those outlined in Fig. 3.12, and the change in anode current takes place in the direction tending to correct the speed variation which produced it.

Peaked Grid Firing Impulses[3.6]

Where more accurate control of the timing of the firing point is required, this is possible by simple phase control or one of the modifications of it just referred to. A method frequently adopted is to maintain the grid normally at an adequate negative voltage and to apply superposed on this bias a positive impulse of a peaked wave form and of large amplitude to ensure that the triode fires at a precisely determined part of the cycle. Means must be provided to vary the phase of such pulses if quantitative control of the output is called for. One of two methods can be employed to secure this type of control: (1) The use of a synchronously driven distributor which connects a positive supply of sufficient voltage momentarily to the grid terminal once during every half-cycle of positive anode voltage, the phase of the impulse being varied to secure variable control of the output by giving the brushes of the distributor the necessary angular displacement. (2) By utilising the principles of magnetic saturation in adopting a special design of grid transformer which gives a peaked output voltage for a sine wave input.[3.7]

One form of such a transformer is shown in Fig. 3.14A. The main body of this unit has a laminated core of silicon steel and carries the primary winding and main alternating flux, the section of the core being large enough to avoid saturation. The output winding which feeds the grid of the triode is of small section permalloy and saturates easily, so that a condition of saturation is soon reached after the main flux increases from zero.

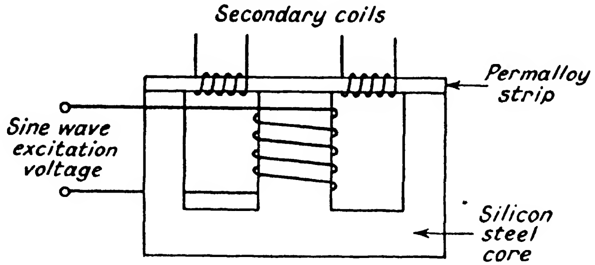


Fig. 3.14A.—Transformer with small section secondary core for producing peaked output voltages.

Assuming at first that the arrangement is as shown in Fig. 3.14A, the alternating primary current is then shown by curve 1 (Fig. 3.14B) and the main flux by curve 2. The flux through the constricted position of the core is indicated by curve 3, the condition of saturation which occurs soon after the main flux has reversed, giving rise to a flat-topped curve.

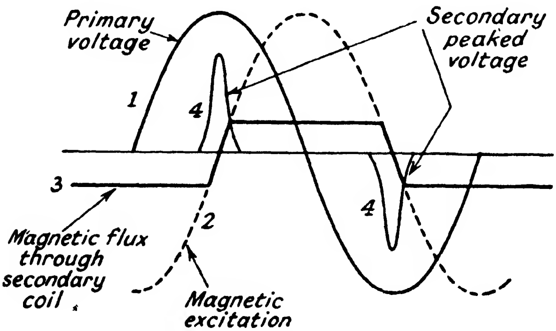


Fig. 3.14B.—Voltage and flux relations of the circuit of Fig. 3.14A.

The voltage from the secondary winding which is proportional to the rate of change of flux is therefore zero over the flat portions of the curve, and appears as a sharp peak each time the flux changes. Voltage pulses of opposite polarity thus occur each time the resultant flux reverses.

Since the voltage pulse extends over the time during which the flux through the secondary winding is changing, it is clear that the duration of the pulse will be shorter the smaller the amplitude of curve 3—*i.e.*, the earlier saturation occurs.

The conditions under which magnetic saturation of the secondary core occurs thus fixes the width of the output voltage pulses without affecting the phase relation of their peaks.

To displace the position of the peak output voltage which is necessary when adjustment of the valve output is required, either of the following methods can be adopted:

(1) By the addition of an auxiliary primary winding fed through a phase displacing component (condenser or inductance), so that the resulting main flux to which the output voltage pulses bear a fixed time relationship can be displaced relatively to the supply voltage.

(2) By the addition of a saturating winding on the transformer core. This results in the arrangement of Fig. 3.15A.

In the first case the main flux is the resultant of that due to the two primary windings which have a phase displacement relative to each other.

In the second case (Fig. 3.15B), suppose the saturating D.C. winding imposes a constant flux in the negative direction represented by the line 3 with respect to the axis. When the flux due to the alternating winding is superposed on the steady component the variation of the resultant flux is similar to that shown by the dotted line in Fig. 3.15B, the effect of the saturating winding being to displace the magnetisation curve 2 of Fig. 3.14B in the direction of negative ordinates.

Since saturation occurs when the resultant flux reaches the same magnitude as in Fig. 3.14B, it will be clear that the curve of the flux through the permalloy will be unsymmetrical about the time axis, and the sloping portion of this curve which determines the output voltage pulses is now retarded as compared with Fig. 3.14B.

Likewise, if the saturating winding is fed so as to produce magnetic bias of the opposite polarity, the peak output voltage will be displaced in the opposite direction. Adjustment of the valve output is thus made possible by phase adjustment of the firing point due to the

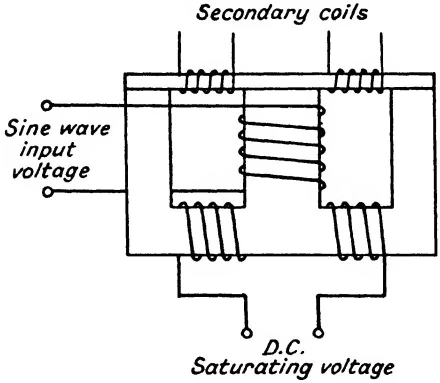


Fig. 3.15A.—Independent saturating winding added to the unit of Fig. 3.14A.

degree and polarity of the magnetic bias in the grid transformer caused by the current through the saturating winding.

The limit to the adjustment of the valve output is set by the fact that when the steady flux is increased beyond a certain point, saturation of the whole core takes place and peak voltages are no longer delivered from the secondary. Moreover, before this condition is reached the rate of change of flux is reduced so that the peak output voltages broaden and become reduced in amplitude. It will be noted that in Fig. 3.14B, since the applied voltage leads to flux by 90°, the peak secondary voltages occur at the instant of maximum anode voltage.

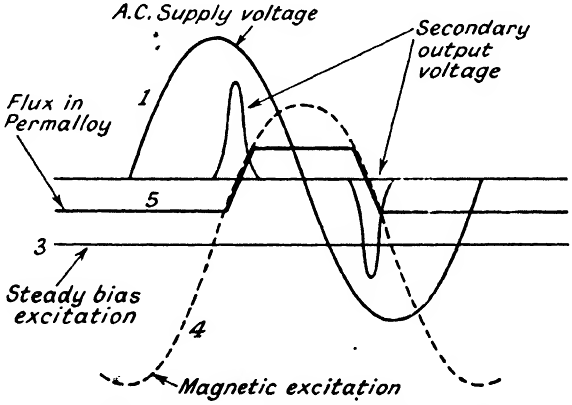


Fig. 3.15B.—Voltage and flux relations for the iron circuit of Fig. 3.15A.

Regulation of the power output by means of peaked voltage obtained in the manner described finds practical application in the control of single and polyphase thermionic and mercury pool rectifiers (*q.v.*) and to secure accurate control of discharge tubes employed as stroboscopic illuminants.

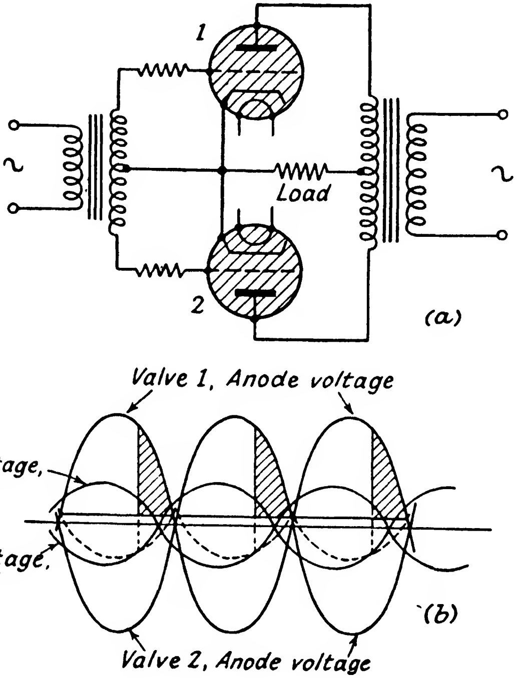


Fig 3.16.—Biphase connection of gasfilled triodes with grids fed through centre tapped transformer.

Biphase Connection of Triodes

The connection of two grid-controlled gasfilled rectifiers, as shown in Fig. 3.16, with the anodes fed from the opposite ends of the secondary winding of a mains transformer with load connected between the centre point and the common cathode connection, results in a biphase circuit which behaves in the same way as a single valve, but with double the mean anode current. Each valve passes current in turn during succeeding half-cycles of the anode supply voltage. Variations in the phase angle of the grid circuit will function in the same way as those described in previous circuits, but are a little more difficult to arrange for two valves in phase opposition.

The load is connected in the common cathode circuit. Similar conditions with corresponding changes in output current can be applied to circuits with three or more phases.

A variation of this type of biphase connection is shown in Fig. 3.17, where the two grids have a common alternating voltage, the phase

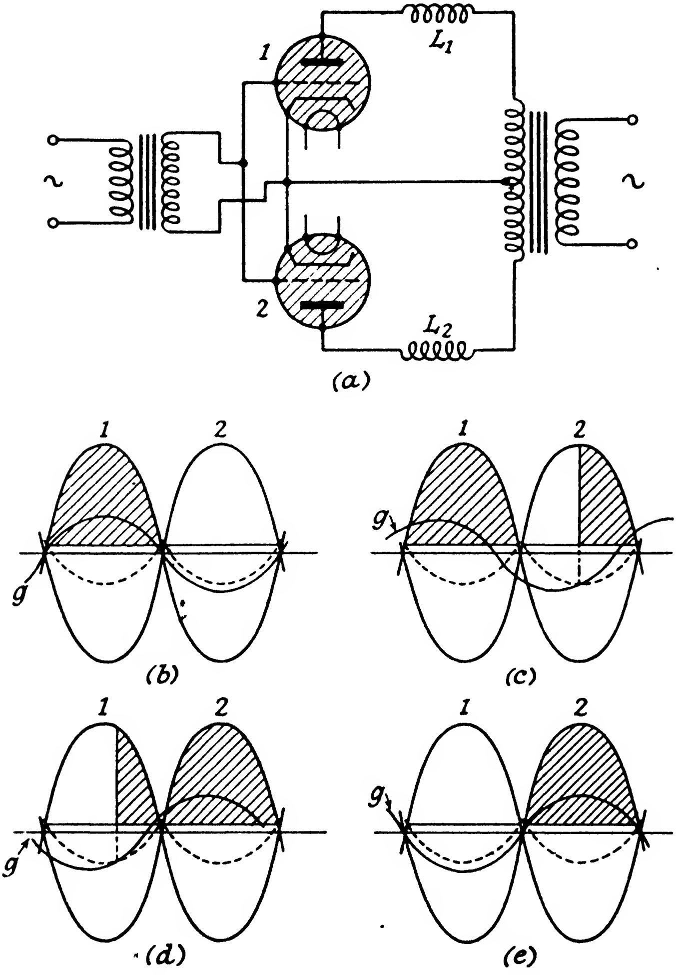


Fig. 3.17.—Biphase connection of gasfilled triodes with a common alternating grid potential.

and/or amplitude of which may be varied. The two anode voltages are in phase opposition, and either one or both of the triodes is conducting through a portion of the cycle. If the load is divided between the anodes, as is the case of two windings of an electromagnet, the connections can be made so that the resultant field is that due to the sum or difference of the anode currents. In the case of a differential winding, the excitation can be varied from a maximum in one direction through zero to a maximum in the reverse direction. Alternatively, if connected in the common cathode returns, the currents are additive and can be varied over the range of maximum to half-maximum.

Two other cases, of course, are possible: firstly, with both common anode and common grid potentials; and, secondly, with a common anode voltage with the grids in phase opposition through connection to the ends of a centre tapped transformer. These do not lead to any variations of the previous cases, since the common connection of the anode circuit results in a similar but parallel as opposed to biphase connection.

Parallel Operation of Gasfilled Triodes

The possibility of operating two similar gasfilled triodes in parallel under conditions where both of them can be made to fire simultaneously arises in connection with (1) circuits in which the maximum reliability of operation is called for and where duplication of the valves ensures continuity of service if for any reason one of them is put out of action; (2) applications calling for a higher anode current than can be furnished by a single valve of the type available and in which it is not possible to secure a single valve of higher current rating; (3) operation of two such valves at reduced anode current to secure longer life from the combination.

Unfortunately, the simplest arrangement of parallel connection in which the two anodes are connected together and fed through the common load circuit with the two grids likewise connected together to a common grid bias supply and to the signal circuit will not function satisfactorily. Individual valves of the same type have certain tolerances in characteristics, and the grid control curves of two such valves are not, except by chance, identical. Even if it is possible to secure identity of characteristics by selection and matching, slight changes in characteristics which occur during the life of the valve may prevent this identity of characteristics being maintained.

Consequently, in such a parallel connected pair, assuming at first a steady value of the grid bias voltage, when the firing impulse arrives one valve will tend to fire slightly before the other. As soon as one valve fires, the common anode-cathode voltage across them both falls to a low value, the value of the arc drop, and if the grid bias voltage remains unchanged the state of the quiescent valve is removed farther from that required for firing, and this second valve will not fire at all.

Somewhat different conditions arise when the grid voltage is alternating and the grid firing impulse is due to a phase change. For the same reasons as in the previous case, one valve fires first, resulting in a large reduction in the common anode voltage. The critical grid voltage of the second valve is therefore immediately reduced, and the alternating grid voltage does not therefore pass from a higher negative value through the critical value till later in the cycle. As a result, if stable operation is secured at all, the load divides unequally between the two valves and the regulation is therefore unsatisfactory.

To ensure that both valves fire simultaneously, the circuit must be arranged so that the firing of one results immediately in the firing of the other. This condition will be obtained if the passage of the discharge in one valve either (1) imposes a high positive peak voltage on the grid of the second valve, or (2) produces a momentary increase in its anode voltage.

The second alternative is generally the easiest to apply and can be secured by the method shown in Fig. 3.18. Here the anode circuits of the valves both include the inductive winding of a closed iron circuit. The sudden rise of current through one of these coils due to the firing of the corresponding valve induces by transformer action a

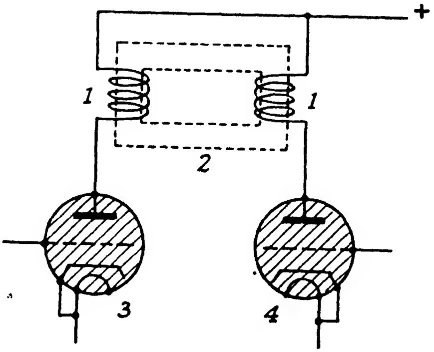


Fig. 3.18.—Parallel operation of gasfilled triodes.

transient voltage which increases the anode potential of the other valve and thus causes it to fire simultaneously.[3.8]

Inverse Parallel Operation

As distinct from the previous case, the connection of two gasfilled triodes in inverse parallel with the anode of one connected to the cathode of the other, as shown in Fig. 3.19, is also employed considerably, particularly in connection with servo mechanisms where it becomes necessary to drive a motor in either the forward or reverse direction. The motor may be a D.C. machine, the field coil being in series with the pair of gasfilled triodes. The polarity of the field coils, and therefore the direction of motor rotation, is determined by which of the two triodes passes current. Electron current passes through the circuit in the direction of the full arrows in Fig. 3.19A when triode 1 is fired and in the direction of the dotted arrows when triode 2 fires. Here the grid circuits are shown free, since the circuit permits of several methods of grid control, some of which are referred to the practical applications which follow.

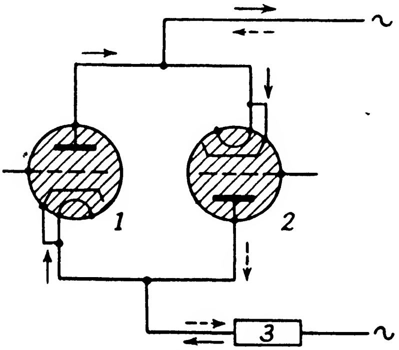


Fig. 3.19A.—Inverse parallel connection of gasfilled triodes.

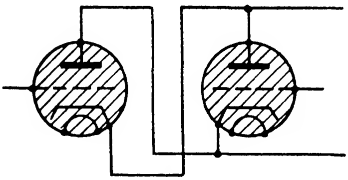


Fig. 3.19B.—Alternative method of representing triodes in inverse parallel.

An alternative method of representing inverse parallel connection frequently adopted is shown in Fig. 3.19B.

Methods of Producing Phase Change in the Grid Circuit 3.9

Variation of the phase of the grid potential relative to the anode may be secured by means of an adjustable resistance, condenser or inductance in the grid circuit. In many cases where the control is secured by a variable resistance a change in amplitude of the alternating grid voltage takes place simultaneously, and although the desired control may be secured most conveniently by means of such a variable condenser, the analysis of the change may be quite complex. Capacitance change as a means of control is free from this complication and often a preferable alternative. Change in inductance may also be used either by (1) variation of the coupling between two coils (Fig. 3.20 (*a*) is an elaboration of this applied to a selsyn type of transformer where 3-phase supply is available); (2) adjustment of the position of an iron core in a coil; (3) the use of a saturable reactor, phase adjustment being secured by varying the saturating current. Fig. 3.20 (*b*) shows in a bridge connected network. This permits of several modifications.[3.10] In one such circuit the signal voltage after amplification is applied to the saturable winding which is connected in a bridge network to control a pair of biphase connected triodes. The polarity of the signal determines which triode fires.

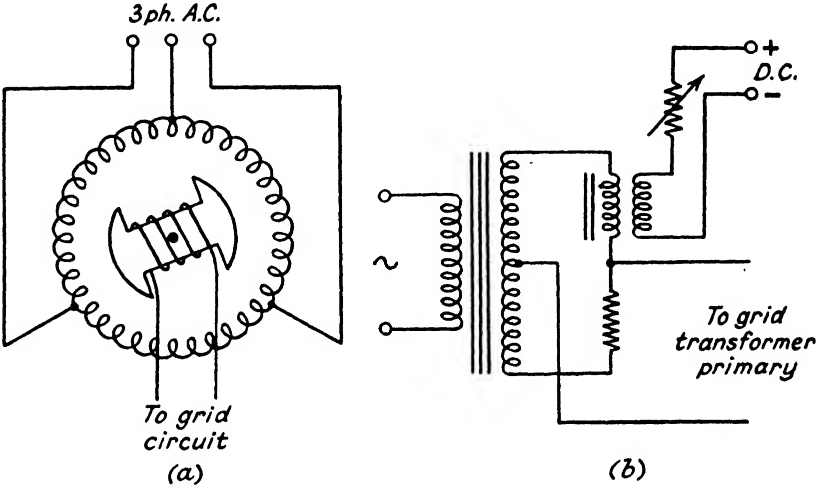


Fig. 3.20.—Phase change of grid voltage through variation in inductance.

Of these methods of phase variation, capacitance has the advantage of rapidity in response, since the moving mass can be made very light so as to minimise inertia when rapid pressure or displacement changes take place. Moreover, since the electrodes can be shaped as desired, the displacements can be made to follow any required law.

The disadvantage of capacitance is that it is a high-impedance control, so that difficulty arises if the capacitance is separated by any appreciable distance from the amplifier and a low-impedance coupling will be required.

Inductance variation when secured by a moving core also has the advantage that the moving member is completely isolated from the electrical circuit. Its mass can be increased to prevent rapid movement and damp out hunting. The iron core can sometimes be floated on a column of mercury, which in turn is expanded by temperature or external pressure changes.

Inductive Loads

The analysis of the circuit operation with inductive loads is in practice complicated because it involves the impedance of the rectifier valve and the transformer and their effects on voltage regulation. Cases may also arise in which there is direct voltage in the circuit as would be provided by the back e.m.f. of a motor or battery.

If these factors are neglected and the circuit assumed to include a pure inductance and resistance in series, the mean output current of a half-wave rectifier with an inductive load can be deduced theoretically without much difficulty.* It can be shown that in single-phase half-wave rectifier circuits the mean output current depends on both the grid ignition angle and the phase angle of the load. In biphase circuits there are two regions of control. In the first, the mean output current depends only on the grid ignition angle; in the second, it depends both on the grid ignition angle and on the phase angle of the load. In the case of three or more phases there is a third region in which the mean output is independent of both the grid control and the phase angle of the load.[3.11]

Some Practical Considerations

While the theoretical deductions previously concerning the conditions under which the discharge is established are borne out in actual use, it may be found that some departure from these results occur in practical applications, because the ideal conditions presumed do not exist. Since the time required to establish the discharge when the electrode potentials are favourable is of the order of a few microseconds, it is clear that inadvertent operation may take place through

---

* See Appendix B.

the existence of unsuspected transient voltages of very short duration, either in the grid or anode circuit. Spontaneous operation will, therefore, assuming the valve is in working order and free from insulation leaks, indicate the existence of surges which with all usual methods of measurement will escape notice and which only oscillographic records will detect. It has been assumed in the previous discussion that the voltage is sinusoidal and no account has been taken of the possible existence of harmonics which may cause appreciable changes at the point at which the valve fires. The limitation of the frequency of the supply voltage, when this is high, has been already referred to, and the point of firing cannot be fixed to an angle closer than the period representing the time of ionisation. In all cases where the grid resistance exceeds 10^6 ohms, or in phase circuits where the capacity change is small, adequate shielding of the grid circuits is required, otherwise neighbouring electrical circuits may cause oscillations to be superposed on the signal grid voltage and result in premature operation. The limitations set by irreducible inter-electrode capacities makes the tetrode (*q.v.*) preferable to the triode for high-impedance grid circuits.

In view of the possibility of premature firing by transient voltages, it is frequent practice in circuits where an alternating voltage is employed in the grid circuit to hold the valve non-conducting to include a condenser across the current limiting grid resistor.

This gives a D.C. bias component due to grid rectification and prevents accidental firing of the valve due to transients which may occur as the amplitude of the A.C. grid voltage changes.

In order to limit the time during which the grid voltage is positive, and also make the operation as far as possible independent of small changes in the operating characteristics of the valve, all processes of control involving phase shifts should ensure that the grid voltage curve intersects the critical control voltage curve at a not too acute angle,[3.6] and it is advantageous in many cases to employ a peaked wave form to ensure this condition.[3.7] For similar reasons the operation is liable to become critical if the amplitude of the grid voltage is too low.

A further point of interest concerns the distortion of the grid voltage wave form when alternating supply control is used, due to the drop in voltage caused by grid current across the grid resistor. Under conditions of established discharge where the grid voltage is positive, electrons pass to the grid from the plasma and a relatively large voltage drop occurs across the resistor. When the grid voltage passes through zero and becomes negative, positive ions pass to the grid and a further but smaller drop occurs till the discharge is cut off (Fig. 3.21).

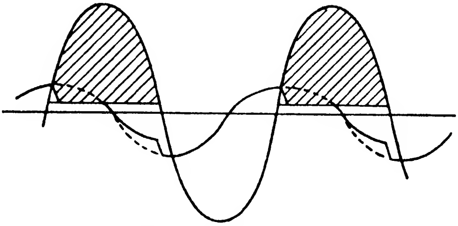


Fig. 3.21.—Voltage drop across grid resistor.

Switching Heater and Cathode Circuits

If the discharge passes before the cathode is sufficiently heated, all parts of the emissive surface will not have reached the same temperature and serious local disintegration may occur. In addition, the large voltage drop across the valve will then force positive ions back on the cathode and cause rapid destruction of the emissive surface with short life to the valve. It is essential, therefore, (1) that the heater voltage shall be fully maintained, (2) the anode circuit shall be closed only after the expiry of adequate preheating of the cathode. This, of course, implies that the cathode shall not be switched off before the anode. Overvoltage of the heater must also be avoided, since its effect is to drive off the active surface material. Underrunning is by far the more destructive, and if prolonged is fatal to the valve. The heater voltage should be kept within the maker's tolerance, usually ±5 per cent. This must be the measured terminal voltage on load and not the open circuit voltage of the heater transformer winding.

Many attempts have been made to eliminate separate switching of the anode circuit. Among these may be mentioned special designs of valve in which an auxiliary cathode prevents conduction from the main emissive surface by screening until the temperature is high enough;[3.12] another in which an initial high negative grid bias furnished by a charged condenser which discharges during the heating period;[3.13] and finally one in which the grid bias is controlled through a separate vacuum valve with a cathode of high thermal inertia.[3.14] None of these have been generally adopted and some form of sequential switching is almost always used. This is preferably made automatic to prevent possible errors on the part of the operator.

The safe preheating time depends on the size of the tube. It may vary from about 15 secs. to about 15 mins. for large valves. Even with the same tube, the safety period is longer if the valve has not recently been in use and, with mercury valves, if recently transported.

It would be an undesirable complication to have an automatic switching device with a variable delay period and not necessarily a safe one, so that the fixed period switching device which is invariably used must have a delay period which is safe under all circumstances.

The fact that the bimetallic thermal switch is cheap and robust, though not very accurate as a time delay switch, has ensured its general adoption as a means of delaying the closure of the anode circuit so as to make the switching automatic. It has one disadvantage in that the delay in closing also occurs on opening the circuit of the heater of the switch, and the contacts do not separate until it has been switched off long enough to cool down. It is thus possible to open the circuit of the bimetal switch and close it again before the contacts have had time to separate, so that damage to the valve cathode is not entirely obviated. There are several ways in which this possibility can be avoided. One of them is shown in Fig. 3.22, requiring the addition of an A.C. relay with two sets of contacts. With the main supply disconnected, all contacts are in the positions shown in Fig. 3.22. Closing the main switch S completes the heater circuit of the valve and also the heater 1 of the thermal delay switch. After the required period, the bimetal contact arm 2 closes on contact *b* and completes the circuit of relay A/2, which operates and locks in through a_1. At the same time contact a_2 moves to the left, switches the heater 1 of the bimetal switch out of circuit, and prepares the circuit of the anode transformer primary. The thermal switch then cools down and finally closes on contact *c*, completing the anode circuit of the valve through the anode transformer. If at any time the main switch S is opened, if only momentarily, relay A/2 releases and the whole sequence must be repeated before the anode of the valve can be closed. Since the valve anode circuit is closed only after the thermal switch has reverted to its original position, the arrangement is more satisfactory than a single thermal switch, since it avoids any permanent deformation of the switch arm which may occur through being left in circuit continuously.

A particular case illustrating conditions where this protective device is useful is the one where the valve is withdrawn from its holder and replaced by another one.

The necessity for the delayed switching of the anode circuit is an unfortunate but unavoidable feature of the gasfilled triode, and one which is sometimes the deciding factor in favour of the hard vacuum valve if the application is one which permits the choice of either. It becomes most troublesome where the circuit is required for intermittent service. With small valves there is usually little objection to leaving the heaters continuously in circuit, but with larger units the power consumption may be a consideration, so that the expense of a protective switching arrangement like that previously described may be justified. It is not desirable for a large potential difference to exist between heater and cathode or for the former to be at a floating potential with respect to the rest of the circuit, and for such reasons the cathode and heater are invariably connected together externally.

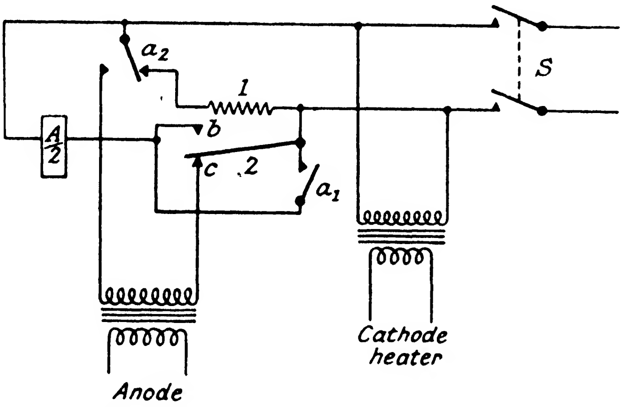


Fig. 3.22.—Cathode heater switching circuit.

Protection against Overload

Protection against overload should be provided for by the inclusion of quick-acting relays in anode circuit of a gasfilled triode. Fuses are insufficiently rapid in action to prevent damage due to peak current overload. One of the advantages of grid excitation by superposed A.C. and D.C. is that the operation of the overload relay may be caused to remove the A.C. grid voltage supply, leaving the grid negatively biased and the current therefore effectively cut off. In small valves the reactance of the anode transformer, where used, is often sufficient to limit the short-circuit current to safe dimensions. Relays are still required to limit the recurrent peak current.

CHAPTER REFERENCES

3.1. Pickering, A circuit for rapid extinction of the arc in a thyratron, *Rev. Sci. Inst.*, Vol. 9 (June 1938), pp. 180-2.

3.2. British Patent 209,426; also Hull, Hot cathode thyratrons, Part II—Operation, *G.E. Rev.*, 32 (1929), pp. 393-8.

3.3. Turner, Control of a gasfilled valve through a phase-shifting input valve, *Wireless Engineer*, 14 (May, 1937), pp. 229-41.

3.4. Kusakari, Phase shifter for grid controlled discharge tubes, *Electro-Chemical Journal* (Tokyo) (May, 1939), pp. 115-8.

3.5. Haller, Output of phase-controlled rectifiers, *Electrical Journal*, 31, (April, 1934), p. 161.

3.6. Morack, Voltage impulses for thyratron grid control, *G.E. Rev.*, Vol. 37, (1934), p. 288.

3.7. Kiltie, Transformers with peaked waves, *Electrical Engineering*, 51 (1932), pp. 802-4.

3.8. Windred, The parallel operation of gasfilled triodes, *Electronic Engineering*, 18, No. 225 (November, 1946), p. 387.

3.9. Everest, Phase shifting up to 360°, *Electronics* (November, 1941), p. 46.

3.10. Baker, Fitzgerald and Whitney, Industrial uses of electron tubes, *Electronics*, 2 (1931), pp. 467-9.

3.11. Klemperer and Strobl, Grid-controlled rectifiers with capacitive load, *Arch. f. Elektrot.*, 27 (July 1, 1933), pp. 485-8.

3.12. Lowry, A self-protecting cathode, *Electronics*, Vol. 8 (December, 1935), p. 26.

3.13. ——, Protecting the cathode of a mercury vapour tube, *Electric Journal*, Vol. 33, No. 4 (April, 1936).

3.14. Miles and Morack, Thermal delay relays for cathode protection, *Electronics*, 8 (April, 1935), p. 124.

3.15. Everest, Phase shifting up to 360°, *Electronics* (November, 1941), p. 46.

3.16. Devoy, New thyratron circuit for motor control, *Electronics*, Vol. 24 No. 4 (April, 1948), p. 116.

CHAPTER 4

The Gasfilled Triode as a Simple Switching Device and Some Applications in Relay Circuits

Merits of the gasfilled triode as a switching device. Further considerations. Some basic circuits. Switching by condenser discharge. Signal pre-amplification. Differentiating relay circuits. Overload relay. Cathode ray time-base circuits. The gasfilled triode as a fly-back switch. Linear time base and amplifier. Other forms of scanning circuit. Means of stabilisation. Velocity modulated sweeps. Frequency division. Switching selector for double-trace screen recording. Temperature control. Printing and wrapping machinery. Register control. High-speed counters. Multiplier circuits. Cascade connection. Other modifications. Frequency measurement. Measurement of short time intervals.

WITH the increasing adoption of electronic devices in industry the gasfilled triode has fulfilled and is fulfilling an important function in the solution of many problems which can be attacked only with difficulty, or which may not be soluble at all, by other and alternative methods. It is well, therefore, to mention first of all some of its merits as a relay or simple switching device before proceeding to specific applications of its use in industry.

Merits of the Gasfilled Triode

It has been shown that, assuming for simplicity a steady direct anode voltage is applied to the valve, the gasfilled triode can assume one of two stable conditions: the anode current is entirely suppressed or is fully established. There is no intermediate condition. In this respect it is the true analogue of the electromagnetic relay, the contacts of which must be in either the open or the closed position. Hence in this respect the term "gasfilled relay" is fully justified, though this is only one of several functions it may perform, in some of which it does not act as a simple switch.

The anode current can be fully and permanently established by an impulse of very short duration—of the order of a few microseconds—in the grid circuit. This is an outstanding feature of the gasfilled triode and one which distinguishes it markedly from the vacuum valve when used as a switching device.

For a very short impulse on the grid the anode current in the vacuum valve is of the same transient nature as the grid signal, and therefore frequently too short in duration to actuate a switch directly.

In addition, the triggering action of the gasfilled valve is very useful when the grid voltage is changing slowly and produces a snap closure of any switchgear controlled by the anode current. In the case of the vacuum valve the anode current changes slowly with a slowly varying grid potential, and some additional components will be required to obviate the tendency of any electromagnetic relay in the controlled circuit to chatter when near the point of operation or release.

Further, the change in grid voltage required to start the discharge results in a much larger anode current than the same grid voltage change would produce in a vacuum valve, so that where an electromagnetic relay is controlled, a larger and more robust unit with greater loading capacity can be used. Moreover, the power expended in the grid circuit to fire the valve is very small—of the order of a few microwatts—so that a signal circuit with very low power output, such as a thermocouple or emission type photocell, can provide sufficient power to control a relatively large load, the combination constituting a switching device almost devoid of inertia and often capable of high repetition speed of operation.

The gasfilled triode shares with the vacuum valve the advantage of silence in service and ability to operate even with high resistance contacts in the grid circuit. These, again, are notable features which are distinctive from the use of an electromagnetic relay.

Some Further Considerations

With these advantages in its favour it must also be stated that the gasfilled triode has in some relay circuits little or no advantage over the vacuum valve and the latter will function equally well.

If the signal impulses are not too short, nor too closely spaced, a telephone relay controlled by a vacuum triode may be just as good as a gasfilled triode, since load of practically any magnitude can be handled by contactors following a telephone type relay. In such cases the higher cost of the gasfilled triode and the necessity for automatic switching for preheating the cathode may outweigh the advantage of higher anode current. Not all applications require a large change in anode current, and provided the grid voltage change in the vacuum valve is sufficient to give the required change in anode current, the necessary conditions will be met without recourse to the gasfilled valve.

When an electromagnetic device such as a contactor is controlled, this will introduce a time element of its own, and while the firing of a gasfilled triode may only entail a period of a few microseconds, the period required for the completion of the control may be of a much higher order. Speed of operation, therefore, implies the completion of the whole cycle of events, and the short operating period of the gasfilled valve must not be divorced from the circuit as a whole.

Again, though the power expended in the grid circuit is very small, the energy required to bring about the required grid voltage charge may be much higher. For instance, suppose the grid voltage change is brought about by a phase shift through the increase in capacity of a condenser. The work done in the mechanical displacement may be much greater than the electrical energy expended in the grid circuit of the valve.

While, therefore, the gasfilled relay is an exceedingly useful and ofttimes an indispensable electronic device, its adoption must be decided upon only after the problem is considered from all aspects.

Some Basic Circuits

So many different conditions arise under which gasfilled triodes are used that the classification of circuits and applications according to type is not always possible. For instance, the valve may at one and the same time perform a switching operation and yet be essentially a commutating device, so that the separation of the practical applications under chapter headings may at times appear somewhat arbitrary. Figs. 4.1 and 4.2 show some examples of relay or switching circuits in which the gasfilled triode essentially performs the function of an on and off control. Fig. 4.1 shows control of the load by means of a light-sensitive device. In Fig. 4.1, (*a*) if the light cell is of photo-conductive type such as the selenium resistance bridge, the circuit is the same as that of Fig. 3.8, (*c*) page 67, and the valve either fires or does not do so according as the light is less than or greater than a certain intensity, since the bridge is a resistance decreasing in value with increasing intensity of light. In this case the phase change resulting from reduction in illumination corresponds to the retardation of the grid voltage relative to the anode voltage and immediate establish-

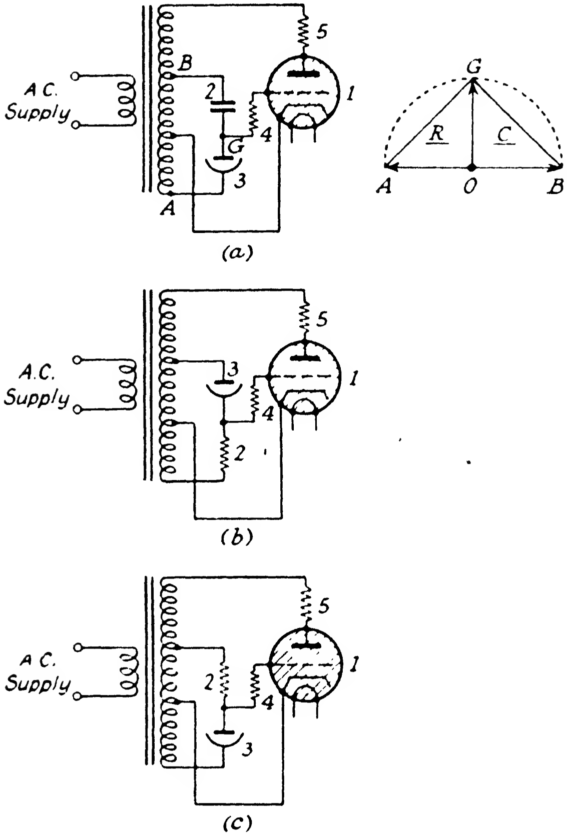


Fig. 4.1.—Switching circuits in which the load 5 (a relay) can be operated by change in illumination on the light cell 3. These are all trigger action circuits and no variation of the mean anode current of the valve is possible by varying the light intensity on the photocell.

ment of the full anode current (*cf.* Fig. 3.7, page 67). When cells of the emission type are employed the circuit behaves in the same way, but the mode of operation is rather different. As distinct from photoconductive cells, current passes in an emission cell in one direction only—*i.e.*, electrons move from the cathode to the anode. On A.C. supply, therefore, current passes only when the anode of the photocell is positive to the cathode during alternate half-cycles. The trigger action in this case is due rather to a distortion of the wave than to a pure phase change of the grid voltage.

In Figs. 4.1 (*b*) and 4.1 (*c*) light on the photocell produces a change in amplitude of the grid voltage. In Fig. 4.1 (*b*) the valve fires when the light exceeds a certain value. In Fig. 4.1 (*c*) the reverse action takes place, and the discharge is fully established when the light is reduced below a certain value.

These circuits are, of course, automatically resetting by reason of the alternating anode voltage. If the load is an electromagnetic relay, its coil must be shunted with a condenser of sufficient capacity to prevent hum and chattering at the point of operation.

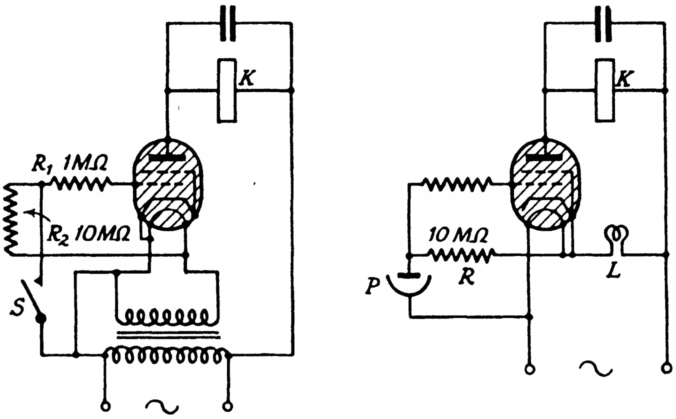


Fig. 4.2A.

Fig. 4.2B.

Other types of simple relay circuits.

The circuits of Fig. 4.1 (*b*) and 4.1 (*c*) should be carefully distinguished from those cases where the light change can be made to give a quantitative variation in mean anode current according to the light intensity. For instance, in Fig. 4.1 (*b*), if the resistance 2 is replaced by a condenser of suitable value, the circuit is converted into one in which the mean anode current of the gasfilled triode increases or decreases progressively as the light intensity on the photocell increases or decreases. Similarly, in the circuit of Fig. 4.1 (*c*), if the resistance 2 is replaced by an inductance of suitable nature, light variation produces a progressive change in mean anode current, but in the direction reverse to that of the previous case.

Fig. 4.2 (A) shows a circuit which includes a tetrode, which is preferable to a triode for high impedance circuits to operate as a relay where a low voltage and high resistance contact is required to control the load. Here the signal grid of the triode is biased through resistances

R1 and R2, with the contact S open. Closing S removes this bias and returns the grid to the cathode, causing the valve to fire and actuate the load circuit through the relay K. If R1 and R2 are high resistances, of the order of megohms, the current through the contact S will be negligible.

In Fig. 4.2 (B) the source of light is incorporated in the valve heater circuit and may be housed in the same case. Where a lamp and valve heater of the right rating can be secured for series operation, this is a cheap way of avoiding a separate transformer in cases where the photocell has to operate by reflection from a distant mirror surface. The photocell P and resistance R shunt the heater, the voltage drop across which provides the necessary voltage for the photocell. When the photocell is illuminated, the emission maintains the grid sufficiently negative to prevent the valve from firing. Cutting off the light removes this bias and allows the discharge to pass. Both these circuits are, of course, self-resetting.

Though these are essentially relay circuits, since no variation in the value of the mean anode current is possible, there is no reason why in many cases the corresponding circuits in which the signals produce a phase change on the grid which results in a variation of the mean anode current should not also be used as relay circuits, provided the light change is large enough to produce the required change in mean anode current to operate the relay.

If the positions of the photocell and the condenser are reversed in Fig. 4.1 (A), the control changes from a simple on and off to one in which the light change results in a variation of the mean anode current, but which nevertheless can, as mentioned above, be employed as a relay circuit.

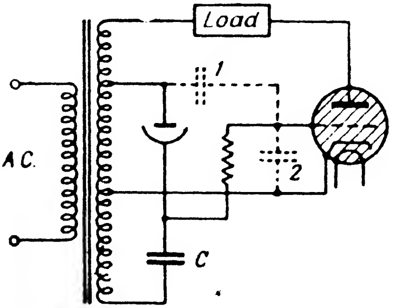


Fig. 4.3.—The effect of interelectrode capacitance.

This circuit is redrawn in Fig. 4.3 with the interelectrode capacities of the valve and photocell shown dotted, because these stray capacities involve a point of further interest, since they are not always negligible in determining the functioning of the circuit. The capacity of the condenser C must always be greater than the residual capacity of the photocell, otherwise the discharge will pass whether the photocell is illuminated or not.

Furthermore, the mean anode current is not, in general, proportional to the illumination, but becomes more nearly so as C is increased. If the value C is 0·001 to 0·003 μf., which is usually sufficient to reduce the mean anode current of the triode to zero when a gas-filled photocell is used and the light completely removed, the relation between light and current is approximately linear.

Switching by Condenser Discharge

Fig. 4.4 shows a useful circuit utilising the principles of operating a relay through a condenser discharge previously referred to on page 57. The circuit of Fig. 4.4 is arranged so that in the non-operating condition the photocell P is obscured. The position of the slider connected to the triode cathode is then adjusted until the cathode is made sufficiently positive to the triode grid to prevent the valve firing with adequate margin of safety. On closing switch S, condenser C1 charges to the full supply voltage through resistance R1. As soon as a flash of light reaches the photocell P, the triode grid

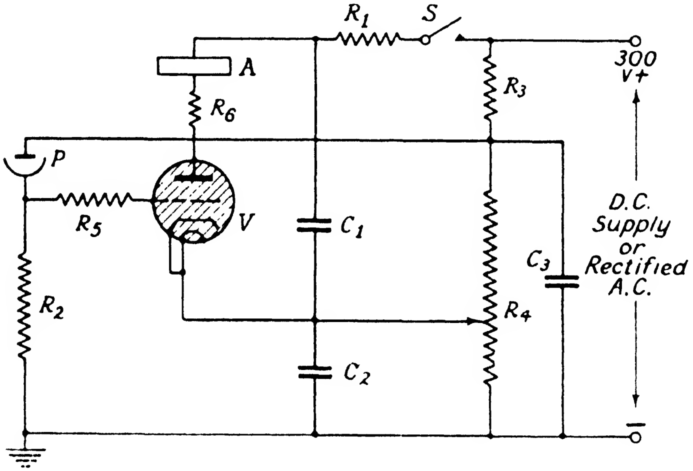


Fig. 4.4.—Circuit in which a photocell operates a relay by discharging a condenser through a gasfilled triode. V=Osram GT1C; R1=20,000-50,000 ohms; R2=1 megohm; R3=2,000 ohms; R4=3,000 ohms; R5=50,000 ohms; R6 depends on relay resistance; C1=2-6 mf; C2 and C3=2 mf.

negative potential is reduced and the discharge established. Condenser C1 is then rapidly discharged through the triode V and relay A. Its voltage falls to a low value, so that the triode discharge is extinguished. The condenser C1 then starts to charge up again ready to operate relay A from the next light flash.

A circuit of this type has several advantages for special applications. Since the condenser discharge takes place very rapidly, a current of high peak value passes through the relay, so that a robust type of relay can be used. In some cases an electromagnetic device of some other kind such as a guillotine or punch can be operated. The peak current, of course, must be limited to the peak current rating of the triode by the addition of extra resistance in the valve anode circuit if the inductance and resistance of the relay or other controlled device is insufficient to secure this condition. A single operation of the relay with an immediate reset results from a single light flash on the photocell and the light change may be of the order of microseconds.

If the light change is sustained instead of being transient, condenser C1 will recharge until its potential is again sufficient to fire the triode, and this cycle will repeat its operation at intervals depending on the time constant of the condenser charging circuit. Where this condition is to be avoided, the coupling between the photocell circuit and the triode grid must be made through a condenser so that steady voltage changes on the grid are excluded. The amount of energy available for operating the device A will be greater the larger the capacity of the condenser C1, but will be limited by the peak current rating of the triode. The resistance R1 must be large enough to prevent the discharge being permanently established through the valve V from the supply, but not so large as to prevent the condenser charging up to its full potential in the interval between the firing impulses. If the firing impulses are frequently recurrent, it is a matter of adjusting the values of condenser C1 and resistance R1 to secure a suitable time constant. Condensers C2 and C3 are included to smooth out variations of voltage across the potentiometer tappings which may be caused by the transient impulses.

If the circuit is required to function in the reverse direction—viz., when the light is suddenly cut off after being incident on the photocell—the positions of the photocell P and resistance R2 must be reversed and the cathode potential readjusted to secure the requisite grid bias under these new conditions.

Signal Pre-amplification

When the light change is too small to give an input impulse of sufficiently large amplitude to fire the triode, the circuit can be preceded by one or more stages of valve amplification. Fig. 4.5 shows the circuit of Fig. 4.4 preceded by one stage of valve amplification. It will be noted that the photocell P and the input load resistance R2 occupy the same relative positions as in Fig. 4.4, but the relay operates by a light change in the reverse direction—viz., when light normally incident on the photocell is suddenly cut off. This is due to the fact that the signal polarity is reversed on passing through the valve stage. The gasfilled triode requires a grid impulse of positive polarity to fire it; hence the light change for a preceding single valve stage (or any odd number of stages) must produce a negative impulse on the grid of that valve.

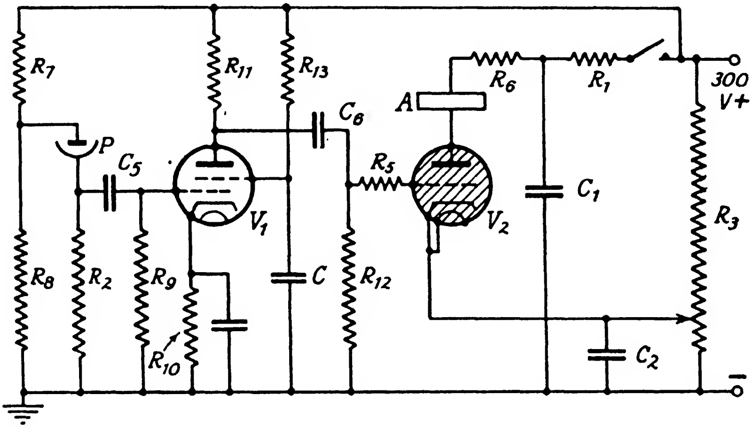


Fig. 4.5.—The circuit of Fig. 4.4 preceded by a condenser coupled stage of valve amplification. R11 = 50,000 ohms; R12 = 100,000 ohms; R13 = 1 megohm; C = 1 mf.; V1 = Osram Z66; V2 = Osram GT1C; R7 = 30,000 ohms; R8 = 10,000 ohms; C5 and C6 = 0·1 mf.; R2 = 20-25 megohms; R9 = 1 megohm.

Action in the reverse direction can, as before, be secured by reversing the positions of the photocell and the resistance R2.

The circuit of Fig. 4.5 gains in sensitivity for two reasons. Firstly, there is the amplification due to valve V_1, and secondly the input signal can be made much larger than in the case of the circuit of Fig. 4.4. With small gasfilled triodes, the permissible grid resistance is generally limited to values of the order of a megohm or so. This limitation is to some extent removed in the circuit of Fig. 4.5, where the load resistance may be of the order of 20 to 25 megohms and limited only by the possibility of insulation leakage and resulting in a correspondingly greater input signal. These advantages are, of course, secured at the expense of the additional components of the extra valve stage.

Transformer coupling of the gasfilled relay to the first valve can

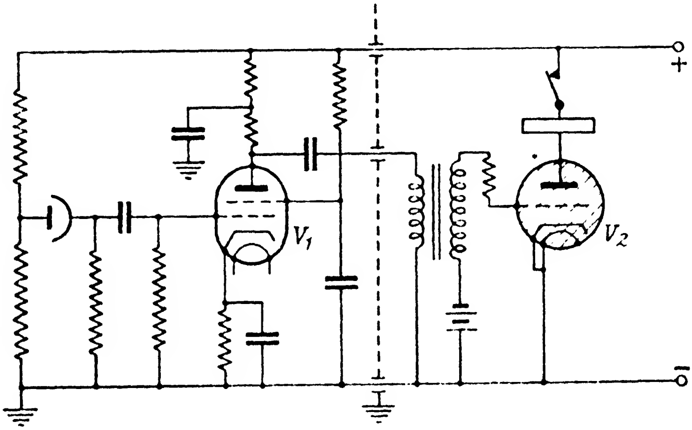


Fig. 4.6.—Gasfilled triode relay circuit coupled to a valve stage with parallel feed transformer.

also be used (Fig. 4.6). Here further advantage can be secured by the voltage step-up in the coupling transformer, but the circuit shown does not involve the condenser discharge and automatic resetting principle of the two previous circuits. Consequently, when the gasfilled relay fires, the relay locks in until the circuit is opened by a separate switch in the anode circuit. It should be noted that with transformer coupling the polarity of the grid impulse to the gasfilled triode can be reversed by reversing either the primary or secondary leads of the transformer to secure a positive impulse to the grid of the gasfilled triode.

The emission type of photocell should feed into a high impedance circuit, otherwise the combination is relatively insensitive and a large light-change is required to fire the valve. Since the gasfilled triode is limited in permissible value of grid leak, a tetrode is nearly always preferable. The field of application of such a combination is a very extensive one, involving innumerable cases where this combination operates either as a switch or may in addition perform some other function.

It is impossible to describe here all the conditions which may occur in practice and which in general involve elaboration of the simple circuits outlined. Many applications involving light sensitive cells are described elsewhere.[4.1] In the applications which are hereafter described, attention has been directed particularly to the particular way in which the gasfilled triode has proved advantageous rather than on the circuit details which vary so widely in individual cases.[4.2]

Differentiating Relay Circuits—Overload Relay

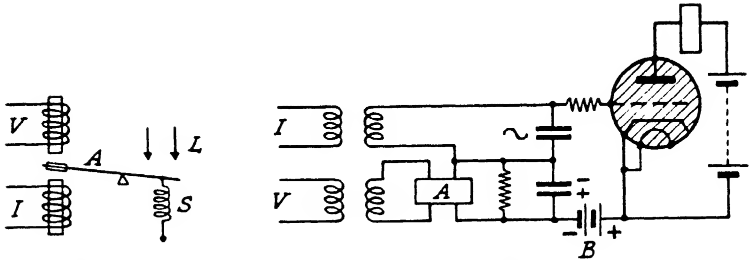
The basic circuits previously referred to lead to a number of specific instances in which the gasfilled triode operates as a tripping device.

Firstly, there is the case where an independent circuit can be monitored for voltage or current overload. Assuming at first that steady potentials are applied to the triode, then with a fixed bias of suitable value the anode circuit can be coupled to the circuit it is desired to monitor in such a way that a voltage of suitable magnitude is continually injected into the triode anode circuit in a direction to reinforce the applied steady voltage.

If the voltages are suitably adjusted, the triode will fire and actuate a safety device or indicator when the voltage injected from the monitored circuit exceeds a preset value.

Similarly, with a fixed steady anode voltage the monitored circuit may be coupled to the triode grid with correct polarity, so that when the voltage or current in the monitored circuit falls below a preset value, the triode will fire to function as an undercurrent or no-voltage tripping device.

Frequently and more conveniently the same results may be secured with alternating electrode voltages for the triode. These, of course, are merely particular cases of the general one in which the triode acts as a detector of transients. By combining these two cases it is possible to secure a "quotient" or under-impedance relay, in which both the current I and the voltage of an independent circuit simultaneously control the trip circuit, which functions when the ratio V/I falls below a preset value. The voltage V, or a portion of it, is rectified and acts as a restraining control, while the current I provides a grid voltage tending to operate the triode. The mechanical analogue of



(a) (b)

Fig. 4.7.—Under impedance relay.

this dual control is indicated in Fig. 4.7 (*a*). Here the armature A is held in position on a fulcrum by the spring S, which balances its tendency to rotate and close contacts L when no magnetic forces are applied. The field of the electromagnet V assists the spring in this restraint, while the magnet I tends to cause the armature to move and close the contacts.

In the relay circuit (Fig. 4.7*b*) the battery B corresponds to the spring S of Fig. 4.7 (*a*) and causes the firing of the triode to coincide with a limiting minimum value of V/I, so that the triode discharge passes whenever this value is reached. Such a circuit can in addition be modified to operate on the magnitude of a factor $\frac{I_1 - I_2}{I_1 + I_2}$ where I_1 and I_2 are current measured at the terminals of the circuit. A rectified restraining voltage proportional to $I_1 + I_2$ is applied to the grid network and the tripping voltage is proportional to $I_1 - I_2$. This latter voltage is rectified and the grid circuit network must be such that the time constant of the tripping voltage is greater than that of the restraining voltage. A percentage current differential relay of this type is shown in Fig. 4.8.

It will be clear from these examples of superposition of voltages from two sources on the grid of the triode that the conditions for using the gasfilled triode as a reverse current or reverse power relay are not difficult to meet.

For the purpose of providing a firing impulse the injected voltage from a circuit being monitored for reverse current is merely a special case of under-current detection previously referred to.

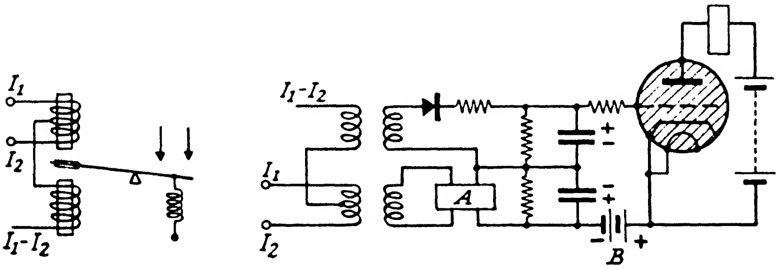
For reverse power, two injected voltages, one proportional to the current and the other proportional to the voltage in the monitored circuit, are fed to the triode grid in series aiding, so as to provide during normal service the restraining bias to prevent the triode firing. Reversal of polarity of either voltage will reduce this negative bias and actuate the relay circuit.

By suitable adjustment of the magnitude and phase relationship the two voltages can be alternating and superposed so that during normal service the resultant voltage restrains the valve from firing. Power reversal will cause the direction of one voltage vector to reverse, and the resultant will then be such as to cause the valve to fire.

A power reversal relay of this type may lose its directional discriminating properties under short-circuit conditions, as the ratio of current to voltage then becomes sufficiently large to provide a grid voltage which will fire the valve under any circumstances.

In most of these relay circuits provision has to be made against inadvertent operation by surges, and a condenser connected between the valve grid and cathode is provided for this purpose. Its presence does introduce a time factor into the operation of the circuit, but this is hardly avoidable.

High-speed directional and reactance relays utilising somewhat different principles have also been used. A restraining voltage is applied to the grid of the triode sufficient to prevent the discharge from passing. This restraining voltage is made to disappear periodically for a moment, and during this short interval the valve is given the opportunity of measuring an alternating voltage also applied to the grid circuit. By altering the phase of the instant of removal of the restraining voltage the valve will operate or not operate according to the relative magnitude of the then applied grid and anode potentials. Reference should be made to the original article for further details.[4.3]



(a) (b)

Fig. 4.8.—Percentage differential current relay. A=rectifier (full wave).

Cathode Rays Time Base Circuits[4.4, 4.5, 4.6, 4.7, 4.8]

When it is required to record on the screen of a cathode ray tube the way in which some variable changes with time, it is most usual to arrange the time scale as a horizontal axis with the change in the variable in the direction at right angles to it. Though various types of time scale are used, the horizontal linear scale is most frequently used. All such time scales are generally referred to as time bases, and are formed by applying a gradual increase in potential between the horizontal deflection plates so that the spot is drawn across the screen at a uniform speed. In the case of recurrent phenomena the deflection voltage is made to collapse suddenly at the end of the trace and immediately start building up again, so that the spot flies back to its starting point and repeats its traverse. By correct timing this and all the successive traces can be exactly superposed so that the eye sees a stationary figure.

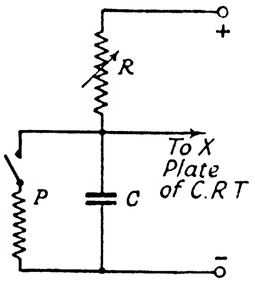


Fig. 4.9.—Principle of the line time sweep circuit for a cathode ray tube.

The horizontal deflection voltage required to give the time scale is obtained from the potential across a condenser which is gradually charged by connection to a direct-current source through a high resistance. If at the end of the traverse the condenser is suddenly short-circuited, its voltage will disappear and the spot will fly back to its starting point. Fig. 4.9 shows the circuit in principle, the condenser C being charged through resistance R and finally shorted by switch P. When connected through a resistance to a D.C. supply the condenser voltage does not rise at a uniform rate. The rate of charging at first is rapid, but this gradually decreases as the condenser voltage builds up. Consequently, if applied directly to the deflection plates of the cathode-ray tube, the condenser voltage would not produce a uniform time scale. Linearity of the time base can, however, be secured by one of two simple methods: (*a*) by using a D.C. supply of much higher voltage than that at which the condenser is shorted so that only the initial part of the condenser charging curve—which is approximately linear—is used; (*b*) by including in the charging circuit a constant current device, such as a screen pentode valve. The current through such a valve is independent of the anode voltage over a fairly wide range, so that rate at which the condenser charges up can be made uniform. Adjustment of the screen voltage enables the charging rate to be changed from one constant value to another constant value. The rate at which the condenser voltage rises, and therefore the speed of traverse of the screen spot, can also be changed by altering the capacity of the condenser and the value of the charging resistance.

The Gasfilled Triode as a Fly-back Switch

In order to make the spot return quickly to its starting point to repeat the trace for recurrent sweeps, an electric device must be used as a switch for this purpose. For this operation the gasfilled triode is very suitable, the resetting being secured by a triggering impulse on the triode grid which fires the valve and momentarily discharges the time-base condenser, making the spot fly back suddenly to its starting to repeat its traverse. Circuits which perform this cycle automatically to produce a time base in this way are known as relaxation or saw-tooth oscillators.

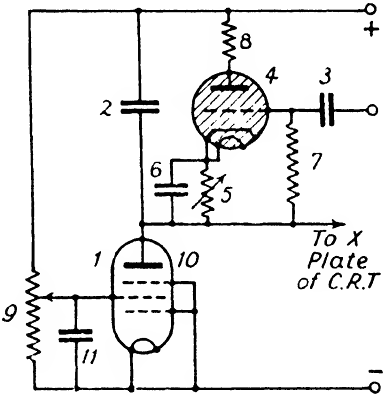


Fig. 4.10.—The use of a pentode valve as a constant current device to secure uniform voltage rise on the time base condenser.

The gasfilled triode has considerable advantage over cold cathode discharge devices in such circuits, because the voltage range between the firing and extinction conditions can be made much larger and can be adjusted by varying the voltage of the control grid of the triode.

Referring to Fig. 4.10, the screen pentode valve 1 is the constant current charging device which ensures that the voltage across condenser 2 builds up uniformly until a point is reached determined by the grid bias of gasfilled triode 4 at which this valve fires, causing the condenser voltage to collapse. The rate at which condenser 2 charges can be adjusted by varying the screen potential of valve 1. The grid bias of the gasfilled triode determines the amplitude of the trace on the cathode ray tube screen.

Each time condenser 2 discharges through the gasfilled triode 4 the condenser 6 receives a charge which tends to leak away through resistance 5 during the interval that the timing condenser 2 is charging. The effective bias on the gasfilled triode 4 is provided by the potential across resistance 5, and the time constant of this resistance and condenser 6 must be such that this voltage does not change appreciably during the charging period of condenser 2. Variation of resistance 5 provides an adjustment for the rate of firing of the gasfilled triode 4.

In order to give a stationary screen trace for a recurrent signal, the time-base circuit requires to be synchronised either with an external source of frequency or, as is more general, with the signal circuit; otherwise, if not locked in step by some such mastering control, the pattern will tend to drift owing to unavoidable changes in the timing of the successive sweeps. When synchronised with the work circuit, a small part of the incoming signal is applied to terminal 3 (Fig. 4.10) of the gasfilled triode so that the anode potential of the valve as the firing takes place is slightly altered, and if this synchronising impulse is of peaked wave form the precise instant at which the valve fires can be made very exact.[4.9] In order that the synchronising impulse shall perform the function intended it must be of the same or some multiple of the frequency of the relaxation oscillator. If the synchronising signal is too weak, it will be insufficient to lock the time base circuit in step. If it is too strong, it will distort the signal trace or cause it to shorten by a series of jumps.

Linear Time Base and Amplifier

Fig. 4.11 shows a complete time-base circuit which includes the Osram GTIC gasfilled triode and which produces a "saw tooth" wave form (Fig. 4.12[*a*]), resulting in a time base with negligible departure from linearity for repetition frequencies up to about 500 cycles per second. As the recurrent sweep frequency increases, the deionising time of the gasfilled triode ceases to be negligible compared with the time occupied in charging the time-base condenser.

With a triode designed for handling much larger currents than a circuit of this type demands, and with a comparatively long deionisation period of, say, 30 to 40 microseconds, operation at frequencies much above 500 per second results in the wave form approaching that of Fig. 4.12 (*b*). The condenser discharging or spot flyback

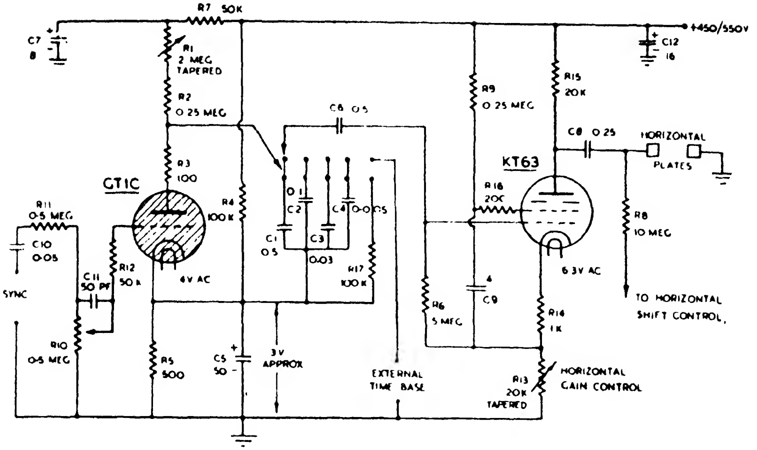


Fig. 4.11A.—Linear time base and amplifier for asymmetrical deflection.

period remains constant, but the charging time is curtailed so that the usable portion of the cycle is reduced. The effect of this on the screen trace is to distort it at one end without necessarily affecting the utility of the record which is free from distortion to the right-hand side of the screen (Fig. 4.12, *d*). As the frequency is further increased the flyback and condenser charging times become comparable, and there is thus a maximum operating frequency. With the Osram GT1C

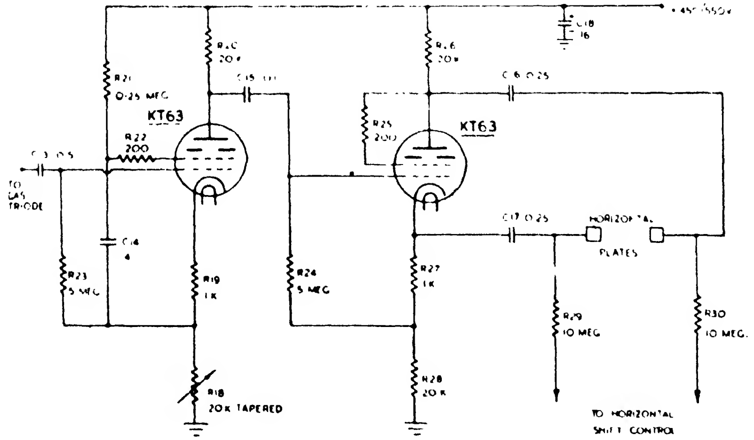


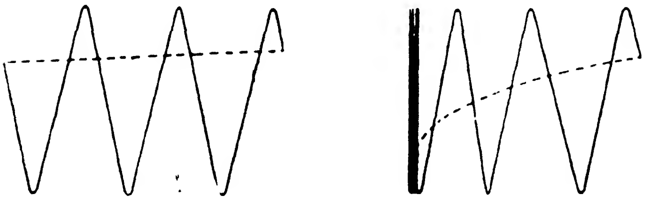
Fig. 4.11B.—Amplifier for symmetrical deflection.

this is about 10 kc./sec., but as the valve may be synchronised at a multiple of the frequency under observation, frequencies of 20 or 30 kc./sec. can be shown on the screen.

The upper limit of frequency at which a circuit of this type will function is not, therefore, entirely set by the deionisation time of the triode, but rather by the necessity of reducing the charging current as the capacity of the condenser is reduced to obtain extinction of the discharge. The charging current must be large compared with the residual leakage current, otherwise the former will contain a component which is a function of the voltage across the time-base condenser and the trace will not be linear. A charging current of the order of a milliampere is about the lower practical limit. Consequently, the very high impedance provided by a pentode valve cannot be utilised

(a) Ideal Saw-tooth Wave produced at Low Frequencies

(b) Time Base running at 8·5 kcs. showing Distorted Waveform



(c) Time Base running at a Low Frequency

(d) Cramping of Trace due to Long De-ionising Time

Fig. 4.12.—Wave forms of linear time base.

to the full extent. As the rate of repetition sweeps increases, the performance becomes more complex than the predictions from the static characteristic curves would indicate. Some of the effects which occur under such conditions have been made the subject of special investigations.[4.5, 4.6] For instance, as the repetition frequency increases, the capacity of the time-base condenser has to be reduced. If the charging current is not reduced, the discharge through the triode will not extinguish when the condenser is discharged if its capacity is made very small.

Where the performance demanded from the scanning circuit is beyond the capabilities of the gasfilled triode, due either to inability to secure a valve with a sufficiently low deionisation time or some other reason, the examination of phenomena requiring sweeps of higher frequency will call for a hard valve time-base circuit, special designs of which have been evolved to meet cases where high-speed repetition traces are involved.

In the circuit of Fig. 4.11A the frequency of the sweep can be adjusted by selection of an appropriate value of the charging condensers C1, C2, C3 or C4. The adjustable charging resistance R1 provides a fine control of this period. The grid of the triode is biased negatively to the cathode by resistances R4 and R5, which restrain the discharge until the anode voltage reaches about 50. Since the D.C. supply voltage (500 volts) is high compared with the anode voltage at which the valve fires, the charging takes place on a linear position of the curve and distortion of the wave form is negligible. To secure a stationary trace free from slow drift, the circuit is synchronised with a submultiple of the frequency under test, a fraction of the signal voltage being injected with the valve grid through condenser C10 and resistances R10 and R11. The process of synchronisation functions best if the time base is set slightly too slow, so that the synchronising signal pulls it up to the required frequency.

As the voltage swing is insufficient for full screen deflection, the gasfilled triode in Fig. 4.11A is followed by a single-stage amplifier. This stage, which must be free from amplitude or phase distortion, has adjustable gain by means of the valuable unshunted cathode resistor R13.

The alternative of a tapped resistance in place of R6 is likely to produce phase shift in the flyback and is less satisfactory.

The coupling condensers C6 and C8 and the associated resistances R6 and R8 are larger than those commonly employed in order to prevent phase shift at low frequencies, and enable the circuit to function down to about 15 cycles per second.

The amplifier is connected to the external time-base terminals if the two-bank five position switch is rotated to the extreme right, in which position a resistance R17 is shunted across the triode to suppress oscillations.

With the 20,000-ohm adjustable gain resistance at a minimum the stage gain is 10 and a control of 10 : 1 is provided. If a higher gain is required for use with an external time base, the KT63 valve may be substituted by a type KT61 with resistance R14 of 400 ohms. This will give a maximum stage gain of 35 with a wider control range of 35 : 1.

The asymmetrical deflection which results from the circuit of Fig. 4.11A produces some defocusing with most cathode-ray tubes and the deflection is not always linear. This can be overcome by a push-pull circuit such as that shown in Fig. 4.11B, which also furnishes a greater undistorted output.

The power supply must be adequately smoothed. Two chokes and three condensers should be included to prevent irregularities appearing in the screen trace, particularly when this is a multiple or submultiple of the supply frequency. The rectifier in the power supply should be of the indirectly heated cathode type, so that some delay is provided for the cathode of the gasfilled triode to heat up sufficiently prior to the application of the anode voltage.

Other Form of Scanning Circuit

The principles previously outlined are, of course, employed in various ways in scanning circuits. One important one is that in which two such scanning circuits of different frequencies are applied simultaneously, one to the horizontal or X plates and the other to the vertical or Y plates of the cathode-ray tube, the vertical trace being slow compared with the horizontal one. This results in an extended linear time base similar to a television scan, and is very useful where it is desired to depict a time interval much longer than would be possible with a horizontal time base. In such a circuit each discharge of the line time base or horizontal scan condenser communicates a voltage pulse to the grid circuit of the charging pentode of the second or vertical time base, so that its condenser receives a constant increment in voltage at the conclusion of each linear sweep and the succeeding line trace is displaced slightly in the vertical direction each time a fresh horizontal trace starts until the whole screen surface is traversed by a series of closely spaced horizontal traces.

Numerous variations of the fundamental circuits just described have been employed to secure some particular advantage in a specific application. For instance, Blumlein[4.10] included inductances in both the charging and discharging circuits to improve the linearity of the sweep and to increase the deflection voltage available at the condenser terminals.

Means of Stabilisation

A method which has been used by Kock[4.11] to minimise the effect of instability of a relaxation oscillator circuit caused by changes which occur in the ignition and extinction potentials of a gasfilled triode which result in variation of the oscillation frequency is shown in Fig. 4.13. In this arrangement, resistance 2 couples the grid and anode so that a varying voltage from the discharge circuit is imposed on the constant grid bias. The grid becomes highly negative immediately after condenser 4 discharges, and becomes less negative as the condenser is prepared for the next discharge.

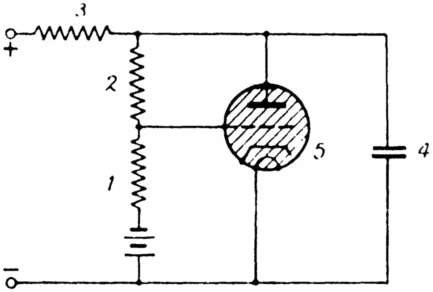


Fig. 4.13.—Stabilisation of sweep oscillator by coupling between plate and grid circuits.

If, for any reason, the firing voltage of the valve rises, then the negative grid bias voltage decreases more rapidly and the valve fires earlier than if resistance 2 were absent. Likewise, if the ignition voltage falls the grid bias decreases more slowly and the firing is delayed. In both cases the effect is to stabilise the point of firing around a preset potential. The degree of stabilisation is increased by making resistance 2 relatively small to resistance 1. At the same time the bias voltage has to be increased to maintain the same oscillation frequency, and the precision of adjustment is limited by the supply voltage available. The frequency range is extended by the fact that the negative bias is increased after the discharge has passed, which reduces the deionisation time. By this method two valves which in the same unstabilised circuit have characteristics differing so as to give 100 per cent. difference in oscillation frequency can, with the added resistance, be made to oscillate at frequencies differing by only a few per cent. Applied to synchronisation, the effect is more evident from Fig. 4.14. Curve 1 is the anode voltage of the oscillator, curve 2 the critical grid control voltage, curve 3 the constant negative bias without the coupling resistance 2, and curve 4 the resultant grid potential with increased negative grid bias and the added coupling resistance 2.

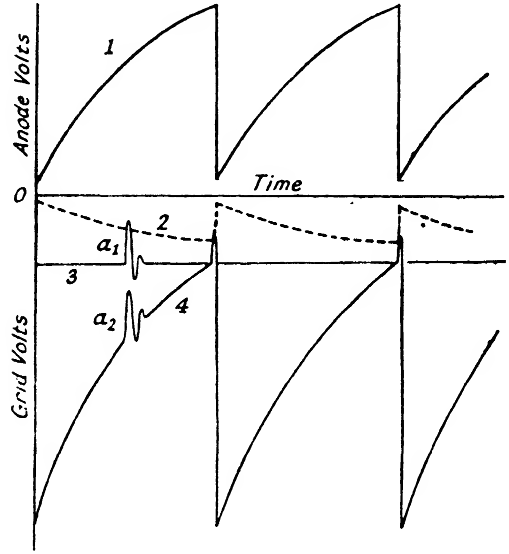


Fig. 4.14.—Stabilisation secured by the circuit arrangement of Fig. 4.13. 1 = Anode voltage of gasfilled triode; 2 = Critical grid control voltage; 3 = Applied grid bias without resistance R2 (Fig. 4.13); 4 = grid voltage secured by increasing negative bias and including R2.

It will be clear that a transient occurring at a_1 in the unstabilised circuit would cause the valve to fire, whereas a similar transient of the same amplitude at a_2 in the stabilised circuit would have no effect at all.

Velocity Modulated Sweeps[4.12]

In velocity modulated television transmission, the intensity of the cathode-ray spot remains constant and the light gradations on the screen are secured by varying the speed at which the spot moves: the lower the speed the brighter the trace appears to the eye due to the persistence of vision. This principle overcomes some of the difficulties of accurately modulating the spot brightness which is required with uniform speed of trace. In a velocity modulated time base, the grid of the charging pentode is connected to the output of a circuit which amplifies the picture signal, so that the rate at which the sweep condenser charges is a function of the instantaneous value of the picture illumination at the transmitter.

The general principle of using a gasfilled triode as a relaxation oscillator as used in a time-base circuit has many other uses. For instance, it has been used as a circuit interrupter on the primary side of an induction coil, as a cheap and easy way of avoiding the corrosion and pitting of contacts which are troublesome on mechanical interrupters or the expense of a mercury jet interrupter.

The rapidity with which a condenser discharge can take place through a gasfilled triode enables the frequency to be made higher with appreciable increase in energy from the spark circuit together with a longer spark, since the induced voltage in the secondary coil depends on the rate of current change through the primary.[4.13]

Frequency Division

A further elaboration of the circuit just described for time bases for cathode-ray tubes has been utilised for the purpose of frequency division—viz., to secure a stabilised source of frequency from a master source of much higher frequency, the output of the circuit being a submultiple of that of the master source. This is an example of a case where a time-base circuit is used for a purpose other than for producing a time scale on the screen of a cathode-ray tube and in which the gasfilled triode operates essentially as a switching device.

One of the difficulties involved in applying the general principle of extracting a subharmonic from a source of frequency is that if the low-frequency oscillator is not very stable it will not always synchronise with the same subharmonic of the main source. To avoid the possibility of the frequency jumping from one value to another the low-frequency oscillator must be designed so that its possible modes of oscillation are kept within close limits. A number of circuits have been designed in which the principle of extracting a submultiple of the source has been used, but the one evolved by Builder ensures that there is no possibility of the output being synchronised to any other than one particular subharmonic of the master source.[4.14]

The circuit includes the gasfilled triode relaxation oscillator circuit previously described in connection with time bases. The anode of the triode is coupled through a fixed condenser to the signal grid of a vacuum pentode valve, which forms the output stage.

In the anode circuit of the pentode is a parallel LC circuit tuned to the desired subharmonic frequency. The inductance of this circuit forms the primary of the output transformer which has two secondary windings. One of these secondaries provides the signal output, while the other feeds a phase shift circuit connected back to the grid of the gasfilled triode.

The grid circuit of the gasfilled triode is also fed through a transformer from the source of higher frequency.

The circuit can be synchronised to a high order submultiple of the higher frequency source even though the conditions of operation vary widely.

A modification of the circuit in which the second valve is eliminated has also been devised. This results in some simplification of layout due to the reduction in the number of compounds, but at the expense of some increased complication of performance.

A Switching Selector for Double Trace Screen Recording[4.15, 4.16]:

In connection with cathode-ray tube switching circuits the gasfilled triode has been employed as an electronic means of depicting simultaneously on the screen of one cathode-ray tube two traces of signals from entirely independent sources. The development of the double-beam cathode-ray tube has, of course, now rendered such circuits redundant, but the method used has some technical interest.

In the original circuit used for this purpose the X plates of the cathode-ray tube are used for the synchronised time base and the Y plates are coupled through condensers to the common anode circuit of two screen pentode valves. The two separate signal sources are coupled through transformers, one to the suppressor grid circuit of each pentode, so that the signals modulate the anode current.

These two pentodes have interconnected grid circuits so arranged that successive impulses to the grids drive each valve to cut off an anode current in a manner resembling that of a flip-flop circuit. These switching impulses, which occur at a rapid and constant rate, are provided from the anode circuit of a gasfilled triode which is rapidly switched on and off by a relaxation oscillator. The latter comprises one of the well-known parallel connected neon lamp and condenser circuits and the gasfilled triode serves to amplify the oscillation pulses.

With the oscillator running at its present frequency the input terminals of the cathode-ray tube are rapidly switched from the anode circuit of one pentode valve to that of the other, so that signal impulses representing successive points are recorded alternately from both sources and persistence of vision enables both curves to be seen simultaneously.

Temperature Control

Several circuits have employed the principles of Fig. 4.15 (*a*) for temperature control. Resistance thermometer 4 provides the out-of-balance voltage signal to the valve, whose mean anode current is controlled by grid voltage amplitude change. The valve may carry the heater current or may control this current through a contactor. In the first case the circuit is arranged so that rise of temperature produces an input signal which reduces the heater current and vice versa.

In Fig. 4.15 (*b*) the control is carried out through a contactor which serves to short circuit a portion of the heater winding to raise the temperature or to insert it to reduce the heating. The cycle of opening and closing of the contactor repeats, so that the temperature oscillates between an upper and a lower limit. The thermal lag of the heater is sufficient to prevent too rapid switching, so that hunting is eliminated. Though the contactor method uses the full cycle of the supply through the heater, the thermal lag of the heater prevents very close control of temperature.

In one modification of these methods[4.17] the thyratron is in parallel with part of the heater elements, so that only a portion of the heater current passes through the valve. Other circuits[4.18, 4.19] provide several pre-amplification stages, and the grid control phase change is provided by the reactance of the interstage couplings.

More elaborate circuits are required to control temperature within

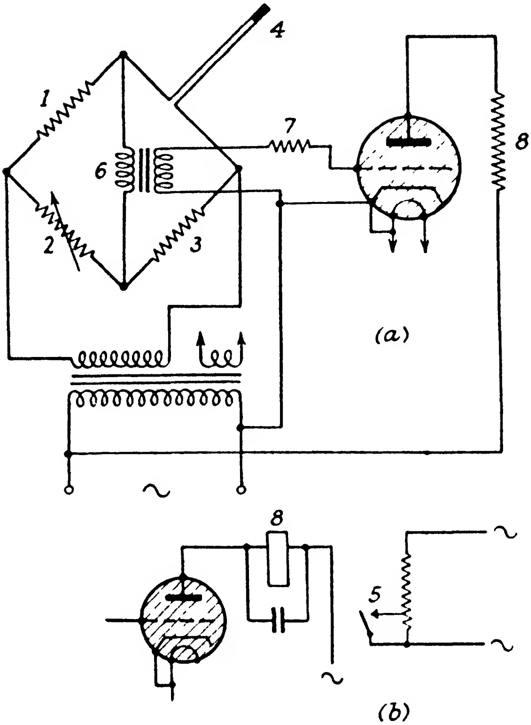


Fig. 4.15.—Temperature control with gasfilled valve, (*a*) direct regulation of heater current; (*b*) contactor switching of portion of heater elements.

fine limits. For instance,[4.20] temperature control of an oil bath over a period of weeks has been secured to within 0·005° C., using a copper manganin thermocouple and reflecting galvanometer in conjunction with a pair of photoelectric cells in such a way that any deflection of the spot due to change in temperature results in the illumination of one photocell being increased and that on the other reduced, the optical arrangement being similar to that shown in Fig. 4.16, the pair of prisms being employed to secure suitable disposition of the photocells. The amplified output of the photocells is fed to control a reversible motor through a pair of grid-controlled gasfilled valves.

In the correctly adjusted condition both cells are equally illuminated and the circuit is adjusted so that neither valve passes current. Displacement of the galvanometer spot results in one photocell being more highly illuminated and the corresponding valve fires to rotate the motor in one direction. Increased illumination on the other photocell fires the other valve and rotates the motor in the reverse direction. The motor moves through gearing a rheostat which increases or decreases the heater current, the direction of movement being such as to correct the temperature change. Several methods of securing the motor reversal are possible. One employs a motor with two separate fields, one for forward and one for reverse rotation, according to which field is excited. The disadvantage of space limitation to accommodate two separate windings on a small motor is avoided by the arrangement shown in Fig. 4.17.

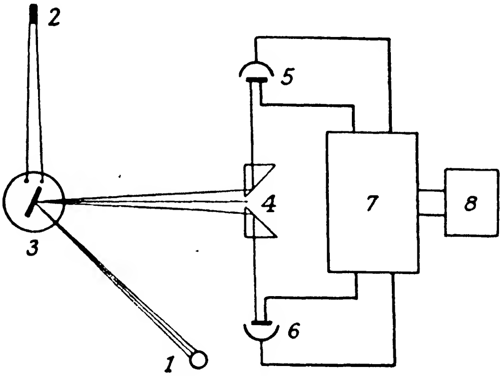


Fig. 4.16.—Schematic arrangement for temperature control using two photocells. 1. Light source. 2. Thermocouple. 3. Galvanometer. 4. Optical deflection system. 5 and 6. Photocells. 7. Amplifier. 8. Reversible motor controlling heater rheostat.

Increase in light on photocell 1 fires valve 5 and causes current to pass through the motor field in the direction shown by the full arrows. This current increases with increasing illumination. Similarly increase of light on photocell 2 fires valve 6 and current passes through the motor field in the reverse direction, as shown by the dotted arrows. Saturable reactors 3B and 4B in the grid circuits of the valves provide the phase changes in the grid voltage required to fire the valves. 3 and 4 are the D.C. saturating windings of the corresponding reactors 3B and 4B. The motor rotation corrects the temperature change by rheostatic control.

Printing and Wrapping Machinery

In order to secure a sufficiently high rate of production to reduce manufacturing costs, printed matter such as paper wrappers, small

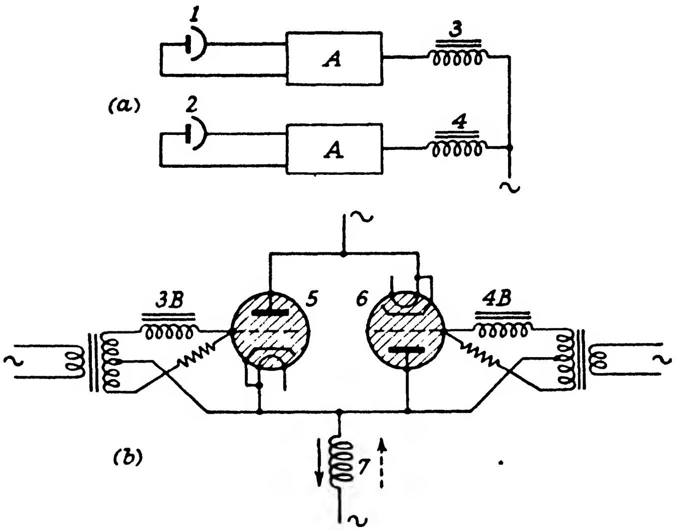


Fig. 4.17.—Temperature control by automatic rheostatic adjustment of heater circuit.

posters, bags, etc., are not printed on separate sheets, but are impressed on the paper when in a roll, the whole of which is printed before the cutting into individual sheets is carried out.

The subsequent operations may in some cases involve cutting, which also has to be carried out at a high speed to cheapen production, or in the case of a coloured design, where the printing takes place in two or more operations, a second printing in a separate colour takes place before the cutting. In the latter case the second impression must register accurately with the first in order to produce a correct visual impression, otherwise the whole effect of colour is lost, and in cases of appreciable displacement of the successive images the effect may be even ludicrous.

In the first case, where cutting of the paper only is involved, it is fed into the machine, which carries some form of cutting knife or guillotine which must come into action at the proper moment so that the design lies centrally on the cut sheet. For instance, in the making of paper bags, the paper must be cut so that when subsequently folded the printed matter is correctly aligned on the side of the bag. It is not possible to secure accurate cutting of the paper in this way merely by starting off in the right position and relying on the cyclic action of the machine to cut all the subsequent sheets in the right place, because slight discrepancies in the gearing of the machine, shrinkage or stretching of the paper result in the paper creeping in one direction or the other, so that the design soon gets out of correct register with the cutter. If an error of only 0·01 inch is present and is progressive in one direction, the paper will, after 100 operations, be 1 inch out of centre, whereas the permissible tolerance may be of the order of ⅛ inch. When the speed of the machine is high it is obviously impracticable to apply any manual method of adjusting for paper creepage, and even at slow speeds this method of correction would be a tiresome business. Consequently, some form of automatic correction needs to be included, and this is conveniently achieved by means of a photoelectric circuit which controls a pair of gasfilled triodes.

A small opaque spot, usually about ½ inch by ⅛ inch, is printed near the edge of the paper and in a fixed position relative to the printed design. In conjunction with a photocell amplifier and one or a pair of gasfilled triodes, this spot serves to control the timing of the cutting operation.

An optical system directs light from a lamp on to the paper in the line of register marks, and this bright light spot is picked up by a photocell with the aid of a second optical system.

As soon as the opaque register mark passes under the light spot, the reduction of illumination on the photocell conveys an impulse to the amplifier and its controlled circuit.

Methods of Application.—There are two obvious ways by which the cutting mechanism can be controlled:

(1) The action of the cutter can be made completely independent of the rest of the machine and operated solely by the approach of the register mark.

(2) The cutter can be operated through gearing from the machine and the relative position and speed of the paper varied by the control gear, so that the cut occurs at the right place, one of several methods of correction being employed to secure this condition.

The latter method of control is applicable to cases where a second impression is made on the paper before cutting takes place.

In the first instance, the circuit of Fig. 4.4, page 97, may be employed and is applicable to small machines cutting narrow paper strips and where the cutter is actuated by an electromagnetic movement with a stroke, say, of ¼ to ⅜ inch. For reliable performance in such a case, the action of the blade must be due to the inertia of the system rather than to the actual pull of the electromagnet, a condition which is secured by passing through the winding a high-peak current of short duration. Another requirement is that the magnet shall be released immediately after the incision in order that the paper feed shall not be impeded.

Both these conditions are met by the type of circuit in which a charged condenser is discharged through the magnet coil by the gasfilled triode on the arrival of the triggering impulse due to the light change on the photocell.

If the circuit is to be operated by the interruption of reflected light—*i.e.*, by a dark spot on a light background—either the circuit of Fig. 4.5 or that of Fig. 4.4 with the positions of photocell P and resistance R2 reversed must be used. These circuit conditions will be reversed if a light spot on a dark background is used.

Register Control.—Two methods by which the principle of correction under heading (2) above can be applied will be referred to. In this case the cutter or the control for the second imprint in the case of multiple printing is kept in correct register with the paper by impulses applied selectively to one of a pair of gasfilled triodes.

The function of one such circuit will be clear from Fig. 4.18. K is a contact which rotates in synchronism with the cutter mechanism and serves to short circuit the grid and cathode terminals of valve V_2 when it closes, thus removing the negative bias applied to its grid. S is the register mark on the paper.[4.21]

The two gasfilled triodes feed respectively the forward field F_1 and the reverse field F_2 of a motor which actuates a differential gearing according to the direction of rotation.

The commutating condenser C connected between the valve anodes results in a circuit of the type described on page 58. One triode is always passing current. The arrival of a triggering impulse at the grid of the quiescent valve starts its discharge and cuts off the discharge from the first valve. The anode current is thus transferred from one anode to the other.

If now the paper is running too fast for correct register, the spot S will cut off the light from the photocell before contact K closes, so that valve V_1 will fire if it is not already passing current. At any rate, current will first pass in valve V_1. Immediately afterwards contact K closes and transfers the discharge to valve V_2, which thus remains conducting for the greater part of the cycle—*i.e.*, until the arrival of the next pair of impulses. The field winding F_2 will thus be excited for most of the time during which the error of register persists.

On the other hand, if the paper is slow, contact K will close first and fire valve V_2 if it is not already conducting. Immediately afterwards S will cut off the light and transfer the discharge from V_2 to V_1 until the arrival of the next pair of impulses, so that the field F_1 will be excited for the greater part of the time.

The forward field F_2 or the reverse field F_1 of the motor is thus excited according as the paper is running too fast or too slow relative to the cutting mechanism and the direction of rotation of the motor determined accordingly. The motor accelerates or retards the paper speed relative to the cutter in the direction which tends to cancel the error in register, so that the circuit is automatically self-correcting.

Certain modifications to these general principles are applied in practice to prevent overrunning of the control, and for this purpose an additional contact is included on the switch K. As the time during which the motor runs in one direction is longer the slower the speed, the control is closer at slow speeds. This restriction can be overcome by using a motor driven by a generator attached to the main press, so that at lower speeds a lower voltage is impressed on the motor, giving a reduced rate of correction.

Another method which dispenses with the use of a motor is to employ a differential gearing (inset Fig. 4.18, *a*). In this case two bevel wheels, B_1 and B_2, run loose on the shaft H, but can be locked to this shaft by the excitation of either of the electromagnetic clutches D_1 and D_2, these taking the place of the field windings F_1 and F_2 in the valve anode circuits of Fig. 4.18.

The direction of rotation of the shaft J, which is controlled by the differential gear, determines the direction of speed correction. Excitation of the clutch D_1 locks B_1 to the shaft H and causes J to rotate in one direction. Excitation of clutch D_2 similarly locks B_2 to the shaft J, which then rotates in the reverse direction.

Fig. 4.19 shows diagrammatically another method, also using a rotary type of switch to distinguish advanced or retarded paper at the instant of cutting or printing. This shows control by transmitted light, the conditions illustrated indicating correct register and the amplifier circuit connected to brush C_1 on the rotary switch making no connection to either valve V_2 or V_3 when the light is cut off.

If the paper is running too fast, the brush C_1 will have already made contact with segment C_3 of the rotary switch at the instant the light is cut off from the photocell by the register mark. The signal impulse will thus fire valve V_3 and energise its control circuit to retard the paper. On the other hand, if the paper is running too slow, the brush C_1 will still be in contact with segment C_2 at the instant the light is obstructed. In this case valve V_2 will fire and energise the control circuit to accelerate the paper.

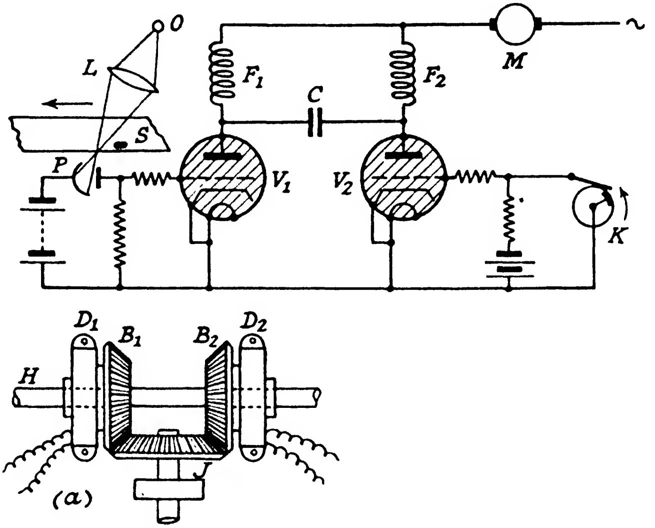


Fig. 4.18.—One method of photoelectric register control.

One of several alternative methods may be employed for securing mechanically the speed change in the paper feed from the selective operation of the gasfilled triodes.

Practical experience has shown that at high speeds it is essential not only to give a space correction to adjust the register, but also a permanent small change in speed. A space change alone may not be sufficient to correct the displacement, since both the amount of correction and the number of times per minute at which it can be applied is limited, and the accumulation of error may therefore exceed the correction which can be applied. Likewise a speed change alone will tend to over-correct and necessitate a correction in the reverse direction, so that the machine will tend to hunt.

In the case of slow paper feeds as applied to wrapping and packing machinery, where the feed does not exceed 50 feet per minute the paper is arranged to be normally slightly too fast or slightly too slow and a one-way correction brought into operation periodically to adjust the error. A single-circuit rotary switch only is then required with a single gasfilled triode. In this case the correction is applied always after approximately the same number of operations.

Another form of register control[4.22] utilises a series of register

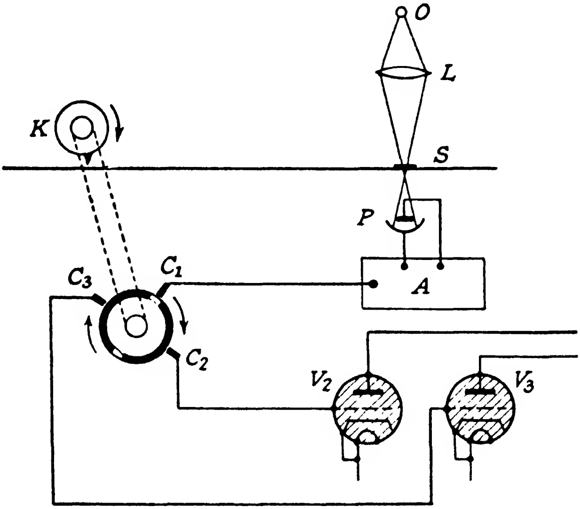


Fig. 4.19.—Diagrammatic arrangement of another control circuit for paper registration. (B.T.H. Co.)

marks 0·01 inch wide and about 0·5 inch long on the side of the paper. The paper is in contact with the printing cylinder, and these marks produce a series of short impulses in the photocell scanning head. Attached to the rotating cylinder is a scanning disc, scanning head and photocell providing a second set of impulses. The two sets of impulses are compared. With correct register the scanning disc cuts off sufficient light at the instant the web scanning circuit is operative to give no motion to a differential reversing motor. If the printing cylinder is retarded, the light is cut off and the differential motor rotates so as to increase the speed of the feed.

High-Speed Counters

The speed of operation of an electrically actuated counter or impulse indicator is invariably limited by the mechanical inertia of the moving parts of the counter itself. Where an industrial process involves counting up to speeds, say, of the order of 250 per minute and the articles concerned are unsuitable in size, weight, or shape to give positive operation to a simple contact, the addition of an electronic circuit, usually photoelectric, offers the only feasible solution. For cases up to the speeds mentioned the requirements can generally be met adequately by a hard valve relay circuit of conventional design with a relay of the telephone or similar type which in turn controls the exciting coils of the counter. This, of course, entails the successive excitation of two magnet coils, that of the relay and finally the counter-coil. The time cycle involved here may be reduced by the substitution of a gasfilled triode, the anode current of which will be large enough to operate the counter-coil direct. Since, however, the increase in operating speed of the counter itself will be secured only by reduction of its inertia and amplitude of movement of its component parts, the mechanism will need to be made very light and the power required to operate it will thus be relatively low, so that the output power current of a small valve of the hard vacuum type will be adequate to meet those cases where the indication of individual impulses on the indicator is possible.

At much higher speeds, where the impulse time and spacing are of the order of a few milliseconds or less, the use of a counter for separate impulse indication becomes impracticable. Such cases may be dealt with by circuits involving gasfilled valves to which multiple counts are recorded on the indicator and the remainder deduced from the condition in which the circuit is left at the conclusion of the counting period.

There are two well-known types of circuit in which multiples in a train of high-speed impulses can be recorded in this way, and a number of modifications to them have been made by individual investigators to meet special requirements. Of these the first, due to Wynn Williams, is shown in Fig. 4.20, and has been employed for the counting of α particles up to speeds of 1,000 per second. The gasfilled triodes are arranged in a ring circuit, each grid being biased by a battery and a portion of the voltage across the cathode resistor of the preceding triode in series. Each triode includes a relay in its anode circuit in series with a normally closed contact operated by the relay in the anode circuit of the following triode. The grid bias of each valve is normally high enough to prevent the signal impulses from starting the discharge. If, however, there is already current passing in one of the valves, the potential drop across the corresponding cathode resistor will reduce the grid bias on the next following valve to a point where it will fire on the arrival of the next impulse.

Thus, in Fig. 4.20, assuming that current is passing in V_1, the grid bias on V_2 is reduced by the change in voltage across R_1. When V_2 fires by the arrival of the next impulse the excitation of relay A/1 opens contact a_1 so that V_1 is reset. At the same time the establishment of current through R_2 reduces the grid bias on V_3 and prepares it to fire by the next impulse and so on. Each signal impulse, therefore, fires one valve, resets the preceding one, and prepares the following one, and this process carries on round the circle of valves, moving one step forward at each signal impulse. A relay in the anode circuit of one of the valves (E/$_2$ in Fig. 4.20) carries an additional contact which closes the counter circuit, which is thus operated each time the ring of triodes completes a cycle of firing.

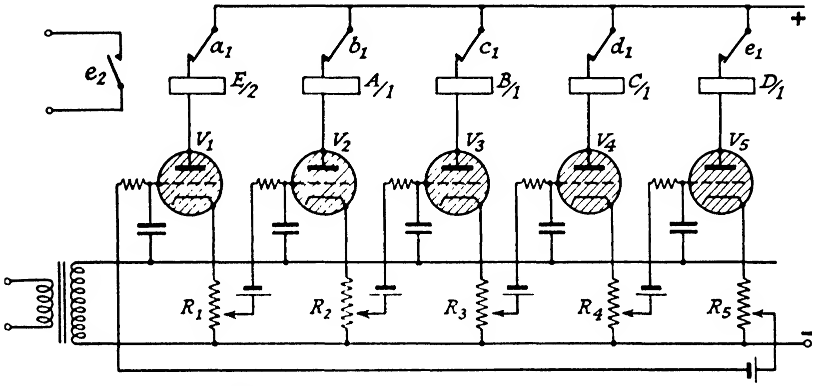


Fig. 4.20.—Wynn Williams gasfilled triode counting circuit.

The essential condition in this circuit is thus that current is always passing in one triode, but is cut off from all the others. If there are *n* triodes, the counter indicates each *n*th impulse. As each relay has nearly the whole time of the cycle in which to operate, any rate of signal arrival can be dealt with by increasing the number of gasfilled triodes.

Alternative Circuits

The chief disadvantage of this circuit is the large number of triodes required for high speed, and the practical difficulty of adjusting it to operate positively has favoured the development of alternative circuits, which incorporate some modification of the scale of two types of counter.

This method of impulse resolution employs the principle incorporated in the circuit of Fig. 4.21. It has already been mentioned on p. 57 that a gasfilled triode with a D.C. anode supply can be reset by switching to cathode potential one plate of a condenser connected across the anode load. In Fig 4.21 valve V_2 takes the place of the switch 4 in Fig. 3.2 (*b*). This circuit has two stable states corresponding to the conditions which exist when one valve is passing current and one cut off. The condition where both valves are cut off simultaneously is unstable and cannot be maintained. Consequently, when this circuit is switched on, ignoring the connections shown dotted, one valve will fire immediately, say V_1, and as a result condenser C will be charged to the potential across R_1 and to the polarity shown. The arrival of a positive signal impulse in the common grid circuit will therefore fire V_2, so that the right-hand side of condenser C will be connected to the cathode of V_2, the anode potential on V_1 will be reversed, and its discharge interrupted. Similarly, the next succeeding signal impulse will fire V_1 and reset V_2, and so on. Alternate signals therefore produce an amplified output impulse on the anode of the same valve. A circuit of this kind is called a scale of two counter by

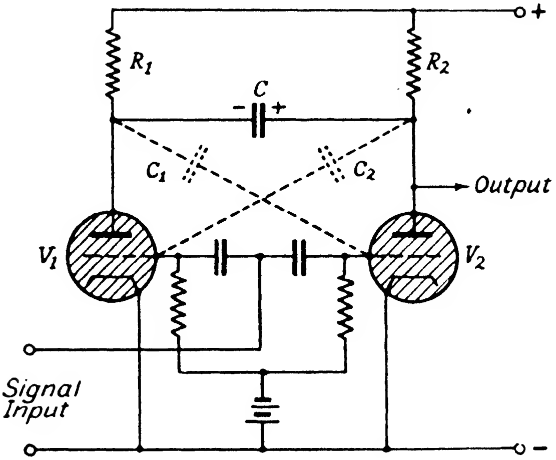


Fig. 4.21.—Simplest form of scale of two counter.

reason of the fact that the output circuit furnishes amplified signals of half the input frequency.

A second and similar pair of valves receives a signal at every second impulse, and one of the valves of the second pair fires at each alternate impulse—*i.e.*, at every fourth impulse from the signal source.

Similarly, further pairs of valves may be added so that the signal frequency in passing any such pair is half that of the frequency of the preceding pair. A counter included in the third pair is therefore operated by every eighth impulse.

This type of circuit is easier to set up than the previous one and permits of mains operation.

Fig. 4.22 indicates a circuit incorporating three such pairs of valves indicating signal impulses in multiples of eight. Assuming V_1 is first conducting, the first impulse fires V_2 and resets V_1. At the same time an impulse is passed on to the second pair of valves, V_3 and V_4, but this is a negative impulse, so that no effect is produced.

At the next impulse, however, which fires V_1 and resets V_2 the rise in voltage at the anode of V_2 resulting from its extinction is communicated as a positive impulse to the common grid circuit of V_3 and V_4. In consequence the discharge which is already passing in either V_3 or V_4—it cannot at this stage be determined which one—is transferred from this valve to the other one in the same way as in the case of V_1 and V_2. In a similar way a positive triggering impulse is transmitted to V_5 and V_6 by the firing of V_3 but not V_4.

If the circuit is to start from zero, then it is clear that all the left-hand valves of each pair—*i.e.* V_1, V_3, V_5, etc.—must be initially in the conducting state, and this condition is secured by the use of a multiple contact switch which connects the grid of each of these valves to its cathode in this order.

The scale of two counter is both simple and reliable in performance providing it is not operated too near to its limiting speed or by signal impulses of irregular wave form. When the repetition of signal impulses becomes very high, the anode voltage of the valve which has just been extinguished may not have sufficient time to rise to an appreciable fraction of its full value before another impulse arrives and causes it to fire again. Since the rise in anode voltage constitutes the signal passed on to the next pair of valves, this impulse may be too low, with the result that the circuit appears to have missed a count. The grid bias needs to be correctly set for satisfactory opera-

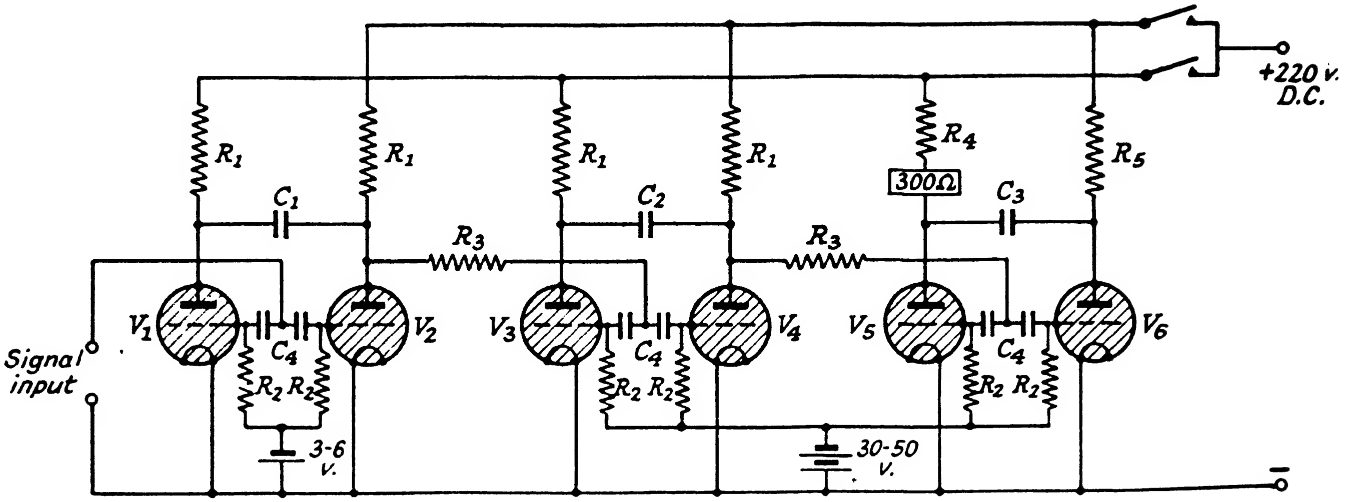


Fig. 4.22.—Multiple scale of two counter for high-speed recording. R_1 = 10,000 ohms. R_2 = 100,000 ohms. R_3 = 20,000 ohms. R_4 = 1,000 ohms. R_5 = 1,300 ohms. C_1 = 0·1 μf. C_2 = 0·25 μf. C_3 = 2 μf. C_4 = 0·01 μf.

tion. If it is too high, the stage will not function; if it is too low, it may fire at double its correct frequency—*i.e.*, at the frequency of the preceding stage. This condition can always be detected by stroboscopic examination of the discharge or even by moving a straight object such as a pencil rapidly in front of it. When firing correctly, the images in each stage should be spaced twice as wide apart as in the preceding stage. The grid bias may need adjustment if the rate of counting is changed over a wide range. Another effect which may also appear is due to the low resulting charge on the commutating condenser due also to the small rise in anode voltage, and this may be insufficient to extinguish the other triode, so that both valves will pass current simultaneously and the circuit will be made completely inoperative.

Of these effects, the first may be eliminated by providing a stage of valve amplification between each pair of triodes[4.23] so that the impulse passed on by one pair is amplified so as to be greatly in excess of that required to secure certain operation of the next pair. To prevent feed-back of signal impulses, this amplification stage is necessary in correcting the second effect which has been secured by the cross-connection of the condensers shown dotted in Fig. 4.21. The reduction of anode potential when one valve fires is then communicated to the grid of the other valve, which is held highly negative and prevented from firing until the condenser charge has leaked away. The existence of this high negative grid voltage also tends to promote collection of positive ions and reduces the deionisation time. Moreover, the addition of these condensers enables the capacity of the condenser C to be reduced so that it is possible for the anode voltage to rise more rapidly and the possible rate of counting is further increased for this reason also.

The scale of two counter, though the simplest form of high-speed recording device, has one obvious drawback. The sum total of the impulses counted is not immediately apparent from the indications of the circuit. The operation of each stage corresponds to a power of two or indicates a count of 1,2,4,8,16,32, and so on according to the number of stages operated.

For instance, in a six stage scale of two counter, if the second, fourth and sixth stages are in the operated condition, the total record is $2+2^3+2^5=42$.

There is no simple method of transforming this record automatically into the denary scale of everyday life and the conversion has to be made in each instance by calculation or by reference to a set of tables.

Though this is a simple process, it is a nuisance, and it is very easy for errors to be made in the conversion.

One method of overcoming the difficulty is to make each stage a scale of two counter operating in conjunction with a scale of five counter of the ring connection type previously described. Alternate impulses in the scale of two counter then step the discharge one valve forward in the scale of five counter so that the complete circuit is traversed after ten impulses.

At the arrival of the tenth impulse, the output valve passes on an impulse to a similar following network whose function it is to record the tens.

Similar following networks record the hundreds, thousands and so on. Each of the scaling counters is usually provided with driver valve, which ensures that the incoming impulses are correctly shaped to secure positive operation.

Circuits operating on similar lines are in use employing hard valves, which, of course, have to be used for very high rates of counting where the impulse spacing may approach the deionisation time of the gasfilled valve.

Though the networks using hard valves function substantially in the same way as the circuit already described, the circuitry is rather different.[4.33]

With scale of two counters, it has been general practice to couple a neon indicator lamp to the anode circuit of one valve in each stage so as to indicate whether or not that stage is in the operated condition.

A much better arrangement is that in which a shunted milliammeter is included in the common anode feed to all the valves. Connection to the anodes of the respective valves is made at different points of the shunt. Thus, while the total anode current remains always the same, the proportion of it which passes through the meter increases in uniform steps as the anode current is transferred from one valve to the next.

The meter needle thus moves in a series of steps, which can be numbered 1-10.[4.33]

Using hard valves, phenomenal speeds of counting have been attained up to 100,000 per second.

Apparatus working at such high speeds is useful in connection with Geiger tube circuits for recording radioactivity or for measuring short time intervals.

Such a counter will record the individual oscillations of a stabilised oscillator. As the period of the oscillator is known, a short time interval can be accurately recorded by counting the number of oscillations from the instant of closing and opening circuit to the recorder.

Multiplier Circuit[4.24]

A circuit which incorporates the elements of a single tube inverter circuit enables higher ratios of multiplication to be secured than is possible from a scale of two counters with an equivalent number of valves, and is shown in Fig. 4.23.

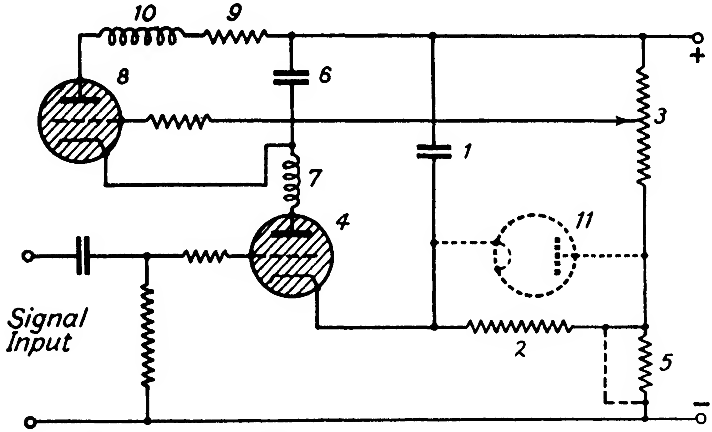


Fig. 4.23.—Multiplier circuit for high-speed counting.

When no signals are being received, the condenser 1 charges through resistance 2 to the potential across resistance 3, and the gasfilled triode 4 is cut off by the negative bias due to the voltage drop across resistance 5. Condenser 6 is several times larger than condenser 1, and may at first be assumed to have no charge. The arrival of a positive signal impulse will fire valve 4 and will discharge condenser 1 through inductance 7 until the voltage across condenser 1 is less than that across condenser 6. This condition is secured as a result of the inductance 7, which opposes and prolongs any current change through its coil. Condenser 1 is thereafter charged again through resistance 2 after the fall in anode voltage of valve 4 has allowed it to reset. The cycle then repeats until the charge received by condenser 1 causes the voltage across it to exceed the algebraic sum of the voltages across resistance 3 and the critical control grid voltage of valve 8. When this occurs, valve 8 fires and discharges condenser 6 through resistance 9 and inductance 10. Thus valve 8 will fire once for every specified number of times which valve 4 fires, the multiplying ratio being determined by the setting of the potentiometer 3. The inductance 10 can be replaced by a counter-coil for impulse recording.

This description assumes that condenser 1 charges to the full potential applied to it between each impulse, but since the charging is exponential this does not occur. The error is small if the time constant of condenser 1 and resistance 2 is small compared with the impulse spacing. At high speeds the multiplying ratio changes, since condenser 1 discharges into condenser 2 before the former is fully charged. This variation is corrected by the addition of the rectifier 11 shown with the connection altered to the dotted lines. Rectifier 11 then stops the charging of condenser 1 when the rectifier cathode becomes negative enough for it to conduct. By limiting the charging period of condenser 1 only the linear portion of the charging curve is utilised, thus shortening the charging time without altering the time constant of the charging circuit, so that the multiplying ratio is constant from a low value up to an impulse spacing time which is comparable with time constant of the charging circuit. The lower practical limit is set by leakage on condenser 6 and its associated wiring. Satisfactory operation with a multiplying ratio of 10 is claimed by the inventors over the range 5 to 3,600 per minute.

Cascade Connection

A method by the same authors of securing higher ratios by two cascade circuits is shown in Fig. 4.24. The transformer coupling 1 ensures that valve 2 fires every time valve 3 is triggered off. The second multiplier circuit which is shown on the left-hand side of Fig. 4.24 operates in the same way as the circuit of Fig. 4.23. The overall ratio for this circuit between the impulse applied to the grid of valve 4 and the output of valve 5 is the product of the ratios of these two circuits. Recording speeds up to 7,200 per minute have been secured with this circuit. The glow of the rectifier 6 provides an indication of the limiting speed of accurate recording, since this will be uniform and flash at the impulse speed during satisfactory operation of the circuit. If the speed is too high, the glow will be extinguished for periods exceeding that between impulses.

The signal impulse must, of course, hold the grid voltage of the first valve below the critical value for a time greater than the ionisation time.

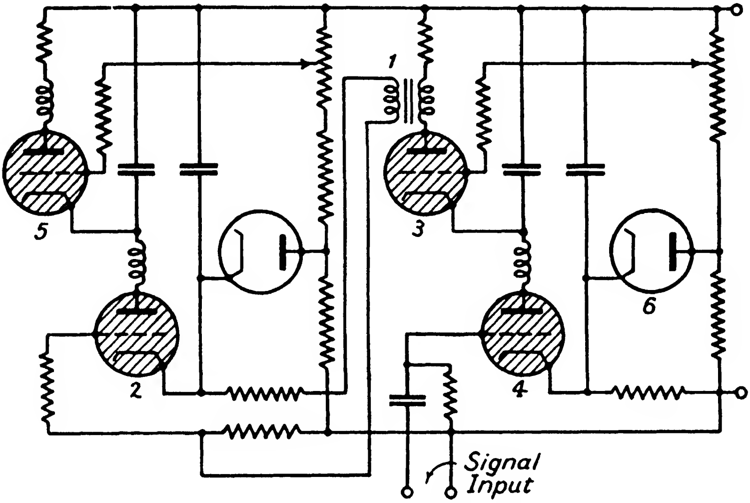


Fig. 4.24.—Two cascaded circuits for securing higher ratios.

The authors also describe a regenerative photocell valve circuit which includes hard valves for securing a steep wave front at the signal amplifier input in the circuits just described and suitable for counting at high speed.

Other Modifications

The output circuit of any network including scale of two counters may be connected to a telephone line selector switch (25 points) which moves one step forward each time the valve to which it is coupled is extinguished. With a five-stage counter each step on the switch corresponds to 32 cycles at the input. The points on the switch may be connected to neon lamps behind a panel numbered 0, 32, 64 . . . up to 768, while the second valve in each pair is connected to lamps numbered respectively 1, 2, 4, 8, 16, so that any number of cycles up to 799 can be counted by adding up the numbers shown on the panel. Multiples of 800 can be recorded on a counter connected to the last point of the selector switch. Alternatively, the counter can be arranged to record hundreds, in which case the hundreds digits are omitted from the numbers on the panel.

When starting a count, the switch which ensures that all the left-hand valves start off in the conducting state must also return the selector to its zero position and a separate contact bank on it must be available for this "homing" operation.

By the use of such a switch it is possible without employing an unduly large number of valves to secure a possible rate of impulse recording considerably in excess of the 50-cycle frequency of the ordinary A.C. mains supply, which can then be employed as an alternative signal source for the purpose of checking the performance of the circuit.

Frequency Measurement

Such a circuit also provides a means of measuring frequencies within certain limits. Several alternative methods of applying the circuit for this purpose are available. The signal source can be switched on and off by hand and the interval timed with a stop-watch. A better method is to employ a switch which has a fixed and definite interval of closure. A simple mechanical device which can be attached to a compound pendulum adjusted accurately to beat seconds enables the circuit to be closed on the forward swing and opened on the reverse swing, so that the signal is applied for exactly one second.

Alternatively the input circuit can be kept closed and the revolutions of the selector switch timed with a stop-watch. In either of the former methods there is always a possible starting error of ±1 cycle in each count and with hand operation a further error due to the observer is possible. The last method of timing, particularly if a long train of signals is available, can be made very accurately with a stop-watch graduated to $\frac{1}{10}$ second. By taking a count over a period of 2 minutes or so an accuracy of ±0·2 per cent. is possible.

A number of modifications in the foregoing principles have also been incorporated into circuits designed to meet special requirements. In one,[4.25] for instance, a double triode valve is incorporated and a current indicating meter and commutating condenser coupled to the cathode circuits, giving a direct-scale reading of frequency which is claimed to be linear up to 7,000 cycles per second.

In another,[4.26] the gasfilled triodes are employed to produce a uniform signal of high voltage to the second pair, the large input enabling the plate voltage to change appreciably without rendering the circuit inoperative. A condenser and resistance are connected in parallel with a larger condenser in such a way that each impulse partly discharges the small condenser which resets the valve, the potential being restored from the charge on the large condenser. Although the gasfilled triode has been extensively used in scaling circuits for high-speed counters, possibly an even larger number of circuits have been evolved incorporating hard valves employing modifications of the multivibrator or flip-flop type of circuit. These are, of course, excluded from treatment here, but some references are appended for those who wish to pursue the study of the subject further.[4.27]

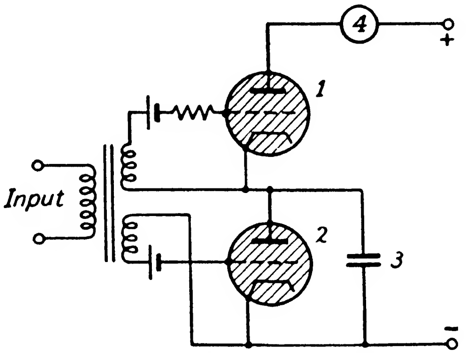


Fig. 4.25.—Frequency measurement.

A method[4.28] which has also been employed for frequency measurement is the cascade connection of two triodes, as shown in Fig. 4.25. This is almost the same in principle as the series inverter circuit dealt with in more detail in Chapter 7. The two gasfilled triodes 1 and 2 (Fig. 4.25) are biased at their grids so that neither normally conducts. Condenser 3 is first charged to the supply voltage by the firing of triode 1 when the positive half of the input signal makes its grid positive and discharged through valve 2 at the end of the signal impulse. The mean current in the circuit is indicated by the moving-coil instrument 4, the current reading of which is cvf, where c is the capacity of condenser 3, v the supply voltage and f the frequency. The reading of this instrument is practically independent of the harmonic content of the wave form providing sufficient input voltage is available, since the circuit operation depends only on reversal of polarity of the wave and is independent of its amplitude. Circuits involving these principles have some advantage over bridge methods in which it is difficult to secure a balance if the signal is not free from harmonics, and over tuned circuits and wave meters which are expensive for measuring lower frequency ranges 4.32.

A simple switching circuit in which successive signal impulses cause sequential operation in another circuit is exemplified by the circuit of Fig. 4.26, which has been used for controlling an electronic chronograph employed for measuring the flight velocity of projectiles.[4.29] A magnetised projectile is fired and passes in turn through two solenoids. A voltage pulse is generalised in the two coils in turn. These pulses are fed to a differentiating circuit to produce peaked impulses and are then applied to the two gasfilled tetrodes shown in Fig. 4.26. The first pulse trips valve T1 and causes a controlled oscillator to start feeding a counter-circuit. The second pulse fires valve T2 and switches the oscillator off. A crystal-controlled oscillator giving 100 kc. is employed, and its standardised frequency enables the time to be evaluated.

The counter-chronograph is described elsewhere.[4.30] In Fig. 4.26 the voltages at various points of the circuit are indicated in round brackets before valve T1 fires, in squares after T1 fires, and in square brackets after T2 has fired.

At first T1 is biased to -19 volts on its grid and T2 to -82 volts. The first impulse of $+30$ volts fires T1 but not T2. After T1 fires its cathode voltage rises to $+73$ volts, and after a time delay imposed by R3 and C3 biases the grid of T2 to -32 volts, so that the second impulse of $+30$ volts fires T2. The action can be followed by noting the voltage changes at the various points of the circuit. The valves are tetrodes and the circuit is reset by opening the anode connection of T1. The neon lamp N indicates the condition of the circuit and glows when the valves are reset.

The conditions secured are such that the grid voltage of valve T3 permits this valve to amplify only after T1 fires, but before T2 fires. The time constant of R3, C3 should be not greater than one-tenth of the measured time interval, so that T2 may be prepared in time for the cut-off impulse. In the original article a further circuit modification is given in which the output voltage is applied to the suppressor grid of a pentode valve.

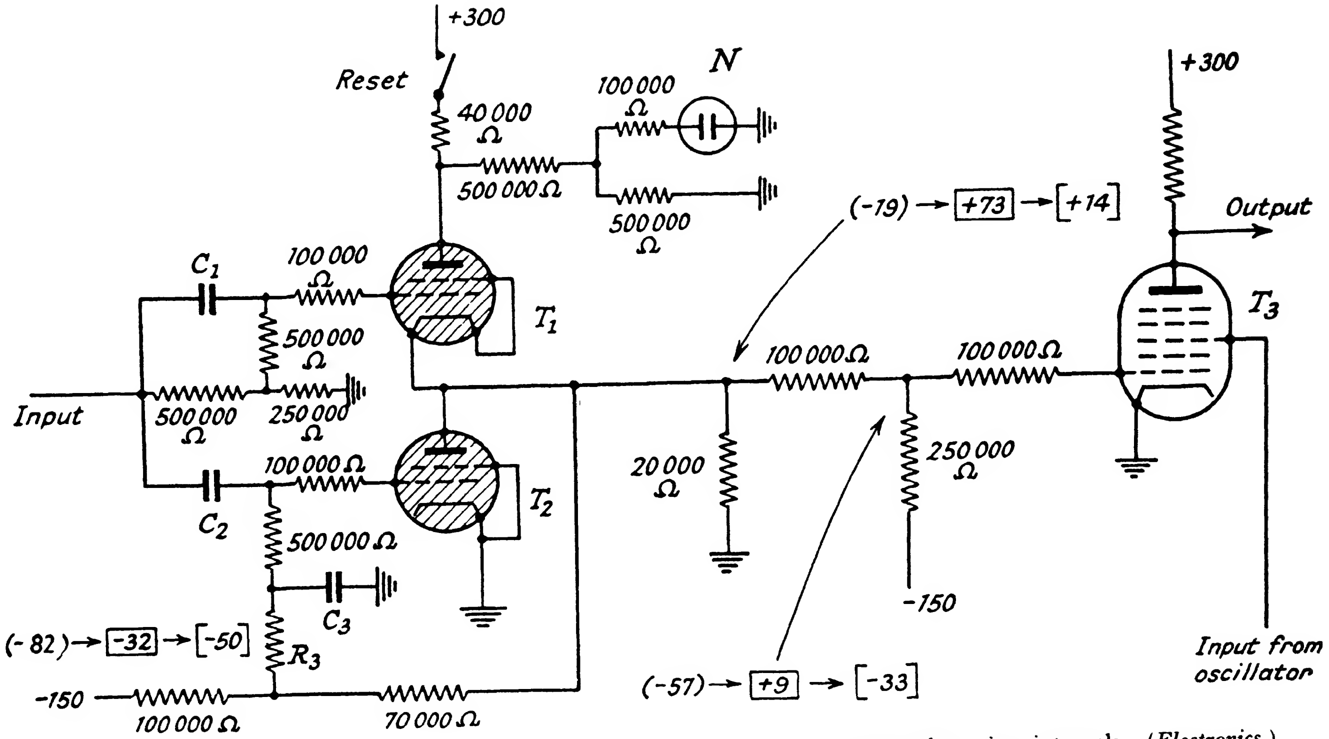


Fig. 4.26.—“ Gate ” circuit for operating an oscillator chronoscope for measuring short time intervals. (*Electronics.*)

Measurement of Short Time Intervals

The circuit of Fig. 4.27 has been successfully employed[4.30] in ballistics for the measurement of velocity or time of flight of projectiles, and covers the range of 1-200 milliseconds with a measuring accuracy of about 1 per cent. The indicating instrument 1 is a ballistic galvanometer having a period of the order of 5 seconds and designed to facilitate reading of its maximum swing. The ballistic galvanometer is an instrument in which the maximum swing is proportional to the quantity of electricity which passes through it, an essential condition being that the time during which the current passes shall be small compared with the period of swing of the galvanometer. If, therefore, a current of constant magnitude passes through the instrument for a short period, the maximum deflection will be a measure of the time during which the current flows.

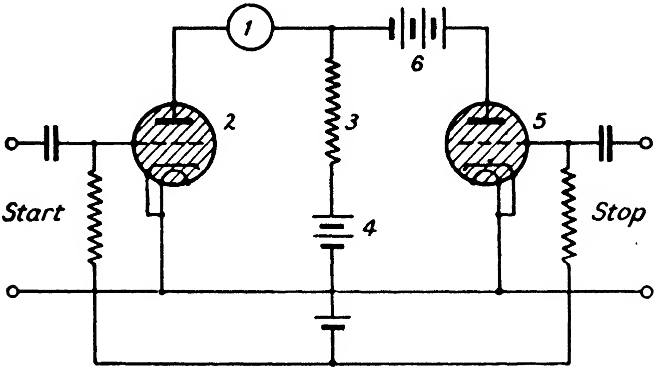


Fig. 4.27.—Circuit for measuring time intervals between signal impulses of the order of 1-200 milliseconds.

The gasfilled triode 2 is fired by a starting impulse at the start terminals and allows a constant current determined by resistance 3 and battery 4 to pass through the galvanometer 1. When the stop impulse arrives at the grid terminals of the other triode 5 this valve fires and switches in the extra battery 6, so that a larger voltage drop occurs across resistance 3. The anode voltage of triode 2 is then reduced below the ionising voltage and the discharge suppressed. The discharge in triode 5 continues until it is switched off.

This circuit is preferable to the plate-to-plate capacity coupling arrangement between two gasfilled triodes, because the current flowing through the galvanometer during the time measurement can be read in the steady state without regard to the transient current and also because the circuit locks out after the galvanometer current has been cut off, so that subsequent impulses on triode 2 cannot re-ignite it until triode 5 has been switched off. The possibility of triode 2 re-igniting due to contact bounce when switch operation is used or from transients due to any other cause is obviated.

Provision is also made to protect the galvanometer against the heavy current which would flow through it if the second or stopping impulse failed to arrive. The original circuit, among other refinements, included means for checking the ballistic constant of the galvanometer with a charged condenser and a known current from the battery 4 and resistance 3.

Another circuit[4.31] having a wider range of application—viz., 0·5 second to 0·5 millisecond—but of lower accuracy, utilises one triode for starting the charge of a condenser on the arrival of the start impulse, while the stop impulse fires a second triode and stops the charging current before the condenser is fully charged.

A voltmeter is used to measure the acquired condenser potential, which is a function of the time interval between the two signal impulses.

CHAPTER REFERENCES

4.1. Walker, Photoelectric cells in industry (Pitman, 1947).

4.2. Smiley, Control circuits in industry, *Electronics*, Vol. 14 (January, 1941), p. 29.

4.3. Wideroe, Thyratrons in relay practice, *Electrical Engineering*, 53 (October, 1934), pp. 1347-55.

4.4. Reich, Thyratron relaxation oscillator, *Rev. Sci. Inst.*, 3 (October, 1932), pp. 580-5.

4.5. Puckle, Time Bases, *Journ. I.E.E.*, Vol. 89, Pt. III (1942), p. 100.

4.6. ——, The thyratron time-base circuit, *Electronic Engineering*, 14 (March, 1941), p. 664.

4.7. ——, *Time Bases* (Chapman and Hall), 1942.

4.8. Neustadt, Thyratron linear time axes for cathode ray oscillograph, *Electronics*, 4 (1932), pp. 198-9.

4.9. Builder and Roberts, *Amalgamated Wireless (Australasia) Technical Rev.*, Vol. 4 (1939), p. 165.

4.10. Brit. Pat. 400,976.

4.11. Kock, A Stabilised sweep oscillator, *Electronics* (April, 1939), p. 20.

4.12. Bedford and Puckle, A velocity modulated television system, *Journ. I.E.E.*, Vol. 75 (1934), p. 63.

4.13. Verman, A thyratron interrupter for induction coils, *Journ. Sci. Inst.*, Vol. 12 (May, 1935), pp. 167-9.

4.14. Builder, A stabilised frequency divider, *Proc. I.R.E.*, Vol. 29 (1941), p. 177.
4.15. Davidson, A double-wave device for use with a cathode ray oscillograph, *Journ. Sci. Inst.*, 11 (November, 1934), p. 359.
4.16. Hughes, A thyratron selector for a double-trace cathode ray oscillograph, *Rev. Sci. Inst.*, 7 (February, 1930), pp. 89-92.
4.17. Zabel and Hancox, The use of the thyratron for temperature control, *Rev. Sci. Inst.*, 5 (1934), p. 28.
4.18. Benedict, The use of an A.C. bridge and thyratron in laboratory temperature control, *Rev. Sci. Inst.*, 8 (1937), p. 252.
4.19. Sturtevant, A thyratron controlled thermostat, *Rev. Sci. Inst.*, 9 (1938), p. 276.
4.20. La Pierre, A precision photoelectric controller, *G.E. Rev.*, 35 (1932), p. 403.
4.21. Brit. Pat. 401,016.
4.22. Wright, The use of register marks and photoelectric control devices, *G.E. Rev.*, 44 (1941), p. 629.
4.23. Lewis, Improvements in the scale of two counter, *Proc. Camb. Phil. Soc.*, 30 (1934), p. 543.
4.24. Lord and Livingstone, An electronic multiplier for high speed recording, *Electronics*, Vol. 7, (January, 1934), p. 7.
4.25. Hunt, A direct-reading frequency meter suitable for high speed recording, *Rev. Sci. Inst.*, 6 (1935), p. 43.
4.26. Kerst, A high resolving power thyratron tenfold counter, *Rev. Sci. Inst.*, 9 (1938), p. 131.
4.27. Lipschutz, A complete G.M. counter system, *Rev. Sci. Inst.*, 10 (1939), p. 21. Johnson, Circuits for control of G.M. counters and for scaling and recording, *Rev. Sci. Inst.*, 9 (1938), p. 218.
4.28. Wheatcroft and Halley, A pentode operated frequency meter of the condenser charging type, *Journ. Sci. Inst.*, Vol. 14 (April, 1937), p. 136.
4.29. Towley, Gate circuit for chronograph, *Electronics*, Vol. 19, No. 5 (May, 1946), p. 144.
4.30. Bradford, The chronoscope, *Electronics*, 13 (November, 1940), p. 28.
4.31. Lord, Electronic timer for very short intervals, *Electronics* (October, 1932), p. 302.
4.32. Willey, A gas relay operated frequency meter, *Wireless Engineer*, 14 (August, 1937), p. 433.
4.33. Brit. Pat. No. 572884.

CHAPTER 5

Indicating, Controlling and Measuring Devices

A direct-current amplifier using gasfilled triodes. Timing circuits. Applications to electric welding. Automatic synchronisation. Servo mechanisms. Frequency stabilisation. Frequency comparison. Measurement of transient voltages. The hot cathode gasfilled valve as a stroboscope. Voltage displacement of neutral point in a three-phase network.

A METHOD, rather different from those already described, of using the gasfilled triode in a measuring circuit is shown in the circuit of Fig. 5.1.

Direct Current Amplifier 5.1

This provides a means of securing a stable mains-operated direct-current amplifier which can be employed for either voltage or current amplification with a power gain of about 10^{10}. This circuit has been employed by the inventors in optical pyrometry for high-speed temperature recording with accuracies of the order of a few parts in 10,000 and for the metering of heat transport in large hot-water plants, as well as many other problems, where potentials of a few microvolts or currents as low as 0·01 microamp are involved. In respect of several characteristics, notably stability, sensitivity and rapidity of response, this circuit is said to be superior to valve amplifiers for direct-current amplification. It incorporates both the principles of negative feedback and phase displacement of the control grid potential.

The input potential is applied to the galvanometer 1 in series with the resistance 2. Light from a lamp 3 is reflected by the galvanometer, and according to the degree of deflection more or less illuminates the photocell 4. The latter is placed across the grid cathode terminals of the gasfilled triode 6, in series with the fixed condenser 5 to form a phase splitting circuit and secures quantitive control of the mean anode current. The photocell, which is of the emissive type, is not simply a pure resistance, so that the grid control is not due wholly to phase displacement, but partly also to grid voltage

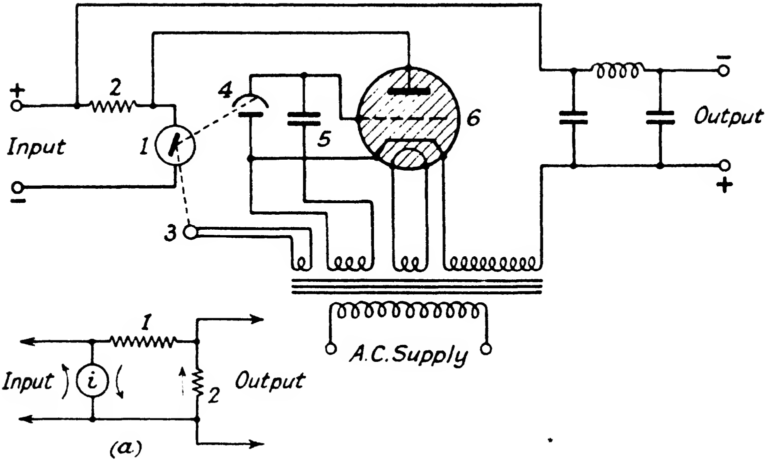


Fig. 5.1.—A direct current amplifier circuit.

distortion. If, for instance, the input current increases, the potential drop across 2 will rise, the galvanometer will deflect to increase the light in the photocell. The change in A.C. grid voltage will then increase the mean anode current by altering the point in each positive half-wave at which the valve fires, thus producing an increased voltage drop of opposite polarity across resistance 2. The circuit is thus restored to its original condition, but with an increased output corresponding to the increased input, smoothed to give a steady direct current instead of unidirectional pulses in the circuit on the right side of Fig. 5.1. The circuit is by this means self-compensating against internal changes or voltage supply fluctuations. The feedback resistance 2 determines the amplification ratio; and its inclusion in the circuit results in a response which is much more rapid than the free period of the galvanometer, and the deflection is only about $\frac{1}{100}$ of what the free deflection of the galvanometer would be for the applied voltage if there were no feedback to balance it. The circuit thus permits the use of a galvanometer which is heavily damped and too sluggish for use as a free galvanometer for direct reading.

As a current amplifier, the circuit can be modified as shown in the inset of Fig. 5.1 (*a*), the output current being proportional to the voltage drop across the low resistance 2 and permitting the amplification of currents of the order of 10^{-7} to 10^{-8} amps.

The overall sensitivity of this combination is of the order of

300 mA. per lumen or 1·4 A. per radian of galvanometer deflection with the lamp at reduced brightness. The value of the feedback resistance 2 determines the degree of amplification.

The original paper includes a discussion of the effects of phase displacement in the feedback and of transients in the anode supply voltage as well as a mathematical deduction of the main characteristics of the circuit.

Time Elements

Some of the circuits and applications of the gasfilled triode which might well be classified as simple switching arrangements involve the addition of some other function which is inseparable from the valve circuit as well, and therefore call for separate treatment.

Perhaps the most obvious of such cases are those in which a time element is involved in the switching operation—viz., the firing of the valve is delayed in order to secure postponement of the closure or opening of another circuit controlled by the valve.

The simplest instance is obtained when a condenser or inductance, or some combination of these, with a resistance is included in the grid circuit of the valve to introduce a time element in the steady state of the grid voltage.

With a condenser connected between grid and cathode and kept charged with the grid negative from a separate D.C. source the discharge in the valve is restrained. If the charging source is removed by opening a switch and the condenser allowed to discharge through a high resistance across its terminals, the negative grid voltage will decrease at a rate determined by the component values until a point is reached when the valve fires and excites the relay.

If the condenser capacitance is C and the leak resistance R, then the time required for the grid voltage of the triode to fall from the original voltage E2 of the charging source to E1, the critical grid voltage at which the valve fires, is $t=RC\log_e\frac{E1}{E2}$. This arrangement is, of course, applicable whether the anode voltage is steady or alternating.

Alternatively, if the anode voltage is alternating, the condenser may be initially uncharged with the triode grid substantially at cathode potential and the anode discharge established.

At the starting of the timing period the condenser is connected through a high resistance by the closure of a switch to a source of

D.C., which will tend to make the grid increasingly negative. The negative grid voltage then builds up until it exceeds the critical grid voltage corresponding to the peak anode voltage on the triode, when the valve will cease to fire during the next following positive half-cycle and the discharge will be cut off. In both these cases (Figs. 5.2, 5.3) the condenser voltage change takes place exponentially. Circuits using elaborations of either of these two arrangements form the basis of many electronic timers. The first type of circuit is more usual.

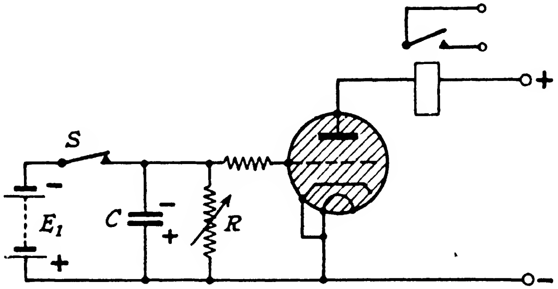


Fig. 5.2.—Delayed firing secured by means of a discharging condenser. Time period starts when switch S is opened.

These principles are equally applicable to the same form of circuit, using a hard vacuum valve in place of a gasfilled triode, the only difference, apart from the fact that the anode current change is of a lower order of magnitude, being that the point of switching is rather less precise, since in a hard valve the current rises or falls gradually as distinct from the trigger action in a gasfilled triode.

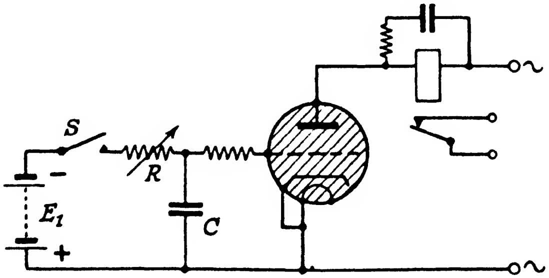


Fig. 5.3.—Timing period starts by closure of switch S and utilises the condenser charging period. The anode supply voltage is alternating and the discharge ceases after the time period.

However, there are some useful modifications of these circuits, which will be referred to later, and which are possible only with gasfilled triodes.

Extension of the Basic Circuits

In all such circuits the time interval, though adjustable over a certain range by changing any or all of the values of the condenser C, the resistance R and the charging supply voltage E_1, is fixed within certain tolerances for a fixed value of these components.

In practice the reliable timing range is from a few cycles up to 2 or 3 minutes. Longer periods become increasingly inconsistent owing to unavoidable leakage of the condenser charge. After the circuit has once operated, nothing further happens until it is reset by some other and independent switch control. When a number of sequential switching operations are involved, each with the same or different time element, there are several possible alternatives. The most obvious is to duplicate the basic circuit and use a number of them in cascade, so that first circuit on operating brings in the second, the second actuates the third, and so on.

With more than one or two separate time elements this arrangement becomes unduly cumbrous by the multiplicity of components required. A better arrangement would be to employ a dual or triple bank uniselector switch. This is an electrically operated switch largely used in telephone circuits, in which a bank of 25 fixed contacts are arranged on a semicircular framework and contact is made in turn with each by a movable arm rotating on a central pivot and moved round through a pawl and ratchet wheel and link mechanism operated by an electromagnet. Each time the electromagnet is excited the pawl engages the ratchet wheel, and when the electromagnet coil is broken the moving contact arm steps one contact forward by the action of a spring. Thus any one of 25 (50 with a double-contact arm) contacts controlling separate circuits can be selected by successive closures of the driving magnet.

If a sequence of time intervals of different periods are involved, the selector switch on each operation can be made to switch in the timing condenser for the next period. If a selector switch with three banks is used, one of these contact banks can be used to accommodate the timing condensers, another the independent contacts of any controlled circuit, and the third to secure automatic resetting by the return of the contact arm to its zero position after reaching a predetermined position. Before passing on to consider the possible modifications of the circuits of Figs. 5.2 and 5.3 it should be noted that a simple delayed time switching can be secured with an all A.C. circuit.

All A.C. Circuit[5.2]

With the switch 1 (Fig. 5.4) open, and the cathode heater in circuit on an A.C. supply, rectification takes place in the grid cathode circuit and the condenser 2 charges up to the polarity shown. When switch 1 is closed, the full line voltage is applied to the valve anode, but the accumulated condenser charge gives the grid a negative bias and restrains the valve from firing until the charge has partly leaked away through the high resistance leak 3.

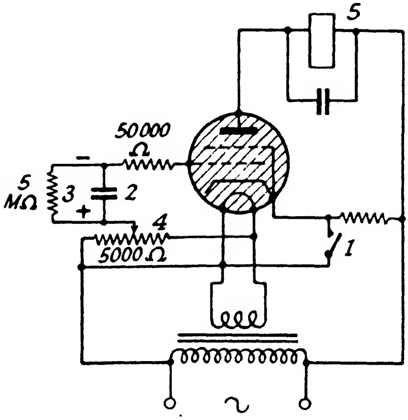


Fig. 5.4.—Delayed action switching device with adjustable time period including at 2050 shield grid thyratron.

The potential on the grid is actually one with two components: that due to the negative condenser charge and an A.C. component which is a fraction of the cathode heater voltage according to the position of the slider 4, the movement of which towards the heater terminal—*i.e.*, to the right in Fig. 5.4—increases the negative component of the A.C. voltage during that portion of the supply voltage cycle when the anode is positive, and in which it is possible for the valve to fire.

The value of the grid condenser 2 and resistance 3 are selected to give the maximum time delay required, and the potentiometer 4 then serves to provide adjustment for shorter periods as required. The size of the grid condenser and resistance are less if the transformer connection is made so that the valve anode is positive at the instant that the point of connection of the heater to the potentiometer 4 is negative.

On the expiration of the time period the valve fires and actuates the relay 5 (or other load), which remains excited until switch 1 is opened, when the condenser starts to charge again ready for the next timing period. By a suitable selection of component values the condenser charging time can be reduced to a few cycles of the supply frequency, so that the circuit can be repeatedly brought into action at short recurrent intervals.

More than One Time Interval[5.3]

Where more than one time interval is involved, it is sometimes possible to secure this without the addition of selector or stepper switches and with only one valve and relay. By the addition of a parallel connected condenser and resistance in series with the relay of the basic timing circuit of Fig. 5.2 a two-interval switching sequence can be secured which is very useful for some purposes, since each time interval is independently adjustable. Such a circuit is shown in Fig. 5.5 (*a*) with an explanatory diagram in Fig. 5.5 (*b*). The grid circuit is the same as that of Fig. 5.2 and functions in the same way, giving the first delayed switching initiated by opening switch S and being determined by the values of the grid circuit components.

When the valve fires, unidirectional current passes in the anode circuit, condenser C1 charges up, and then cuts down the anode current, since its acquired potential opposes that of the anode supply. Thus, if the value of condenser C1 and resistance R1 are suitably chosen, the anode current will be reduced finally to a value less than that required to hold in the relay which will release, even though the triode is still conducting.

If V_s is the steady supply voltage and V_p the voltage across the valve, the final steady anode current will be $(V_s - V_p)/(R_1 + R_r)$, where R_r is the relay resistance, and if this is less than the current I_r required to hold in the relay, the relay will release. This release occurs if R_r exceeds the value of

$$(V_s - V_p)/I_r - R_1 \quad . \quad . \quad . \quad . \quad . \quad (1)$$

otherwise the relay will not release and the circuit will function in exactly the same way as that of Fig. 5.2—viz., as if condenser C1 and resistance R1 had been omitted.

The second period t_1 (Fig. 5.5, *b*) can be estimated from the circuit constants, but not to a high degree of accuracy, since the relay inductance differs in the on-and-off position and introduces a complicating factor. It will be more profitable to state some general con-

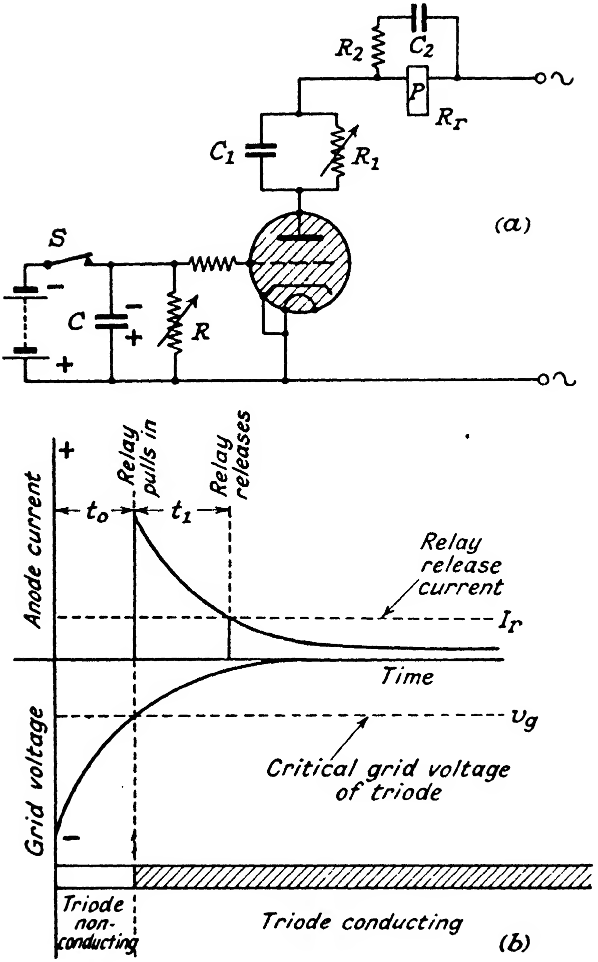


Fig. 5·5.—(*a*) Circuit for two variable switching periods; (*b*) time-current variation.

clusions resulting from the variation of the components in the anode circuit. When R1 is very large, say $=\infty$, t_1 has its minimum value $=R_rC_2 \log (V_s-V_p)/R_rI_r$, t_1 increases as the value of R1 is made less until R1 reaches the limiting value given in expression (i), when t_1 becomes infinitely large. Further reduction of R1 has no effect, since the relay will not release at all. If the minimum value of t_1 is insufficiently small, it can be reduced by decreasing C1 or including extra resistance in series with the relay, always provided this is not sufficient to prevent the relay pulling in. The interval t_1 in practice can be adjusted from a few cycles to about 10 secs. Above the upper limit, the leakage of the electrolytic condenser C1 makes consistent operation uncertain.

The condenser C2 across the relay is included to hold the relay in during the non-conducting half-cycles. R2 is employed to prevent a surge when first closing the anode circuit.

The anode supply voltage may be A.C. or D.C., but this is one of the circuits which will not function if a hard valve is substituted for the gasfilled triode, because when the anode current starts to rise it will, while insufficient to operate the relay, still be charging condenser C1, which will rise in voltage enough to prevent the anode current ever reaching the pull-in value for the relay.

Repeated Cycling

By the addition of two extra sets of contacts on the relay the circuit of Fig. 5.5 can be made automatically repeating so that the two-period cycle recurs as long as required. This addition results in the circuit of Fig. 5.6, which operates thus: Before the cycling starts switch S is closed and the valve discharge is restrained. Opening switch S as before starts the first-time delay period until the negatively grid potential has fallen to the point where the valve fires.

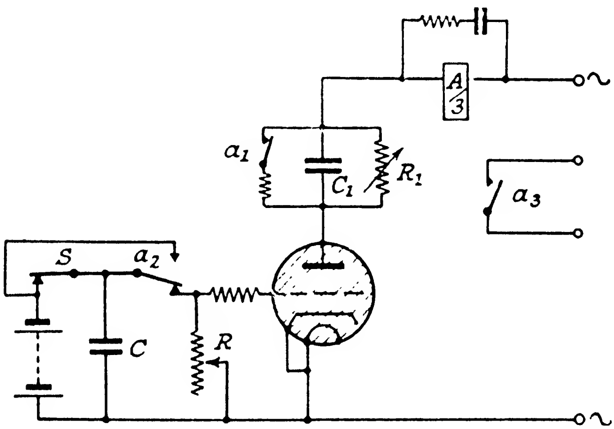


Fig. 5.6.—Additional contacts added to relay to make the circuit of Fig. 5.5 repeat the two cycle timing interval.

Relay A/3 then operates, opens contact a_1 and closes a_2 at its upper contact. The latter contact closure recharges condenser C. After the expiry of the second time interval due to the action of the anode circuit R1, C1, the anode current is so reduced as to release A/3. When this occurs contact a_1 closes, short circuits condenser C1, and at the same time contact a_2 reapplies a high negative potential to the grid to cut off the anode current. This completes the cycle, which repeats indefinitely.

This circuit again is one which permits of the use of some form of stepper switch in the anode circuit, so that after each cycle comprising the two time intervals, the values of either R or R1 (or alternatively the condensers C or C1) can be changed to secure the next pair of time intervals. In this way it is possible to get repeated time cycling, but with different values of the time intervals.

Further Circuit Modifications

The use of extra switchgear to secure more than one time interval can also sometimes be avoided by additional components in the triode grid circuit. Consider first the modification of circuit shown in Fig. 5.7. With the switch S in the position shown, the triode grid is substantially at cathode potential and the valve is conducting with the anode relay excited. Condenser C1 is maintained at a negative potential on its upper plate by a separate D.C. source. On moving the switch S to the right the timing cycle starts, the grid potential first rises in the negative direction, reaches a negative maximum, and falls to zero as the charge lost through resistance R exceeds that gained through R1. The triode ceases to fire when the grid voltage exceeds a certain (negative) value and starts again when the potential falls to this value, giving the conditions shown in Fig. 5.7 (*b*). In this case the valve starts and terminates in the conducting state with an intermediate period of non-conduction, the periods t_1 and t_2 being determined by the values of the condensers and resistances.

The numerical values of t_1 and t_2 can be calculated from the circuit constants, but the expression is complicated and it is, as before, perhaps preferable to state the general effects of varying the values of the grid circuit components. The period t_1 is relatively short, and both t_1 and t_2 are not independently variable, since changing R or R1 (or C or C1) affects both periods. The effect of altering R1 is to change t_2 much less than t_1, whereas variation of R has the opposite effect.

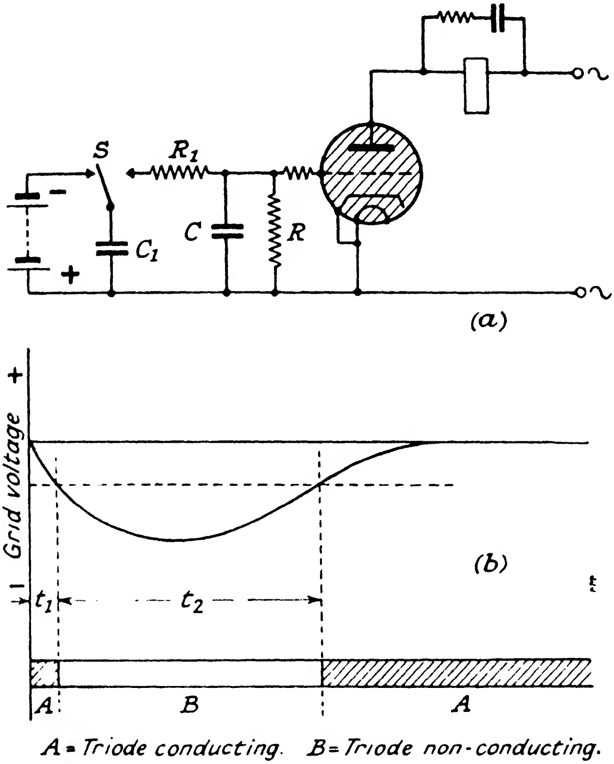


Fig. 5.7.—Three switching operations with two variable time delays, (*a*) circuit, (*b*) grid voltage variation.

Though this circuit may be in itself of less practical use, it also permits of the incorporation of an RC circuit in the anode load, as in the case of Fig. 5.5. The effect of this addition results in the anode current finally falling to value less than the hold on current of the relay, even though the valve is conducting, so that, although the cycle of the discharge in the valve is the same as that of Fig. 5.7, the relay performs one extra operation and is left in the off position. The relay sequence is then on-off-on-off, the first three conditions being exactly the same as in the previous circuit.

With the addition of the anode RC circuit referred to, the cycle of anode current is that shown in Fig. 5.8. The grid voltage changes are the same as those of the circuit of Fig. 5.7, since the final position of the relay is not due to grid voltage change in the valve.

The addition of an anode RC circuit to that of Fig. 5.7 does, however, involve another feature, inasmuch as the first release of the relay may be due to either the grid voltage having become more negative than the critical value corresponding to the peak anode voltage or to the anode RC circuit cutting down the mean anode current to the relay release value, whichever occurs first. It is assumed here, as is usually the case, that the circuit constants are such that the first of these conditions obtains; if not, the four-sequence cycle of the relay will not be obtained.

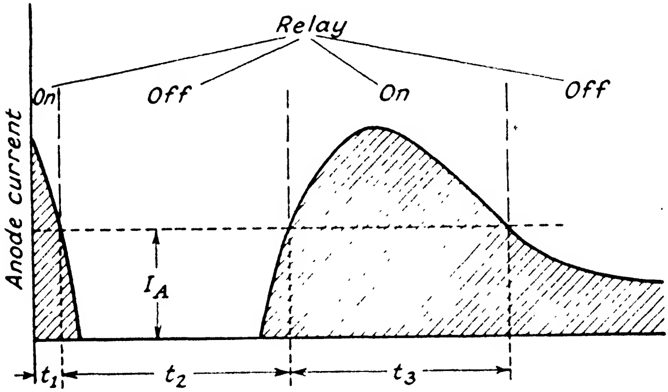
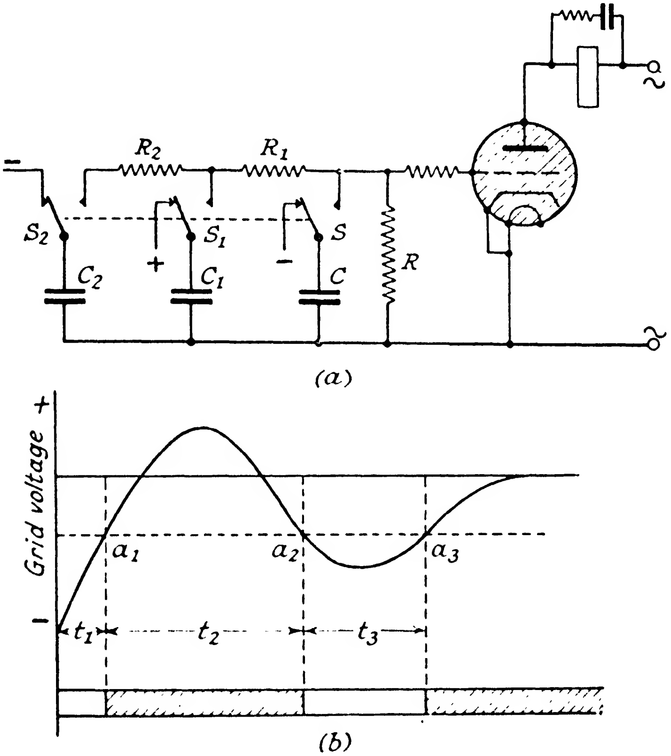


Fig. 5.8.—Four switching operations with three variable time delays.

Multiple RC Circuits

The principles of these circuits can be elaborated still further by duplication of the resistance and condenser networks in the grid circuit. Fig. 5.9 shows such an arrangement in which the start of the timing cycle is controlled by a triple coupled switch S, S1, S2.

Initially, with the circuit in the condition shown in Fig. 5.9 (*a*) the valve has fired and the anode relay is being held in. Operating the switch so that all contacts make on the right-hand side immediately applies a negative voltage from condenser C to the valve grid. Thereafter, due to the successive incidence of the positive potential on C1 and the negative potential on C2, the grid voltage goes through the potential variations shown in Fig. 5.9 (*b*), the valve firing and exciting the relay at points a_1, a_3, and being cut off with relay release at a_2, thus giving three periods, t_1, t_2, t_3, corresponding to the conditions on-off-on. It is fairly clear that computation of the periods involving six circuit components, though possible, is unduly complex. Variation of any of these components or of the initial charging voltage affects each time interval, so that, although the arrangement has its uses as a fixed time cycler, independent variation of the periods is not possible. The addition of an anode current limiting RC circuit can also be made here if required, giving a further period t_4 so that the relay finally takes up the off position.



(a)

(b)

Fig. 5.9.—Multiple RC grid networks. (Shaded area indicates periods during which the valve conducts.)

Independently Variable Periods

Inability to provide independent variation of the time periods is a certain restriction in the multiple period timing circuits so far dealt with. One method of avoiding this restriction consists in the inclusion of a gas discharge device such as a neon tube between the two RC grid circuits, so that the charge from the condenser of the first circuit is shared with the condenser of the second circuit by one discharge impulse, as it were, instead of passing through a coupling resistance (R1 in Fig. 5.7). Thus, in Fig. 5.10, assuming that the striking voltage of the neon lamp N is constant, the condenser C1 will transfer a fixed portion of its charge to condenser C2 as soon as the voltage across the neon tube reaches the striking potential. In consequence, the first time interval is determined by the circuit components on the left-hand side of the neon tube N, and the duration of the second period by the components on the right-hand side. Thus the two periods are independently variable. If it is assumed that the neon tube discharge is rapid enough for all the charge on C2 to come from C1, and none through resistance R, calculation of the time periods is relatively simple (Fig. 5.10 [*a*]), though in practice the striking voltage of commercial neon tubes is not a very constant characteristic. In Fig. 5.10 (*b*) the heavy line shows the grid voltage changes of the valve, assuming that the neon tube discharges once. The sequence of the triode relay is thus on-off-on. Addition of the anode RC circuit included in the circuit previously described results in the relay being finally left in the off position with the discharge passing in the triode.

If the source charging condenser C has sufficiently high voltage, condenser C1 will discharge across the neon tube more than once, giving several cyclic intervals, these being slightly extended in time, as shown by the dotted curves of Fig. 5.10 (*b*), resulting from slightly different striking and extinguishing voltages at successive discharges. With a slightly increased complication the neon discharge tube could be replaced by a second gasfilled triode, with the advantage of controlled firing voltage and smaller voltage drop across the valve.

Application to Electric Welding

Grid-controlled gasfilled rectifiers are extensively used in some forms of electric welding equipment. It is not proposed here to attempt to deal with the subject of welding in any of its aspects, since a number of publications devote their whole attention to the subject and reference should be made to them. The advantages which result from the use of gasfilled valves as control devices have also been fully discussed elsewhere.[5.4, 5.5] Attention will therefore be confined to some of the electrical circuits employed. In all cases the valve functions as a special form of timing switch, enabling current to pass through the metal junction for a specified and controlled period,

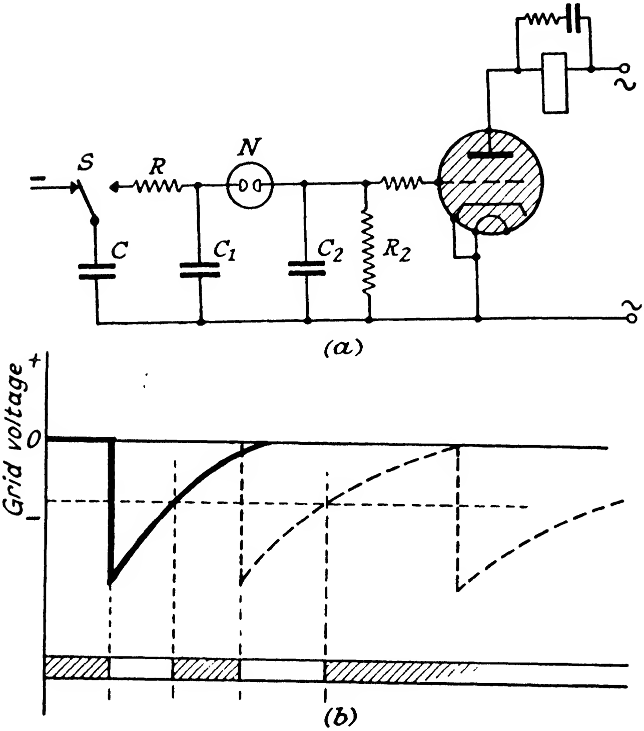


Fig. 5.10.—Modification to secure independently variable time periods.

which permits of variation over wide limits from the duration of a few cycles of the supply voltage to a period a hundred times as great, according to the demands of the particular case for time of application and speed of repetition.

Some circuits include thyratrons; some include ignitrons. Many employ both, either in the main or the auxiliary circuits. In general thyratrons are used with a separately connected transformer, since the valve is a high-voltage, low-current device, and the necessary current change is secured by variation of the impedance of the primary of a current transformer in the valve anode circuit.

Ignitron power valves are usually connected directly in series with the welding transformer. The thyratron, having a relatively high mean to peak current rating, is suitable for seam welding where it can be operated at its peak rating for, say, 50 per cent. of the cycle. Ignitrons can handle very high peak currents, but the ratio of mean to peak rating is low, particularly with air-cooled types, making them suitable for spot or projection welding. Water-cooled ignitrons permit of a higher mean anode current rating, and therefore render them more applicable for seam welding.

In low-speed spot welding, where a contactor provides sufficiently close control of the welding current, some form of timing circuit similar to those already described enables the valve to function so as to determine the duration of the closure of the main contactor which feeds the welding transformer, and enables time intervals within the range of, say, 0·25 sec. to 10 sec. or more to be measured off. In the circuit of Fig. 5.11B the valve performs the double function of a

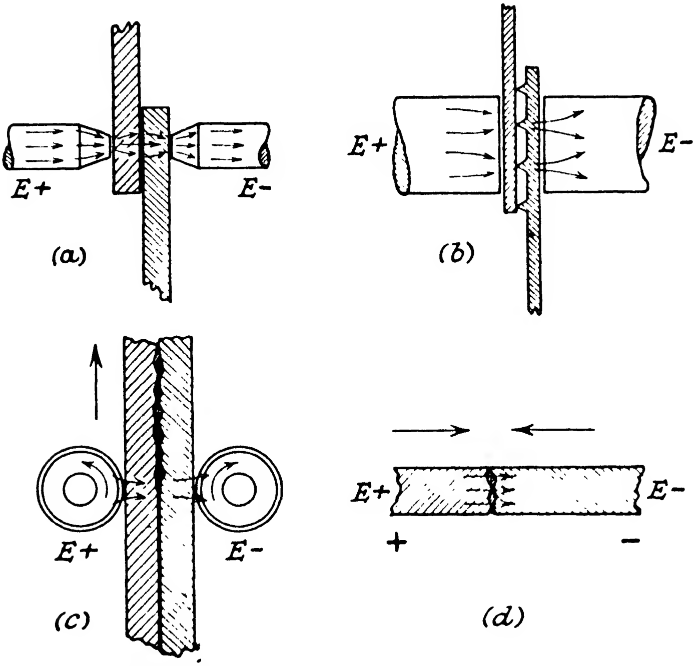


Fig. 5.11A.—(Small arrows indicate lines of current flow.) (*a*) *Spot welding.* Converging electrodes produce concentration of current with intense local heating and fusion at selected point in overlapping material. (*b*) *Projection welding.* Flat electrodes held together by pressure. Fusion takes place at projecting points in overlapping material. (*c*) *Seam welding.* Electrodes are rollers which force the work upwards in the direction shown by the arrow. The upper portion has been welded. (*d*) *Flash welding.* Work forms the electrodes which are excited before being pressed in contact.

timer and a rectifier, so that a robust D.C. contactor can be used to control the power from an A.C. supply. The contactor controlling the welding transformer primary winding is shown by the contact a_1, and is operated by the relay or coil A/2 excited by direct-current pulses in the anode circuit when the valve fires. Condenser 1 and resistance 2 constitute a smoothing circuit across the coil. Extra resistance may be needed to limit the peak current through the valve. The rectifier 3 in valve grid circuit normally restrains the discharge in the valve by holding the grid negative to its cathode. The usual grid current limiting resistance 4 and surge suppressor condenser 5 are included in the grid network.

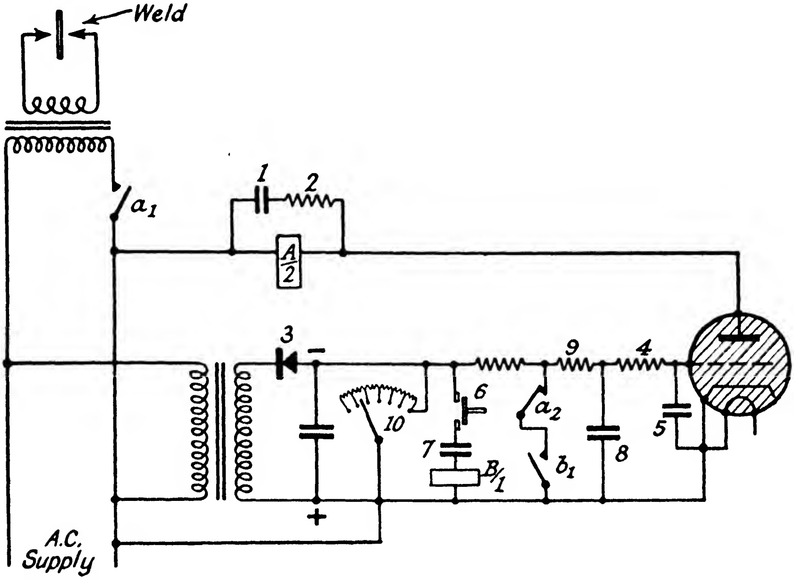


Fig. 5.11B.—Valve acting as a delayed action device for low-speed welding circuit.

When the welding electrodes are applied to the work with sufficient pressure, the switch 6 is closed. Condenser 7 then charges and momentarily energises relay B/1. As a result, contact b_1 closes and short circuits condenser 8, thus removing the negative bias on the valve grid and causing the valve to fire. Relay A/2 is thereupon excited and contactor a_1 closes and applies current to the weld.

At the same instant, contact a_2 opens and removes the short circuit across condenser 8, which thereupon starts its charge-up through resistance 9. The valve grid thus becomes increasingly negative until a potential is reached at which the anode current ceases. Contactor a_1 then opens and the welding period is completed.

The timing period is determined by the setting of the potentiometer 10, which acts as a fine control, and by the values of the condenser 8 and resistance 9. It starts from the instant the contactor a_1 closes—*i.e.*, at the beginning of the weld—so that the welding time is fixed for a given circuit adjustment and is independent of the period during which the switch 6 remains closed.

High-Speed Spot Welding and Seam Welding

The use of gasfilled triodes as a means of controlling short-period intervals necessary in seam welding is probably the best example of their practical utility as high-speed circuit interrupters.

In most cases of seam welding of sheet metal, notably stainless steel and aluminium alloys, the union of the metals is best effected by a succession of closely spaced spot welds, the formation of which restricts the accumulation of heat and consequent burning of the metal, so that seam welding becomes a special case of spot welding in which the spots follow one another in close succession. Seam welding in this manner has the advantage also of reducing oxidation, of retaining without material alteration many of the physical properties of the metals—*e.g.*, hardness, ductility or resistance to corrosion—which might otherwise be affected adversely by too high a temperature, and of preventing distortion in the metal due to excessive heat.

In applying this process, both the duration and magnitude of the welding current affect the quality of the spot, and since the shorter the time the higher the KVA load to reach welding temperature, the gasfilled triode (or ignitron) is the ideal unit for accurate time control for periods of the order of 0·01 to 0·1 second.

In seam welding the individual spots must be close enough to secure a gastight joint between the metals, yet the overlapping must not be sufficient either to slow up the process or to defeat its object by overheating. If there are, say, 10 spot welds per inch and the welding speed is 40 inches per minute, then the current has to be stopped and started 400 times per minute, and since the current during such short "on" periods will be very high, the need for accurate control of the time interval during which current passes is fairly obvious.

No mechanical contactor could withstand the strain operating at such repetition speeds, nor could the current be controlled by their use to any degree of precision where varying periods from one to several cycles of the supply frequency are involved. In addition, the difficulty of preventing burning of the contacts and the inability to synchronise the on and off points of the current with the A.C. supply voltage would extend the "current on" period by an uncertain interval even if the closure of the contactor could be accurately timed.

In the circuit of Fig. 5.12 it might be considered that the triode could be connected directly in the primary of the welding transformer as a current interrupter. The arrangement shown is adopted to utilise effectively the essential characteristics of the valve as a high-voltage, low-current device, and to this end the transformer is employed to step up the voltage applied to the valve anode.

With the valves in the non-conducting state, the series transformer secondary imposes a very high impedance in the power supply to the welding transformer and permits little current to pass. When the valve fires, this impedance is reduced to a low value and about 95 per cent. of the line voltage appears across the primary of the welding transformer.

The timing circuit in the valve grid network also secures more consistency in repetition than would be possible with a rotary switch for periods where only a few cycles of the supply voltage are concerned.

For the accurate control of the welding period to a specified short-time interval the equipment consists of three parts: the timing circuit, the controller and the power circuit.

In Fig. 5.12 the power circuit is shown by the heavy lines. The lower portion of the diagram comprises the timer circuit, which constitutes a single valve inverter circuit which inverts the direct-current supply to this circuit into alternating voltage of special wave form.

Initially, if the condenser 1 is without charge, the full direct voltage to valve 3 appears across resistance 2. The grid potential of the gasfilled triode 3 is due partly to the D.C. bias from the tapping point 4 with a superposed alternating voltage from transformer 5. The latter has a peaked wave form secured by saturation of part of the iron core. The firing grid voltage peak can be made to occur at different points of the A.C. wave by variation of the resistance in series with the transformer primary. This peak is adjusted to take

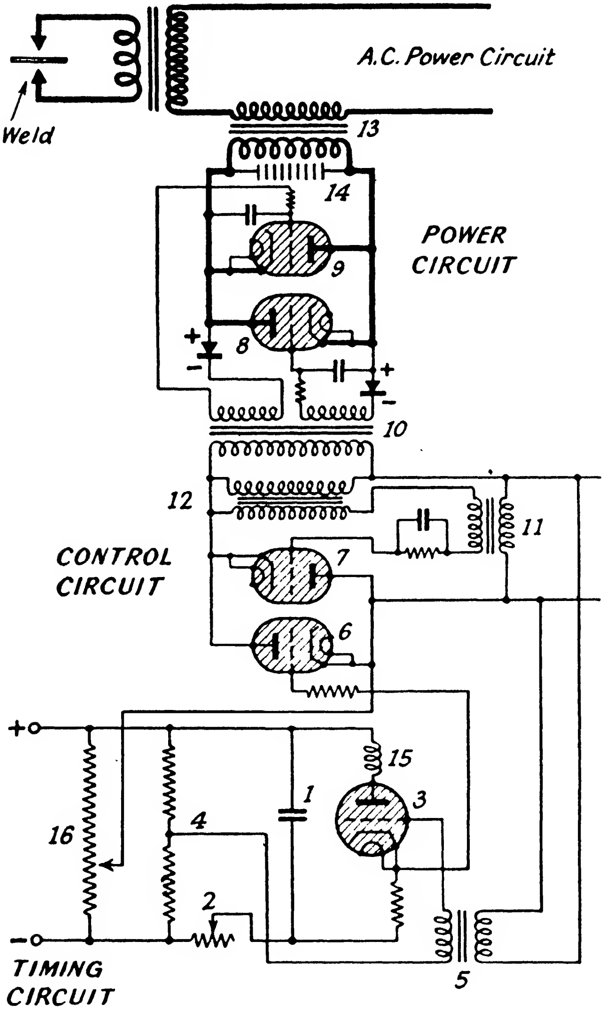


Fig. 5.12.—Diagram of timer controller and power circuit.

place at approximately the power factor angle of the welder, the point which produces minimum transient current. On completing the supply to the timer circuit, condenser 1 charges gradually and the potential of the cathode falls to a point where the valve fires. The inductance 15 also assists in this operation by leaving the condenser with a reversed charge. Condenser 1 is then shorted and the valve circuit resets due to the fall in anode voltage. The transformer 5 provides a synchronising impulse which ensures that the pulsations of the circuit recur consistently always after a fixed number of supply voltage cycles. The variable resistance 2 enables this period to be adjusted from one constant value to another.

The grid voltage of valve 6 is the resultant of the constant bias from the potentiometer 16 and the variable potential of the cathode of valve 3, so that the duration of the conducting portion of the cycle of valve 6 is a fixed portion of the conducting period of valve 3.

The main power valves 8 and 9 are controlled by valves 6 and 7, and the duration of their conducting periods correspond. They are normally held in the non-conducting state by small rectifiers in their grid circuits, which maintain the grids negatively biased from the A.C. voltage from the transformer 10. When valve 6 conducts, a voltage impulse is passed through transformer 10, one secondary of which gives a positive impulse to the grid of valve 9, causing it to fire. Valve 7 is normally held non-conducting by an A.C. bias voltage from transformer 11, but when valve 6 fires on one half-cycle, valve 7 will fire on the succeeding half-cycle due to the reactive voltage fed to its grid from the transformer, and the firing of valve 7 will pass an impulse of reversed polarity through transformer 10, which will fire valve 8. Valves 8 and 9 therefore fire on alternate half-cycles.

The use of such an arrangement in which one valve fires immediately after the firing of the other has two advantages. Full cycles are always fed to the grid of the power valves and the grid characteristics of the leading valve only are involved in the firing cycle. The loading of the timing circuit is also reduced, and may be kept to a minimum by using a tetrode as the leading valve in the controller.

The passing of current through the primary of transformer 13 reduces its impedance to a low value, so that the full voltage of the power circuit is fed to the weld, as shown in the circuit of Fig. 5.12.

The intermediate pair of valves 6 and 7 are employed to ensure that there is sufficient power available to secure positive operation of the power valves under all conditions of use.[5,6]

For spot welding a similar circuit is used, except that only one impulse has to be given to the power circuit varying in duration from one to several cycles. This requires an extra triode, so that the timer valve fires only once and then locks out, the duration of the weld being determined by the setting of potentiometer 16. Fig. 5.13 shows the sequence of voltage changes on the grid of valve 3 (Fig. 5.12). The timing period depends on condenser 1 and resistance 2, but the synchronising peak voltage impulses from transformer 5 ensure that the discharge always occurs after the same number of cycles of the supply voltage. For spot welding, lock-out action is secured by the modification shown in Fig. 5.14. Here V1 is the same valve as 3 in Fig. 5.12, but the inductance 15 of Fig. 5.12 is replaced by transformer T with an extra triode V2. The rest of the timing circuit is unaltered. During the timing period V2 is biased to cut off. When V1 fires, the grid of V2 is made less negative by an impulse through transformer T, causing it to fire. The low voltage across V2 then imposes about 100 volts negative on the grid of V1 and prevents it firing again. Non-recurrent action is thus secured and the control circuit is locked out till V2 is reset by momentarily closing S.

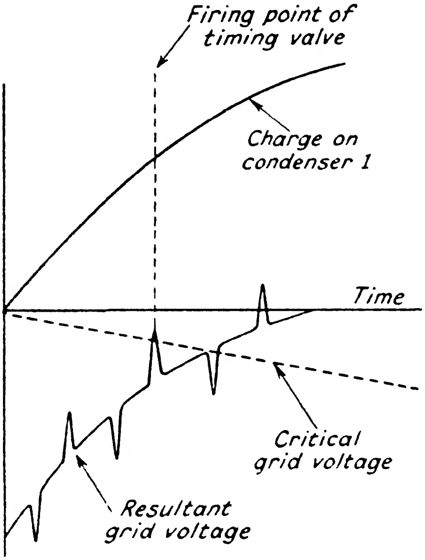


Fig. 5.13.—Sequence of voltage changes in the timer circuit of Fig. 5.12.

Condensers are included in the valve grid circuit to prevent premature firing by surge voltages. A thyrite resistor 14 across the transformer primary 13 (Fig. 5.12) suppresses transient voltages induced in the winding by the sudden change of flux when one of the power valves fires.

Owing to the possibility of D.C. flux building up in the cores of the welding and series transformers, some modification of design is needed to measure off welding periods of less than one cycle.

In these circuits the duration of the "on" and "off" period can be checked by a visual stroboscope. Since current interruptions up to 1,500 per minute and spot welds of one cycle duration or less can be accurately measured off, it is difficult to imagine an equally satisfactory alternative form of control.

One disadvantage is the high peak KVA load of short duration imposed on the supply, but this is common to any conditions of similar loading and not a particular feature of these circuits. Some features of ignitrons as used in welding circuits are referred to in Chapter 8.

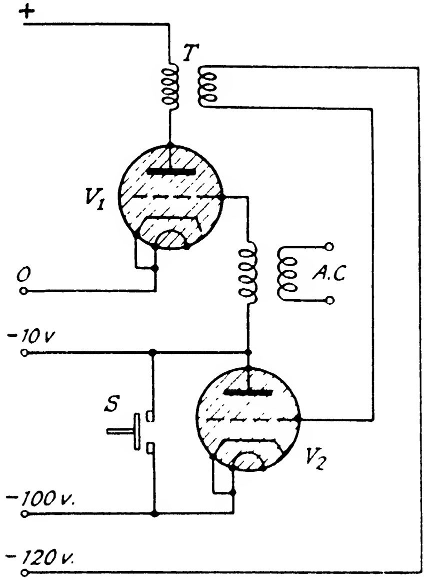


Fig. 5.14.—Lock out circuit to prevent repetition of switching of the timing circuit of Fig. 5.12.

Automatic Synchronisation—Mechanical[5.7]

The quantitative control of the mean anode current of a gasfilled triode which is made possible by the use of a variable capacitance to change the phase of the grid voltage has been utilised to enable a large rotating body to be synchronised with a smaller one, the latter being driven by very small power. Fig. 5.15 indicates in outline the method of applying this form of control. The shafts of the two rotors 1 and 2 carry flat sector-shaped plates 3 and 4. The shafts are arranged in the same line, so that the two plates form a condenser of variable capacitance according to their relative position with respect to each other. When the adjustment for synchronism is correct, the two rotors are running at the same speed with the sector plates half overlapping. With rotor 2 as the master controlling element, if the rotor 1 decreases speed, the sector plates will overlap more and the capacitance will increase. The resulting phase change on the grid of the gasfilled triode will increase the valve current and cause the motor speed to rise so as to reduce and correct the change in speed of rotor 1. Similarly, if the rotor increases in speed, the change in capacitance will reduce the current through the rotor and reduce the speed so that rotor 1 will always rotate in synchronism with rotor 2. To enable the motor 1 to be run up to speed, the switch 5 is opened and the capacitance 6 or resistance 7 adjusted until the plates are in the overlapping position, a condition which at high speed can be determined with the use of a suitable stroboscopic disc. When this condition is secured, switch 5 is closed and thereafter the two rotors lock in step. It should be noted that no power is drawn from the master control motor 2, which may be quite a small machine. The whole of the power required to maintain synchronism is drawn from the supply to the gasfilled triode.

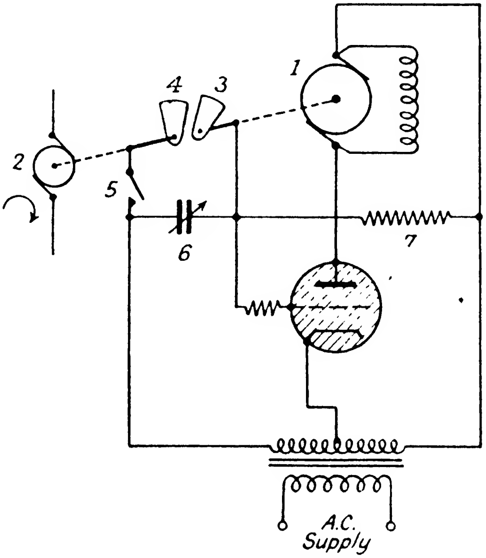


Fig. 5.15.—Mechanical synchronisation—automatically performed.

Electrical Synchronisation[5.8, 5.9]

In the operation of power-station generating plant the problem of synchronisation occurs when it is desired to make automatic the process of switching additional plant on to a live network. Before alternators can be connected in parallel they must have the same terminal voltage, the same frequency, and be in phase, so that both voltage waves pass through zero in the same direction at the same instant. Unless the conditions are fulfilled with only small limiting differences, parallel switching cannot be effected without causing serious surges and unbalancing disturbances in the system.

It has been claimed that the use of the gasfilled triode enables fully excited single and three-phase generators to be switched safely on to a live network automatically without the use of elaborate protective devices, and that power furnished by the permissible small difference in characteristics between the incoming machine and the line can be utilised to supply through the valve the relatively large power required to close the circuit breaker, due allowance being made for the actual line occupied in the closing operation.

A simplified diagram showing one method by which these results have been achieved is shown in Fig. 5.16. A pair of gasfilled triodes is employed and the anode voltage is alternating, so that when either valve fires, the discharge is extinguished at the end of each positive

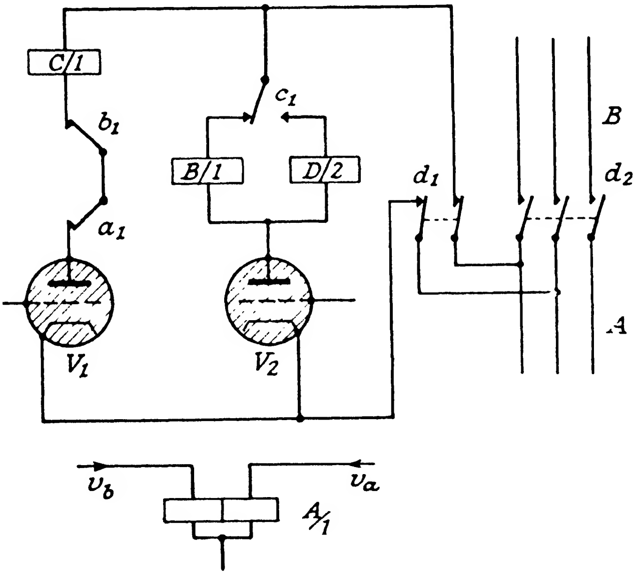


Fig. 5.16.—Simplified circuit showing electric synchronisation of switching operation.

half-voltage cycle. The grid circuits are omitted, but the manner in which they function will be clear from the following description.

The closing of the circuit breaker can take place only when the valves V1 and V2 fire in this sequence. If firing takes place in the reverse sequence, or if the voltage, frequency or phase of the two systems differ from one another by more than the preset limits, the circuit is rendered inoperative and switching cannot take place.

Voltages are tapped off from corresponding phases of the two systems and fed respectively to the two similar coils of the double wound relay A/1, these coils being in opposition and controlling contact a_1. If the excitation of these two coils is equal, corresponding to identity of performance of the two supplies, contact a_1 will remain closed. If their excitation differs by a small amount in current or phase, relay A/1 will open contact a_1 and valve V1 will be prevented from firing at all, so that the circuit will be completely inoperative.

The grid excitation is obtained from a bridge circuit, the input of which is obtained from the secondaries of two transformers in opposition, the primaries being fed from the respective electrical systems. The output of the bridge feeds the triode grids so that the potentials from system A tend, if favourable, to fire valve V1 and those from system B to fire valve V2. If the phase difference is in one direction V2 will fire first. When it does so, relay B/1 opens contact b_1, so that the circuit of valve V1 is isolated. If the phase difference is in the opposite direction V1 will fire first. This excites relay C/1, which causes C1 to make on the right hand contact and complete the anode circuit of V2 through the relay D/2 which operates the circuit breaker. Thereupon V2 fires and after a time element to compensate for the circuit breaker closing time operates d_2 and opens d_1.

This switching takes place when the phase difference is in one direction only, when the two systems are coming more closely into phase, always provided that this phase difference is small enough, a condition which is mastered by the overriding control of relay A/1.

Servo Mechanisms

A type control in which the gasfilled triode or tetrode finds frequent application is that comprising the group of servo mechanisms or follow-up devices which include such varied controls as rotary synchronisers, automatic regulation of voltage speed or mechanical tension, torque amplifiers, etc. During the war servo mechanisms were greatly developed for a number of purposes, such as the remote control of gun mountings.[5.10] Neither the gasfilled valve nor any other electronic device is an essential of a servo control, and many such systems such as the Selsyn are purely electro-mechanical. Nevertheless, electronic devices frequently offer great assistance in such forms of control. As far as the electronic system is concerned all the devices previously mentioned are fundamentally the same. By means of such a circuit the main mechanism or driven apparatus is controlled and maintained in position register with the movement of the driver without any mechanical attachment between the two.

A displacement of the master controller is forced through the electronic circuit to impress a corresponding displacement in the slave mechanism so that the relative positions between the two are restored. In this type of remote control the power necessary to bring about the correction of position is not supplied by the master controller, which may in consequence be of relatively small size. The power consumption required is provided by the electric supply feeding the electronic controller. It is thus possible for a small rotary machine to compel a much larger machine to follow its speed performance.

A typical example of this is the automatic synchronising device previously described (Fig. 5.15), which is a special form of servo mechanism. A more direct means of circuit adjustment than that secured by phase change brought about by the use of a change in capacitance is the use of a photoelectric cell.

The use of a light beam as the controlling medium preserves the freedom from mechanical inertia associated with non-electronic couplings and provides a widely used means of recording the position changes of a moving system of low torque and a self-restoring device for correcting automatically any displacement which may arise in the system.

Since this type of control usually involves a switching operation when the light beam reaches either of two limiting positions, a single photocell with a dual cathode system is an advantage in keeping the optical system within a small space. Alternatively a pair of photocells may be used, each controlling its corresponding gasfilled triode. The latter arrangement may necessitate staggering the position of the photocells in order to place their cathodes sufficiently close in angular displacement. The optical arrangement may take one of several forms, but the light will, in the balanced condition of the system, pass either directly between the two photocell cathodes or illuminate them equally.

Two circuits each one of which is similar to that of Fig. 5.17 are very convenient. In this circuit the grid-phase shifting network which secures quantitative control of the mean anode current of the triode is connected to one side of the valve heater transformer and the cathode to the other side, so that voltages on the phase-shifting circuit are unsymmetrical. Light changes on the photocell, which in practice may conceivably correspond to changes in resistance of the order of 100 to 1,000 M Ω, enable full range of control of the mean anode current to be secured with a capacitance of the order of 100 mm.F.

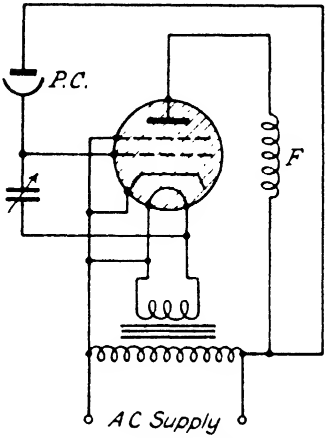


Fig. 5.17.—One circuit of a type which could be employed in duplicate as a servo mechanism control in conjunction with a photocell. P.C. = photocell. F = Motor field coil.

The circuit can thus be made extremely sensitive to small light changes, so that in duplicate it forms a convenient unit for including in the follow-up control. The use of a tetrode eliminates some of the limitations possessed by the triode, but the use of the high-circuit resistances referred to necessitates the use of high insulation in the circuit.

For this reason it may be preferable to use lower resistances and add a stage of pre-amplification. One of the successfully utilised applications of photocell servo controls has been in the automatic direction setting of steerable machines on ships or aircraft. For the purpose of illustration the schematic arrangement of Fig. 5.18 will be considered.

Here light from a lamp L is optically projected on to the surface of a small mirror carried by the compass card and is thereafter reflected as a convergent beam and, in the state of correct adjustment, passes between two photocells P1, P2.

All this apparatus is carried on the steerable machine, which will be considered as being a ship. The position of the compass, and therefore of the mirror M in space, is always the same irrespective of the direction in which the ship moves, but the position of the rest of the circuit relative to the position of M will vary according to the direction of the ship forward movement. It is supposed that when set on a certain course the optical arrangement has been adjusted to take up the condition shown in Fig. 5.18.

If now the ship deviates from its course, this circuit will automatically bring it back. Suppose the deviation is such the displacement of the light beam relative to M results in photocell P1 being illuminated while P2 is dark, or receiving more light while P2 receives less. The result will be to establish current through V1 and the winding FF, which is the forward field of the motor A. The motor will thus be set in rotation, and as it is geared to the vessel's steering mechanism it will produce a deflection in the ship's course which will, if the circuit is connected the right way round, exactly offset the original deviation which set the circuit in operation. The displacement of the ship's course has thus corrected itself.

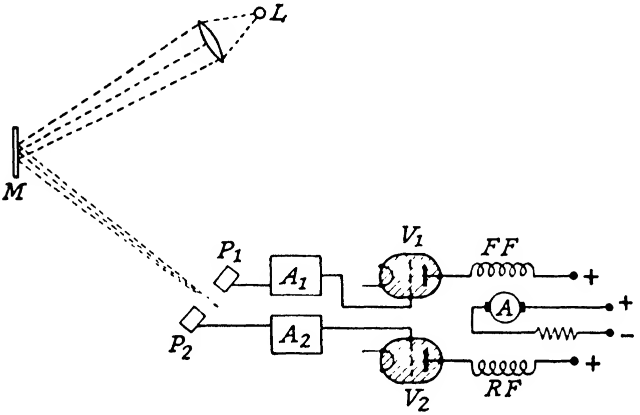


Fig. 5.18.—Schematic arrangement of one form of servo mechanism. An automatic steering control in principle, for ships or aircraft.

Similarly, if the deviation were in the reverse direction, photocell P2 would be more intensely illuminated and would excite the reverse field RF through the firing of V2, and the motor would rotate in the reverse direction to give a similar course correction, but in the opposite direction.

Greater sensitivity is secured by preceding the gasfilled valves by stages of valve amplification—triodes and pentodes. A double pentode is sometimes employed, and has some advantages in stabilising the circuit.

A particular form of servo mechanism is the torque amplifier. One instance[5,11] of a torque amplifier utilising the fundamental properties of gasfilled triodes and applied to a Selsyn system has been described in connection with remote control of large motor-driven rheostats

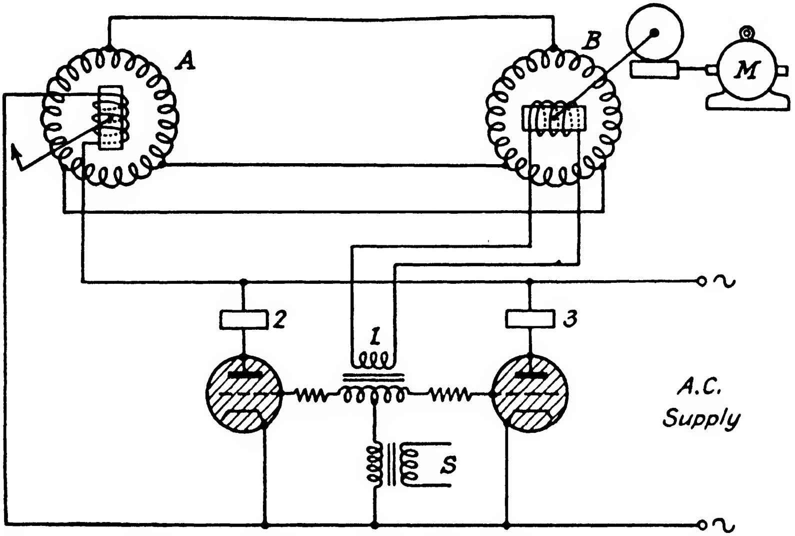


Fig. 5.19.—Torque amplifier in conjunction with a Selsyn. 1. A.C. grid bias voltage. 2. Forward contactor. 3. Reverse contactor.

for pre-setting the position of screwdown rollers in a rolling machine. The principles of this arrangement are shown in Fig. 5.19. The two gasfilled triodes have their common grid circuit transformer coupled to a separate A.C. supply S, which maintains both valves in the non-conducting state. When the two Selsyn rotors are at right angles to each other, the voltage induced in rotor B is zero, and this voltage swings through 180° as the rotor passes through this position. In this relative position both valves are non-conducting and the motor M is stationary. If now the rotor A is displaced in a clockwise direction, the change in grid voltage of the valves is such that the forward contactor closes and the motor is driven in the direction which rotates B clockwise and restores the original relative positions. Contactor operation gives only one motor speed, and the motor is either off or on in one direction or the other. By passing the valve anode current through the field winding, quantitative speed control and more flexible operation can be secured. A double wound field stator or one of the alternative methods of securing selection of speed rotation by current reversal is necessary. By the addition of a second Selsyn at each end driven from the first through reduction gearing with another pair of valves parallel connected with the first pair in their output circuits, but with independent grid circuit, vernier control can be secured. When the mechanism has been approximately aligned to its new position by the first pair of valves, the second set will, due to its coupling through gearing, be sufficiently displaced in phase to make the corresponding valve of the second pair conduct and drive the mechanism into exact register. By this means the setting of tools to an accuracy of 0·001 inch on a large boring mill has been made possible. The notable feature of this type of control is that while the torque on A may be negligible, that on B may be a 50 h.p. motor. If the space relations of A and B are the same, the input of A will be the same as the output of B. Alternatively, if the rotors are at right angles to each other, the voltage induced in B will be zero and the phase of this voltage swings through 180° as the rotor passes through this null point.

A diagrammatic illustration of another form of torque amplifier[5.12] operable from single-phase A.C. supply is shown in Fig. 5.20. In this case there are two pairs of triodes, A and B, which are connected so that one pair, when passing current, gives rotation to the motor in the forward direction and the other pair produces reversed rotation. In addition, if the D.C. speed exceeds a certain value, each pair of triodes can operate as an invertor. This becomes possible if the motor electromotive force exceeds the rectified voltage and no current passes from the rectifying pair but the inverting pair pass current and produce regenerative braking. The phase shifting transformers T_1 and T_2 are rigidly coupled together and are moved simultaneously, but their connections are so arranged that the electrical rotation of one is opposite to that of the other. Rotation of the hand wheel of the synchronous motor X in one direction or the other produces a corresponding torque on the receiver synchronous motor Y, which gives a corresponding phase shift to the grid voltages. Rotation of the D.C. motor then turns the stator of motor Y through gearing in the direction which restores the phase angle of the grid voltage to that corresponding to the position of rest, and the main motor then comes to rest.

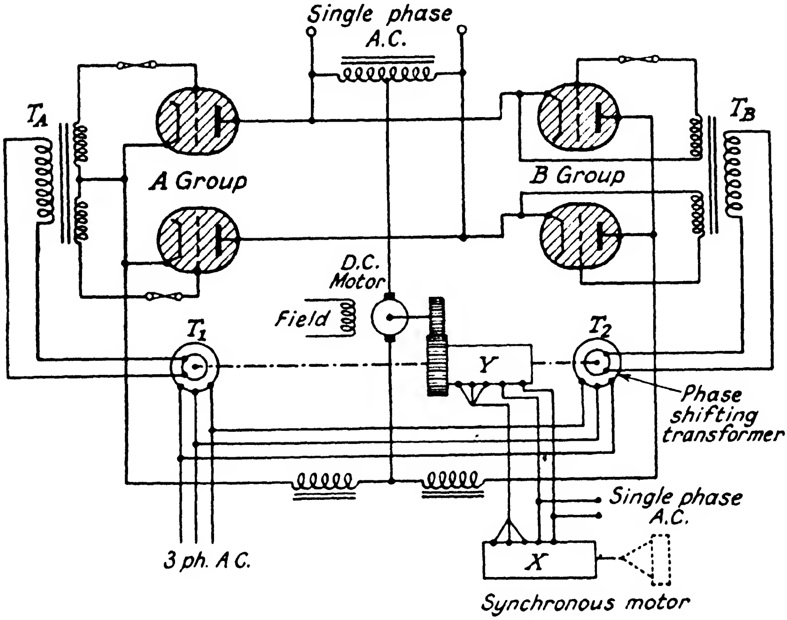


Fig. 5.20.—Torque amplifier.

Mechanical Stability

Unless some precautions are included in the circuit to prevent its occurrence, hunting is liable to be produced in a simple form of servo control. When the displacement error occurs, the circuit immediately starts to correct it, and in so doing may produce over-correction calling for further correction in the opposite direction. This overshooting of the control may repeat in both directions, resulting in a hunting movement in which the system swings repeatedly from one extreme to the other about the mean position of equilibrium. This action is due primarily to mechanical inertia and its resulting time delay in response of the system.

One of the chief problems in applying servo mechanisms to practical problems is therefore the elimination of hunting and the attainment of a sufficient degree of stability.

One method which is known to be corrective in principle, but which may not be easy to apply in practice, is to superpose on the system a controlling force which is proportional to the rate at which the error is produced. This has been applied in practice by introducing at the signal side of the system a network which produces a signal proportional to the error derivative.

An alternative and frequently employed method is to include some form of feedback which will attain conditions of increased stability similar to those which result from the use of negative feedback in a valve amplifier circuit.[5.13]

Frequency Stabilisation

As a means of correcting small changes in the supply frequency of an A.C. source of the order of 1 per cent. or less, the gasfilled triode proves a useful aid for testing equipment in which bridge methods involving sharply tuned circuits are employed or other cases requiring close frequency control.

A standard source of controlled frequency is required, but as the power is very small an oscillatory circuit or a valve-maintained tuning fork will suffice. Without any special precautions it has been claimed that a steel tuning fork will secure closeness of control to the order of 1 part in 10,000 over long periods for the generated voltage and greater accuracy is possible with added refinements.

Fig. 5.21 shows in outline one arrangement which has been used. The lower portion of the circuit shows a D.C. shunt motor driving an alternator which is the source of A.C. whose frequency is to be controlled. F_3 is the alternator rotor field. In the circuit shown the shunt field F1 of the motor M is opposed by an auxiliary field F2, which provides the speed control and is supplied with current from the gasfilled triode V. This valve obtains its anode voltage through transformer T, the primary of which is supplied from the alternator output. The tuning fork F_1, of which the maintaining circuit is not shown, in its vibration closes a mercury contact through one of its prongs during each vibration.

When these contacts are open, negative bias which prevents the valve V from firing is applied to the grid of the valve. When the contacts close, the bias voltage is shorted through a current limiting resistance R, which reduces the grid bias and permits the valve to fire if the anode voltage at that instant is of correct polarity and magnitude.

The motor generator is first run up to speed so as to give approximately the right but slightly lower frequency. When the tuning-fork circuit is set in motion this will operate the valve circuit and increase the motor speed till the output A.C. is locked in step with the fork

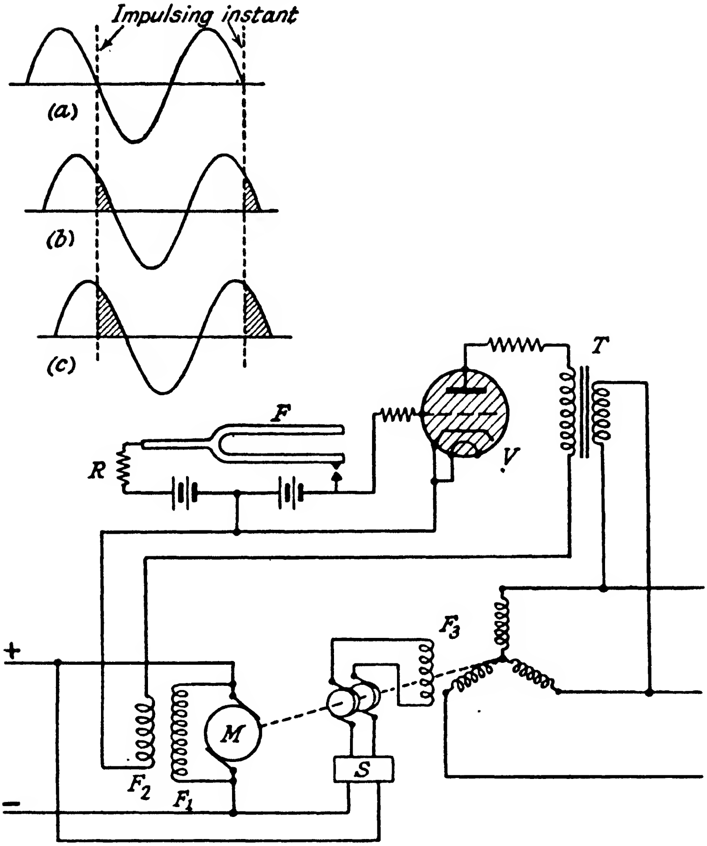


Fig. 5.21.—Frequency stabilisation.

frequency. The mode of operation is made clear by reference to Fig. 5.21 (*a*), (*b*) and (*c*).

In Fig. 5.21 (*a*) the anode voltage is shown passing through zero at the impulsing instant representing correct motor speed. If now the output voltage lags (Fig. 5.21 [*b*]) slightly, the fork impulse fires the valve and current represented by the shaded area passes through the field coil F2. Being in opposition to the shunt field F1, the resultant field is weakened and the motor speed increased. Further lag of the output voltage (Fig. 5.21 [*c*]) still further increases current through F2 and increases the motor speed. The motor speed is thus increased in proportion to the frequency reduction and automatically corrected.

A condition of satisfactory operation is that the alternating field shall be stabilised—indicated by S in Fig. 5.21.

In the original article it is explained that the auxiliary field can be eliminated and the correction applied directly to field F1. This results in two effects. Not all the triode current passes through the field, since the mains supply presents an alternative shunt path. Also the triode transformer winding has the D.C. field voltage applied to it, so that unless the peak A.C. voltage exceeds the D.C. field voltage the triode will not reset. This feature proved effective in that it extended the phase angle over which impulsing can be carried out, and under such conditions the direction of power transmission through the transformer is reversed and the regenerative action enables power to be returned to the A.C. line.

This form of circuit is not applicable, in the case of overspeed, to bring the set down to synchronism. If a second valve is used in a biphase circuit so as to produce current through field F2 in the reverse direction on the opposite half of the supply voltage wave, it will be found that a slight lead of the supply voltage establishes the full value of valve current and increasing lead results in decreasing current, so that the current change available for control varies in a direction which is the reverse of that required. A variant of this form of control is that in which the motor drives a tachometer, which is virtually a direct-current generator with a permanent magnet field, and the output of this auxiliary is employed to stabilise the control of the motor speed.[5.15] In the reference quoted this control is applied in one case to a high-speed pen recorder such as that indicating the output of a thermocouple to prevent overshooting and instability in recording.

The motor receives power from one of a pair of gasfilled triodes according to the direction of rotation. The recorder is in the form of a wire potentiometer to the slider of which the pen is attached. The position of the slider corresponds to a known voltage and the pen moving with the contact indicates the measured e.m.f. Any unbalance in the direct voltage in this circuit is applied to a carbon microphone driven at line frequency from the A.C. supply. The microphone current is modulated by the out-of-balance current applied to an amplifier, the output of which feeds the grids of the gasfilled valves. The direction of motor rotation will then depend on the direction of the out-of-balance current in the recording current. The recorder will thus be urged towards the balance position. To prevent overshooting and hunting, a portion of the tachometer voltage is introduced into the circuit of the measured e.m.f., and its effect is to make the speed of rebalance proportional to the remaining unbalance.

Frequency Comparison

The gasfilled triode provides a convenient means of comparing the frequency of an oscillator with that of a frequency standard over a short period of time and under conditions where other methods introduce certain difficulties. The circuit by Meacham[5.16] is shown in Fig. 5.22. The two oscillators O_1 and O_2 are adjusted so that their frequencies differ by only about 0·1 c.p.s. and their outputs are mixed in the following network to produce beat notes of this differ-

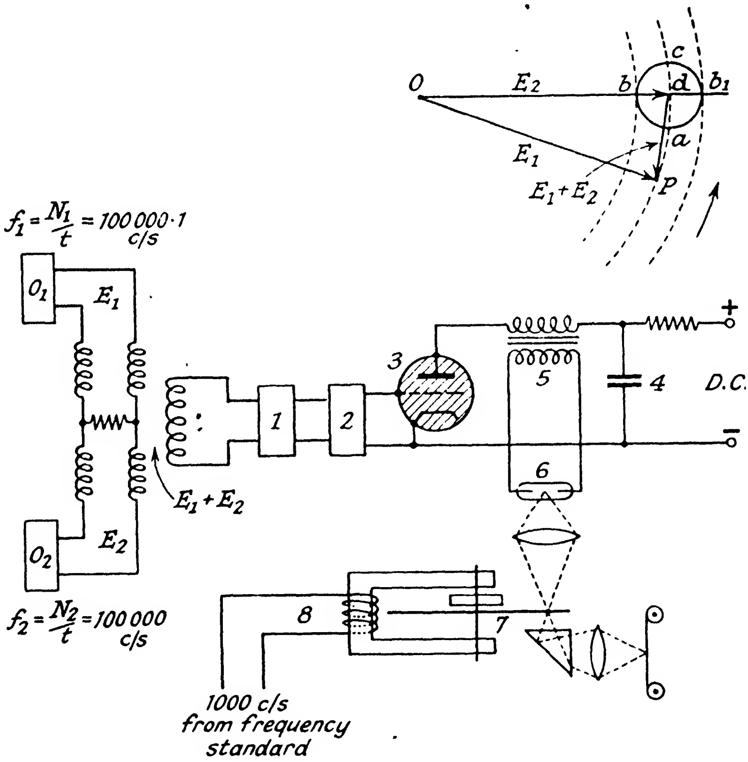


Fig. 5.22.—Circuit for comparing oscillator frequencies over short time intervals.

ence frequency. These signal impulses are amplified and rectified to control the firing of the triode 3 once each beat cycle. The firing of triode 3 discharges condenser 4 and gives a voltage impulse through the step-up transformer 5 to the electric discharge tube 6. The light flash illuminates the translucent scale 7 graduated in milliseconds and driven from a controlled 1,000-cycle standard frequency source. The illuminated portion of the scale is optically projected on to a moving band of film, where it is photographically recorded, so that images of the scale due to successive flashes are separated sufficiently to be measured.

The time elapsing during a single 10-second beat cycle is recorded to the nearest millisecond, and any irregularity in frequency greater than 1 part in 10,000 is apparent. As the frequency of the beat pulses is only $1/10^6$ of that of either of the 100 kc. oscillators, the precision of comparison between oscillators is 1 part in 10^{10}.

One essential condition for accuracy is that the triode shall always fire at the same point of the voltage cycle and that the discharge shall persist for a very short period.

The author gives the vector diagram shown as the inset to Fig. 5.22, where the rotating vectors E_1 and E_2 represent the oscillator frequencies and the resultant E_1+E_2 the beat frequency which varies in amplitude over the beat cycle. The circle with centre *d* has a radius equal to the critical grid control voltage of the triode, and since the vector E_1+E_2 after amplification and rectification is applied as bias to the triode grid, it is clear that the valve will fire whenever the point P falls on the circumference or within the circle. If the point P coincides with *a*, when the voltages E_1 and E_2 are equal, the firing of the valve will occur sooner than if, say, the voltages are unequal and P coincides with point *b* or b_1. The possible error is therefore measured by the ratio of the radius of the circle to the length of the vector E_1, and can be reduced by amplifying E_1+E_2, thus increasing the sensitivity or effectively reducing the circle radius.

Where critical comparison of voltages is involved, their amplitudes must be almost identical, and if the valve fires at all it does so within known and close limits. In the original circuit it is specified that the voltages did not differ in amplitude by more than 0·05 per cent.

Measurement of Transient Voltages[5.17, 5.18]

The characteristic relation between the critical grid voltage and the anode potential may sometimes be utilised to determine whether the signal voltage has any transient component which exceeds a specified peak value, and hence, if the impulses are recurrent, provides a means of measuring the peak value.

If for a fixed anode voltage the critical grid voltage is v and the signal impulses are transformer fed to the grid, adjustment of the bias voltage may be made by means of a potentiometer in the grid circuit, the D.C. bias voltage being connected in series with the transformer secondary. If during the incidence of the incoming signals it is necessary to increase the negative grid voltage to a value V to prevent the triode firing, then the signal source will have a transient component whose peak value in the positive direction is $V-v$. Apart from the operation of resetting the triode, the circuit is then the analogue of the slide-back valve voltmeter, using a hard vacuum valve.

The valve circuit is thus first set up with a variable known D.C. voltage controlled by a potentiometer in the grid circuit and the grid voltage adjusted to the critical value. The unknown voltage is then introduced in series with the known voltage and the potentiometer readjusted to the critical grid voltage. The change in the potentiometer reading in volts indicates the peak value of the unknown voltage. It should be noted that both maximum and minimum values can be detected by this method, according as the unknown voltage is directed, so as to make the grid potential more or less negative. To prevent the possibility of any transients in the anode supply inadvertently firing the valve, this supply should be direct current from batteries. Indication that the valve has fired may be made by including a suitably rated lamp in the anode circuit or a neon indicator between anode and cathode. If the latter is used it will glow when the discharge in the valve is cut off, since the voltage across the electrodes is then a maximum, and extinguish when the discharge passes when the voltage across the valve falls to a low value.

Unless the circuit is made automatically resetting the indications are not particularly informative if the circuit is used without meter indications, since it will only show whether a signal impulse does or does not exceed a preset value.

The simplest method is, of course, to use the condenser discharge method of resetting referred to several times in previous circuits and include a telephone receiver in the anode circuit. A click will be heard each time the condenser discharges. A slow clicking indicates the point at which the recurrent discharge begins. On one side of this point there is silence, and on the other side the clicking sound rapidly merges in a buzzing noise (Fig. 5.23).

When the signal is transformer fed to the valve grid it must be ascertained that the transformer itself does not distort the wave form, and that the detected transient is actually in the signal and not introduced by the transformer.

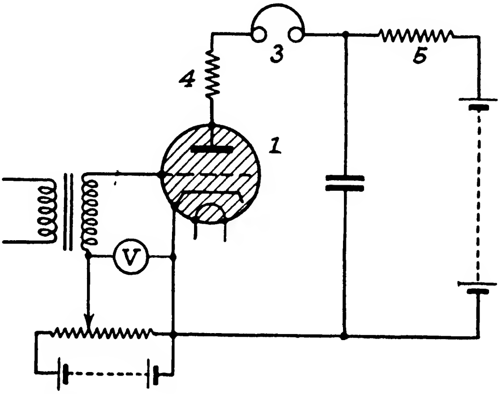


Fig. 5.23.—Peak voltage measurement.

Circuits similar to that referred to, but including two valves, have also been used with the object of obtaining operation on both the positive and negative half-cycles.[5.19] In the case of surges of high peak value, where the peak is inconveniently large, a condenser form of potentiometer may be used comprising a set of series connected condensers across the signal source, the potential across one of them being fed to the grid cathode circuit of the valve.

These methods of measuring peak values of transients are of limited application, since in many instances such transients are non-recurrent and are entirely unpredictable in magnitude and time, or may demand a determination of general time configuration, in which case circuits employing high-voltage cathode ray tubes with photographic recording have to be applied.

Among other circuits which have also been used are those in which the transient after amplification charges a condenser through a hold on circuit which enables the charge to be retained long enough to be measured by a balanced bridge D.C. voltmeter and indicating micro-ammeter.[5.20] In most of the cases where transient recording is carried out by means of gasfilled valves, the record is concerned simply with indicating the existence of a transient at or above a predetermined level rather than ability to measure the surge amplitude.

The Gasfilled Triode as a Stroboscope

The rapidity with which it is possible to establish and extinguish the current discharge in a gasfilled triode and to control these operating points within close limits favours the use of such a device as a short-period illuminant, without the thermal inertia associated with hot-filament sources, for stroboscopic examination of rotating or vibrating objects with a recurrent cyclic movement. Both hot and cold cathode valves (*q.v.*) have been used for this purpose. Reference to the latter for stroboscopic problems is made in Chapter 8, where the subject is more fully dealt with.

The mercury vapour filled triode gives a characteristic bright blue glow, which is frequently sufficiently bright for many instances, but the inert gasfilled valves are less satisfactory in this respect. Moreover, the enclosed electrode system restricts the visibility of the discharge from an external point, so that the standard triodes designed as relay or switching controls are at some disadvantage as sources of illumination in addition to being of relatively low intrinsic brilliancy.

Special designs of valve involving the basic principles of the mercury vapour gasfilled triode have been designed[5.21] in which the bulb of the valve is elongated so as to extend the length of the arc to the anode and render the unit more suitable as a stroboscopic source.

Most of the circuits in which gasfilled triodes are employed for stroboscopic examination utilise the principle of the controlled relaxation oscillator, where the valve performs the function of recurrently discharging a condenser giving a short pulse of current of high peak value at each discharge, the condenser being recharged through a resistance from a source of direct current in the intervals between the discharge pulses. Circuits using these principles have already been referred to in several places.

The discharge through the valve is used, either directly as the source of light, more particularly in valves designed specifically for this purpose, or the current pulses are passed through the primary of a transformer included in the anode circuit of the valve. The secondary of the transformer has a stepped-up voltage which is applied to a separate discharge tube which functions as the source of illumination.

The circuit of Fig. 5.24 embodies the usual phase-change method of grid control with the valve constituting the discharge path for the condenser connected between anode and cathode.[5.22] The optimum conditions of operation are secured when the critical value of the grid potential at which the valve fires is adjusted to coincide with the point where the anode voltage is at its peak value.

An example of the second type of circuit is that shown in Fig. 5.25 due to Spilsbury,[5.23] and is designed to overcome troubles associated with contact pitting and burning which tend to occur with the established method of breaking and making the primary of an induction coil by a vibrating tuning fork with the discharge lamp connected across the secondary winding.

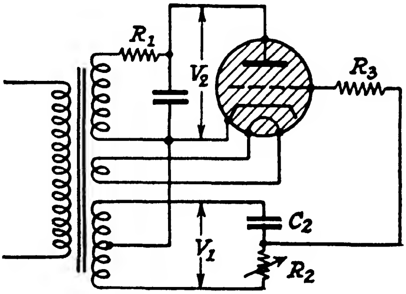


Fig. 5.24.—The thyratron as a stroboscope. $R_1 = 5{,}000$ ohms. $C_1 = 0{\cdot}5\ \mu f$. $R_2 = 200$ ohms. $R_3 = 20{,}000$ ohms. $V_1 = 50$v. $V_2 = 600$v.

In this case the grid is given a steady negative bias from a rectifier fed from a separate winding on the mains transformer, producing a voltage of the polarity shown in Fig. 5.25 and indicated by the lower dotted line in Fig. 5.25 (*a*). Assuming for simplicity that the valve fires when the grid voltage is zero, the discharge of the condenser C1 takes place when the voltage due to the tuning fork applied through condensers C3 in the positive direction equals the steady grid bias.

The discharge of the condenser C1, which tends to become oscillatory, is prevented by the rectifying action of the valve, with the result that the condenser over-discharges and is left slightly negative, as shown in Fig. 5.25 (*b*). The lower limit of the fork voltage is that which gives a peak voltage equal to that of the grid bias. The upper limit occurs when the anode of the valve attains its minimum striking voltage before the grid voltage becomes negative. If this takes place, the valve will fire and remain in the conducting state until switched off. There is sufficient voltage range between these limits to cover any change in characteristics which may be brought about by normal temperature changes. The smoothing of the rectified voltage applied to the grid must be sufficient to eliminate ripple, which might other-

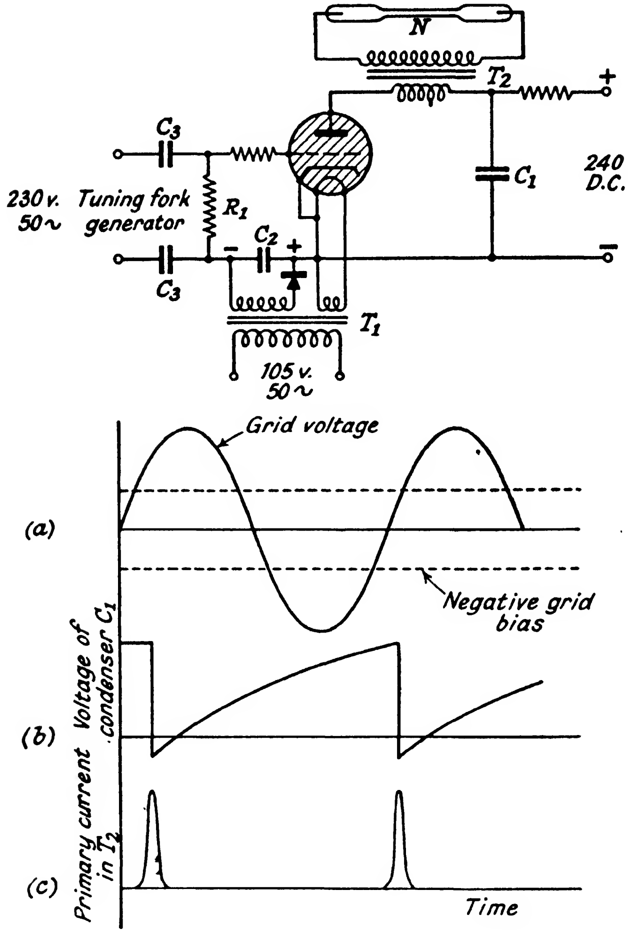


Fig. 5.25.—Gasfilled triode controlling stroboscopic tube.

wise lead to beating between the mains supply and fork frequencies and cause variations in the timing of the flashes in the tube N. For similar reasons the rectifier must present a high resistance to reverse voltage.

Numerous modifications of the fundamental circuits have been employed. In cases where a condenser discharge is employed to produce a high peak current, the time constant (CR) of the condenser charging circuit should be not more than half the time between the recurrent light flashes, otherwise insufficient time will be available for the condenser to acquire the required energy for the discharge.[5.24]

Voltage Displacement of Neutral Point on a Three-Phase Power Line[5.25]

As a protective device to indicate displacement of the neutral point of a star connected three-phase system when the power line has been left working with the earth connection removed, the circuit of Fig. 5.26 has been described by Ockenden.

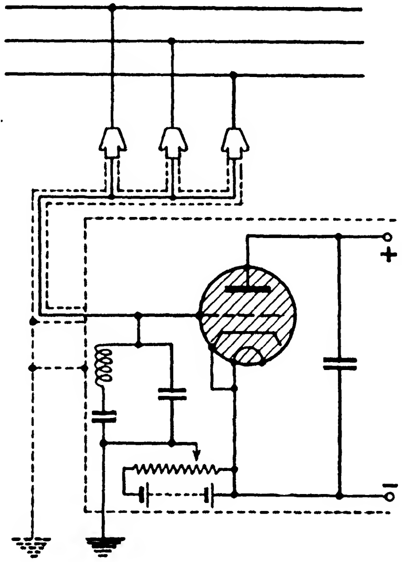


Fig. 5.26.—Circuit for indicating displacement of neutral voltage from earth potential.

This condition exists when a line connected to delta windings at one end and star windings at the other develops a fault which trips out the star winding by means of a normal earth fault protector and leaves the line and fault fed from the delta end.

In the absence of three-phase instrument voltage transformers the measurement of neutral voltage displacement has to be carried out by apparatus connected to the line under conditions where no danger to insulation is involved. The circuit used by Ockenden employs an electrode mounted inside the supporting pins of each of three post-type insulators and star connected. With voltage balance on the lines, the small capacitance currents between cup and electrodes of each insulator sum to zero.

If the neutral point becomes displaced with respect to earth, a similar displacement appears at the star point of the electrodes which is connected to the grid of a gasfilled triode. The rejector circuit between grid and cathode is tuned to 50-cycle resonance and the grid is negatively biased by a separate potentiometer.

The valve fires and operates the necessary protective device when the potential of the positive half-wave developed across the tuned circuit reduces the bias to the critical value. Since the power required is minute, the very small current passed by the post insulators is sufficient to operate the circuit. The tuned circuit ensures that only the fundamental frequency is effective and that harmonics of the fundamental are short-circuited to earth. The anode of the valve is fed with D.C. through a resistance with a condenser connected as shown, so that the circuit is made self-resetting.

CHAPTER REFERENCES

5.1. Gall, A direct-current amplifier and its application to industrial measurement and control, *Journ. I.E.E.*, 89, Pt. II (1942), p. 434.
5.2. Smiley, Control circuits for industry, *Electronics* (January, 1941), p. 29.
5.3. Wouk, One tube, one relay multi-time circuits, *Electronic Industries*, Vol. 5, No. 7 (July, 1946), pp. 48-52.
5.4. Hutchins, Resistance welding improved by thyratron control, *G.E. Rev.*, 40, No. 3 (March, 1937), pp. 116-24.
5.5. Watson, New thyratron controlled automatic arc welding equipment, *G.E. Rev.*, 42 (March, 1939), pp. 114-22.
5.6. Palmer, Thyratron control equipment for resistance welding, *G.E. Rev.*, 40 (May, 1937), pp. 229-35.
5.7. Brit. Pat. 353,056.
5.8. Grosse and Ginger, Automatic Synchronising, *Electrical Rev.* (January 24, 1936), p. 119.
5.9. Grosse, Automatic synchronising, *Electrotek Zeits.*, 55 (August 2,
5.10. Automatic regulators and servo mechanisms, *Journ. I.E.E.*, Vol. 94, Pt. IIa. (1947).
5.11. *The Engineer*, Vol. 158 (1934), p. 141.
5.12. Alexanderson and others, *Electrical Engineering*, Vol. 57 (1938), p. 373.
5.13. Whiteley, Theory of servo mechanisms, with particular reference to stabilisation, *Journ. I.E.E.*, Vol. 93, Pt. II (1946), pp. 353-67.
5.14. Orkney, Precision frequency control, *Electrical Rev.*, Vol. 117 (November 15, 1935), p. 669.

5.15. WILLIAMS, Combined thyratron and tachometer speed control for small motor, *Trans. Am. I.E.E.*, 57 (1938), pp. 565-8.

5.16. MEACHAM, High precision frequency comparisons, *Bell Lab. Record*, No. 20 (March, 1942), p. 179.

5.17. HUGHES, Measurement of peak values of alternating current and voltage by means of a thyratron, *Journ. Sci. Inst.*, 10 (June, 1933), pp. 180-2.

5.18. HICKLING and BRUCE, The measurement of transient maximum and minimum voltages by means of a thyratron potentiometer, *Journ. Sci. Inst.*, 15 (1938), p. 22.

5.19. OFFENBACKER, Electronic devices indicating peak transient voltages, *Elect. World*, 21, No. 123 (May 26, 1945), pp. 80-1.

5.20. RYERSON and ARONSON, Transient peak voltmeter, *Electronics*, 18, No. 9 (September, 1945), p. 110.

5.21. ——, The electric discharge stroboscopic tube, *The Engineer*, Vol. 163 (April 2, 1937), p. 387.

5.22. ROBERTSON and ROGERSON, The thyratron as a stroboscope, *G.E. Rev.*, 36 (October, 1933), pp. 455-7.

5.23. SPILSBURY, A thyratron stroboscope, *Journ. I.E.E.*, Vol. 79 (1936), pp. 585-7.

5.24. EDGERTON, High-speed motion pictures, *Electrical Engineering*, 54 (1935), pp. 149-53; also pp. 485-8.

5.25. OCKENDEN, *Journ. I.E.E.*, Disc. 78 (1936), pp. 530-1.

CHAPTER 6

Applications as Voltage and Current Regulators

Stabilisation of generator voltage. Methods of application. Automatic control of generator frequency. Generator field supplied entirely through gasfilled triodes. Alternative modifications. Voltage control on a lamp circuit. Control of electric motors. The problem of speed variation for A.C. motors. Advantages secured by electronic control. A simpler form of speed control with reversal for a small motor. Auxiliary circuits for closer speed control. Correction for supply voltage variation. Variation of load. Speed variation by field control. Limitation of armature current. Thymotrol system. Applications. Current control by reactors. Compensating reactor voltage drop. Voltage pulse generators. Square wave single or multiple voltage pulses. Peaked voltage generators.

Stabilisation of Generator Voltage

MANY circuits have been devised in which the gasfilled triode operates as a field rheostat for a rotary generator to secure constancy in output voltage. The critical control which the grid exercises over the anode discharge makes this type of valve a convenient device for detecting small voltage changes and for operating further circuits which enable these changes to be corrected. In this respect such circuits are special forms of electrical servo devices. Compared with the vibrator type of voltage controller, they have the advantage of having no current-carrying contacts and the absence of wear and tear associated with them, together with rapidity of response. These factors make them very suitable in theory, at any rate, for machines of any size, though most work so far carried out appears to have been confined to small machines where the field current does not exceed a few amperes.

In the recent past the tendency appears to have been to develop alternative forms of control for large machines, so that valve circuits have received less attention than might be supposed.

In all cases where valve control is used, a portion of the output voltage of the generator is the factor controlling the valve circuit and is fed back to the triode grid to establish the anode discharge by triggering action or to vary its mean value quantitatively by phase shift of the grid voltage to provide the required change in field current of the generator and thus re-establish the original terminal voltage.

Special circuits are frequently adopted to secure the necessary change in polarity of the controlling voltage when the generator output varies either up or down about its mean value.[6.1]

Methods of Application

Increasing the generator field, of course, increases the terminal voltage and vice versa, but the gasfilled triode can be arranged to fire with increasing or decreasing line voltage according to the particular control circuit adopted.

With self-excited generators the firing of the gasfilled triode may be arranged to change the field current by (*a*) providing a variable shunt across a resistance in series with the field winding, (*b*) forming a variable shunt in parallel with part of the field winding. In machines with a separate exciter either operations (*a*) or (*b*) may be performed on the exciter field. This usually has the advantage of smaller power consumption, but on the other hand the time constants of both exciter and generator fields are involved, and more attention may have to be given to stabilising the control circuit due to the greater tendency to hunt.

Finally, the whole of the field and/or armature current may be provided by one or a pair of biphase connected valves in which the mean anode current is varied about an average value corresponding to the normal generator output voltage. At least five possible cases thus arise, though these are not equally effective in response to load changes or desirable for other reasons.

Satisfactory control of the output voltage must include provision against failure of any portion of the circuit which might cause the control to operate in the reverse direction or to assume a condition in which the generator voltage is boosted so as to endanger connected apparatus from excessive rise in voltage.

For such reasons, any valve circuit involving separate grid-bias voltage supplies is excluded and the use of positive grid-drive valves may be called for. In addition, to secure adequate valve life the circuit should be one in which the valve discharge is either cut off or is lightly loaded for the greater part of the time it is in service.

Fig. 6.1 shows in principle the arrangement in which the field winding has a series resistance across which the gasfilled triode is

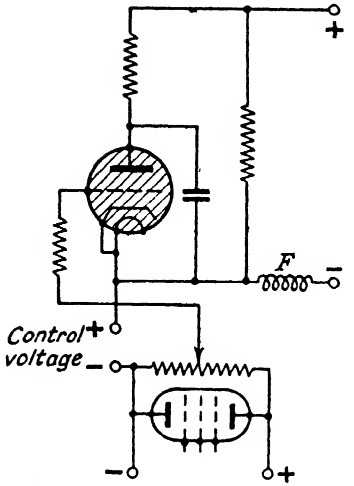


Fig. 6.1.—Schematic arrangement of gasfilled triode in parallel with resistance in the field circuit of a generator.

connected. When the control voltage fires the valve, this resistance is shorted and the field current increased. The triode is reset by the condenser connected between anode and cathode.

In Fig. 6.2 the triode is preceded by a stage of valve amplification which increases the voltage sensitivity. This changes the phase of the signal voltage so that in this case the triode is connected in parallel with the field winding, and the discharge through the valve connects a parallel path across the field coil to reduce the excitation.

If, in these cases, the control circuit is adjusted so that triode fires recurrently at a slow rate in the condition where the line voltage is correct, rise or fall of this voltage will increase or decrease the rate of firing, with consequent variation of the mean anode current and value of the shunt path provided by the valve discharge.

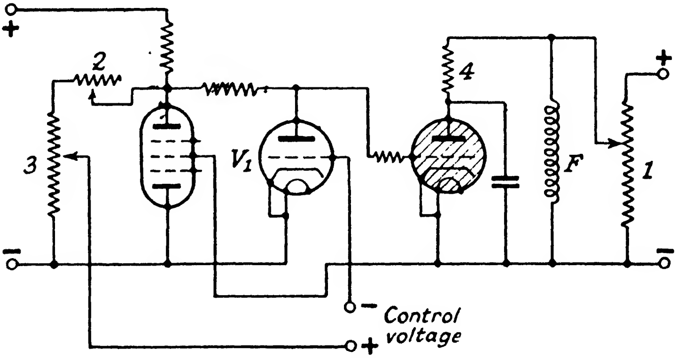


Fig. 6.2.—Control circuit preceded by one stage of valve amplification.

Automatic Control of Generator Frequency

An instance where thyratron control has been used is that of frequency regulation for a variable frequency alternator employed for vibration testing, where it was necessary to maintain the frequency of the voltage source with about 0·25 per cent. in spite of changes in the mains supply.

One method of securing regulation of this order is to employ a Ward Leonard control set comprising two motor generator units, M_1G_1 and M_2G_2 (Fig. 6.3). The alternator G_2 is coupled mechanically to the motor M_2, which receives its electrical supply from generator G_1. The pair M_1G_1 run at practically constant speed, while the speed of the pair M_2G_2 is varied by adjusting the field of the generator G_1.

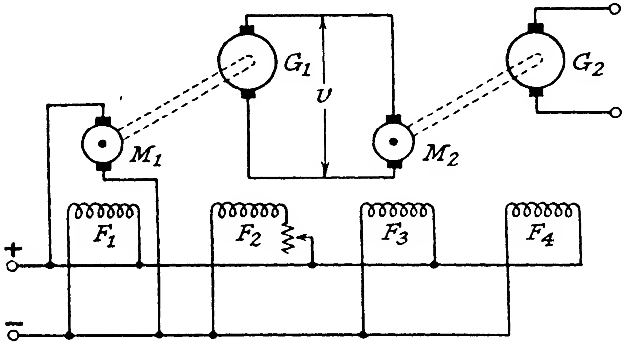


Fig. 6.3.—Two motor generators to which the voltage control of the circuit of Fig. 6.2 can be applied to give close frequency control.

Supply voltage fluctuations have little effect on the field of the motor M_2, but they affect the output by changing the voltage due to (*a*) speed variations in the M_1G_1 pair due to voltage variation in the armature of M_1, (*b*) changes in the excitation of generator G_1. Speed variations of the M_2G_2 pair must therefore be eliminated by stabilising the voltage v.

The circuit of Fig. 6.2 is then employed by applying part of the voltage of generator G_1 to the grid of valve V_1 in the direction that increased generator voltage makes the valve grid more negative, reducing its anode current and increasing its anode voltage, so that the gasfilled triode V_2 eventually fires to reduce the generator field current. Potentiometer 1 is used for rough preliminary adjustment of the voltages, which are finally adjusted by potentiometers 2 and 3. The resistance 4, apart from limiting the discharge through the triode, needs to be selected according to the voltage to be stabilised.

In this case the generator output, field and stabiliser supplies are all independent.

In Fig. 6.4, which is a modified circuit giving more critical control, the generator voltage is also applied to the double stabiliser circuit and the rectified A.C. used to boost the field by the use of a separate field winding.

In a similar way the speed of a D.C. motor could be controlled by means of a small pilot generator on the same shaft, the output voltage of which controls the gasfilled triode circuit.

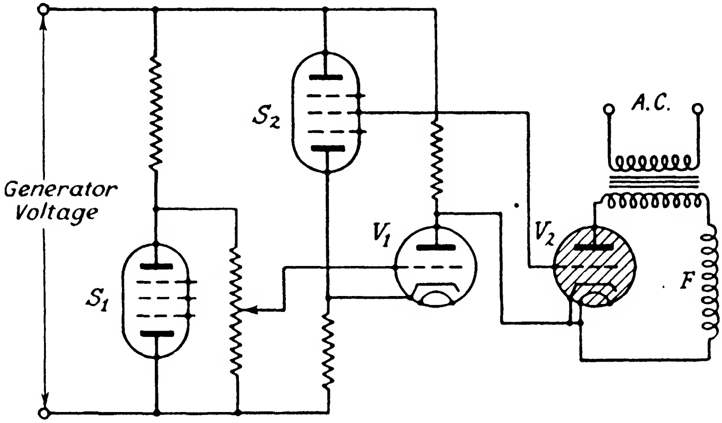


Fig. 6.4.—Common supply for generator control and stabiliser voltages. S_1 and S_2 = stabilisers; V_1 = amplifier valve; V_2 = gasfilled triode; F = separate boosting winding for generator field.

Generator Field entirely supplied by Gasfilled Triodes

An example of a case where the whole of the generator field is supplied and controlled by gasfilled triodes is shown in Fig. 6.5.[6.2] The generator 1, whose terminal voltage is to be controlled, feeds a bridge network of resistances 2 through an adjustable rheostat 3. The opposite arms r_0 of this bridge are constant resistances, while the other pair r_1 have non-linear voltage/current characteristics. These latter resistors may be tungsten filament lamps operated at a temperature which will ensure adequate life, since they have a positive temperature coefficient which provides sufficiently close control for moderate-size machines. This bridge arrangement is balanced at one value of input voltage only. Networks consisting of condensers and inductances have also been used, though better performance results from the use of thyrite resistors used normally for lightning arresters.[6.3]

Under normal operating conditions the output of the bridge 2 is such that the grid of valve 4 is about 2 or 3 volts negative, so that some anode current passes through resistor 5. The generator field 6 is supplied from a biphase connected pair of gasfilled triodes 7 and 8, and the grid voltage of these valves consists of two superposed voltages: (*a*) an independent A.C. voltage of constant frequency and amplitude through the transformer 10 and lagging by 90° on the anode voltage, (*b*) a variable unidirectional voltage which is the resultant of the potential of point 9 and the voltage drop across resistor 5. This component (*b*), according to its magnitude, determines the point in each positive half-cycle at which the valves 7 and 8 fire.

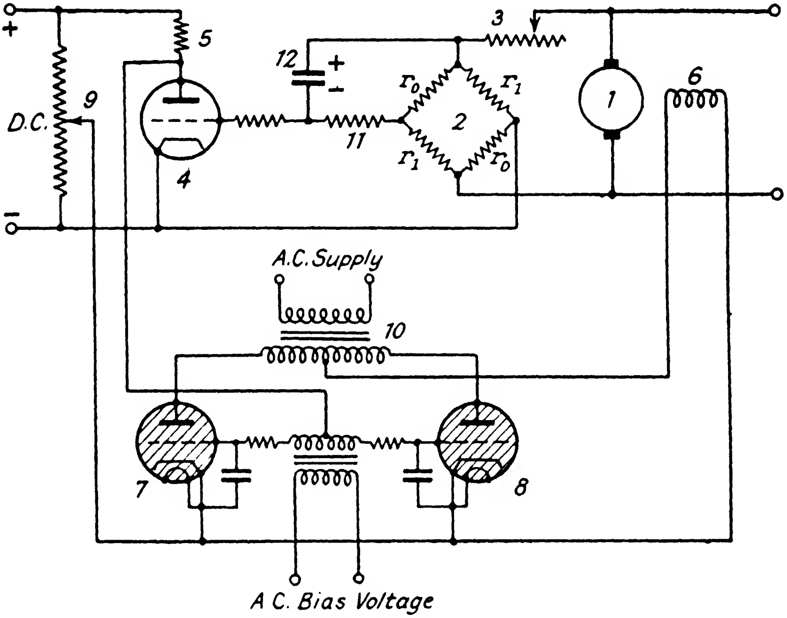


Fig. 6.5.—Generator field entirely supplied through gasfilled triodes.

If the generator voltage rises, the balance of bridge 2 is disturbed and the temperature characteristics of the network tend to change the bias on valve 4 to reduce the anode current. The change in bias on the triodes 7 and 8 causes them to fire later in each positive half-cycle—*i.e.*, the mean anode current through the generator field 6 is reduced. Similarly, if the generator voltage falls, the control circuit operates in the reverse direction.

Initial adjustment of the range of control is made by means of the resistance 3, and it has been claimed that the balance of the bridge can be adjusted close enough to ensure that 1 per cent. change in voltage applied to it results in 100 per cent. change in field excitation.

The system is applicable in principle to A.C. machines of any voltage, but as the sensitivity is proportional to the bridge voltage, the circuit may become somewhat limited in its application to D.C. machines if tungsten lamps are used.

Condenser 12 and resistance 11 constitute an anti-hunting circuit to prevent tendency to instability due to overcorrection of voltage changes. Since the resistance 11 is high compared with that of the bridge 2, the anti-hunting circuit is virtually connected across the generator armature. The voltage across resistance 11 is therefore a function of the differential of the generator voltage and is superposed on the grid of valve 4. It functions thus: Assuming that the generator voltage is being reduced, a voltage will appear across resistance 11, the condenser end being negative. The grid potential of valve 4 is thus reduced and the correcting action of the circuit restrained to a degree depending on the rate of change of voltage which is being forced upon the generator armature. By suitable choice of the values of the condenser and resistance stability of operation is secured.

Another system which has been described[6.4] is that in which each of the three phases of a power system supplies through a transformer an A.C. component to a full-wave rectifier, thus giving a D.C. output which is the mean of the three-phase voltages and which eliminates any disadvantage incurred by regulation from a single phase. This D.C. voltage is applied to a thyrite bridge, as in the case just referred to, and the bridge output is amplified by a pair of parallel connected valves before being applied to the control grid of the gasfilled rectifiers which feed the field of the exciter of the generator.

Another circuit described by the same authors[6.5] utilises the same form of rectifier network, but the subsequent circuit is rather unusual. Part of the output voltage from the rectifier obtained from a resistance load across its terminals is connected in series with an A.C. voltage from an auxiliary transformer to the control grid of the first of a pair of gasfilled triodes. A further D.C. component voltage from the anode load of the pre-amplifier valve is also included in the thyratron control grid circuit, which thus has three separate voltage components. A simpler circuit which includes a single gasfilled triode for controlling the exciter field has been described by Benson.[6.6] This also uses a balanced bridge circuit consisting of opposite pairs of tungsten and carbon lamps which have opposite temperature coefficients,[6.7] so that the bridge balances at one value of input voltage only and gives output voltages of different phase on either side of the point of balance. This bridge is connected to one secondary winding of a transformer fed from the generator output, and the bridge output voltage is connected through a condenser to the grid of the triode. A direct-voltage bias is given to the triode grid from a potentiometer across the exciter terminals.

Another secondary winding of the transformer feeds the triode anode circuit which is in parallel with the exciter field, so that firing the gasfilled triode resulting from unbalance of the lamp bridge due to falling generator voltage, increases the exciter field. A thermally operated time delay switch keeps the triode anode circuit open when the generator is started up till the valve cathode is fully heated, and a damping circuit comprising a series connected resistance and condenser across the exciter terminals is included to prevent hunting and consequent voltage surges.

Alternatively the gasfilled triode may be connected across a resistance in series with the exciter field, but in the balanced condition the steady voltage across this resistance imposes a condition on the circuit in which the valve can fire but cannot regain control, so that the circuit requires the addition of an independent grid-bias battery to offset this voltage and is, for reasons previously stated, less satisfactory.

A modification of this circuit is one in which the transformer secondary, instead of feeding the exciter field directly through the thyratron, is centre-tapped to provide full-wave rectification. One half of this winding feeds two parallel connected diode rectifiers which conduct for the greater part of the time, and the other half feeds the controlled thyratron which functions as in the previous case, but carries current only over a small portion of the cycle.

A later article describes a modification of these controls applicable to small engine-driven generators for private commercial power plants in which the exciter is eliminated.[6.8]

Voltage Control on a Lamp Circuit

A circuit for demonstrating the principle of using a gasfilled triode as a voltage or current regulator, and one which may have some utility as a means of maintaining a constant illumination from a light source within certain limits, can be secured by the use of a suitable phase shift circuit of the type described in Chapter 3, where the mean anode current of the valve is quantitatively controlled by an emission type photocell.

If the anode load of the triode consists of a lamp of suitable rating and the circuit is adjusted so that in the steady state a fixed portion of the light is incident on the photocell, the circuit will tend to stabilise itself in this condition.

If the light from the lamp is reduced, the decreased emission of the photocell will change the phase of the grid voltage in the direction which increases the mean anode current, and therefore raises the brightness of the lamp. Similarly, the circuit operates in the reverse direction if the illumination rises.

This is a particular case of an electrical servo mechanism. Its practical operation depends, of course, on the possibility of securing a lamp and a triode of suitable current rating and on the constancy of the emission of the photocell.

Control of Electric Motors

Increasing use is being made of the gasfilled triode as a means of meeting the demand for variable-speed motor drives from A.C. supply. A notable feature of the direct-current motor is the comparative ease with which it is possible to obtain a wide range of operating speed. In the case of the shunt-wound machine, by weakening the field the motor speed can be increased, and by this means a speed ratio of about 4 : 1 is obtainable. This speed range can be further extended by variation of the armature voltage, and by application of both these adjustments great flexibility of performance becomes possible. The most familiar case is that of the stud faceplate starter, which on switching on applies full voltage to the field, but a reduced voltage to the armature through resistances. As the starter is moved and the motor gathers speed, the armature resistance is cut out and field resistance inserted. In this case adjustment of field and armature circuits takes place simultaneously, though there may be an additional adjustable resistance for field control after the starter is full on.

In the case of the series-wound machine, entirely different performance is secured characterised by high starting torque and ability to deal with rapidly changing load (traction). By utilising both shunt and series fields in the compound wound machine, a combination of the characteristics of both types is secured—viz., constancy of speed of the shunt machine (at constant field intensity) with the high starting-torque of the series-wound machine.

The Problem of Speed Variation for A.C. Motors

Compared with the direct-current motor, all alternating-current motors are at some disadvantage, since in the case of types without commutators they are essentially constant speed devices whose rate of rotation is determined by the frequency of the supply voltage—a factor which does not occur in the case of a direct-current machine—and the number of poles in the magnetic system.

With the established use of alternating current for power systems, the problem of an efficient method of speed control is an important one. Variation of speed over a limited range on A.C. supply is, of course, obtainable with commutator machines, but only at the expense of some complication in design, addition of extra control gear, or by the loss of efficiency in some other desirable characteristic such as torque, and entirely lacking the relative simplicity of control of the direct-current counterpart. If only alternating supply is available and the use of an alternating machine with limited speed range is inadmissible, there then remain the alternatives of accepting a constant-speed machine with variable-speed transmission through gearing or electromagnetic coupling, or the adoption of some form of AC-DC converter which will enable a direct-current machine to be employed.

It is here that the grid-controlled rectifier can play an important part, and there is an increasing tendency to adopt it for electronic control in providing a wide range of speed control, in addition to other desirable characteristics possessed by D.C. motors, for electric motors to be driven from an A.C. supply.

Advantages secured by Electronic Control

Basically all these forms of control involve the gasfilled triode as a half-wave or full-wave rectifier for varying the electric supply to the motor armature, field or both. Since quantitative control of the valve current is possible by phase change in the grid by methods previously outlined, the rheostats or other forms of controller can be made very small compared with those required to give the same range of speed control for the same motor when operated from direct-current mains.

As a first example, the case of a separately excited motor may be considered in which the electronic control acts only as an on-off switch in the armature circuit. Though this is obviously a device of the class treated in Chapter 4, it forms a natural introduction to the more involved types of motor control. Here (Fig. 6.6) the motor is a D.C. machine, the separately excited D.C. field being provided independently from the A.C. supply through a separate rectifier. The armature 1 is connected with the A.C. supply through an iron-cored choke 2, the function of which is to limit the starting current in series with two gasfilled triodes V1 and V2 connected in inverse parallel. Across the anode/cathode path of the valve a resistance of suitable value is connected and the centre point 3 is taken to the mid-point of a two-way switch 4, the other contacts of which are connected to the grids of the triodes respectively. Valves which require a positive voltage impulse on the grid to fire the discharge are employed, because in such valves the discharge is restrained when the grid voltage is zero—*i.e.*, grid connected to cathode. Under such conditions it is not necessary to provide a negative voltage to cut off the discharge, and any failure of this voltage or open circuit in the

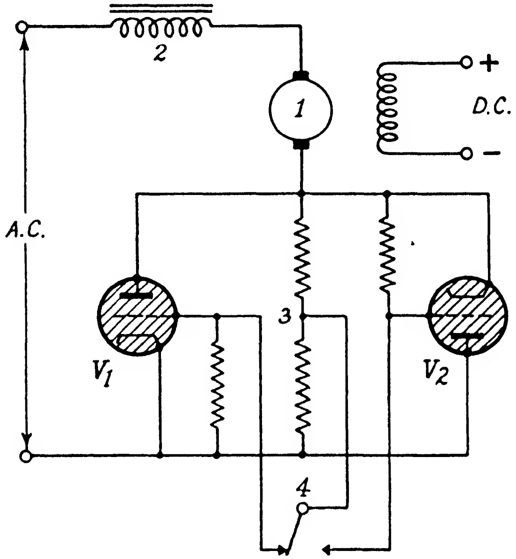


Fig. 6.6.—Simple on-off switching control—with reversal—of separately excited D.C. motor.

grid network prevents the valve from firing and brings the motor to rest.[6.9, 6.10]

Where safety protection against any form of failure is required, ability to revert to the safety condition in this way is necessary.

Closing switch 4 on the left-hand side makes the grid of valve 1 positive with respect to its cathode when the anode of this valve is positive to its cathode, and causes the discharge to pass through it on alternate half-cycles, making the motor rotate on the forward direction. Similarly, closing switch 4 on the right-hand side causes valve V2 to fire on the alternate half-cycles negative to those on which valve V1 fired, and passes current through the motor armature in the opposite direction, producing reverse rotation. Thus the direction of rotation of the motor is controlled by the position of switch 4.

If the switch 4 is open on both sides, neither valve will fire and the motor circuit is obviously open. If it makes contact on both sides at the same time, both valves will fire each on alternate half-cycles and full-wave A.C. will pass through the motor, whose inertia will be too high to respond to the rapidly reversing pulses, so that the armature will remain at rest. The choke 2 limits the current in this case or at starting from rest. If the switch 4 is reversed while the motor is running, the armature will be braked rapidly to a standstill before reversing its direction of rotation.

Such a circuit is obviously suitable only for a small motor, since only the simplest on-and-off form of switching is provided. A choke with variable inductance in series with the lead to the centre contact of switch 4 would provide a means of limited speed control, since it would enable the phase of the grid voltage to be adjusted. The adjustment may be made manually or it may be provided by some controlling circuit such as a photoelectric cell.

A case of this type is shown in Fig. 6.7, in which the photoelectric control has been added to the circuit of Fig. 6.6. Here the photocell P controls the anode current of the valve V3, and this current passes through a winding on the saturable reactor 5. As the light on the photocell increases, the anode current of valve V3 rises and increases the excitation of the saturating winding of the choke, the inductance of which decreases, giving a phase change which increases the mean anode current of the gasfilled valve and increases the motor speed, the direction of rotation having been preselected by switch 4. Change in illumination of the photocell can thus be used to regulate the motor speed.

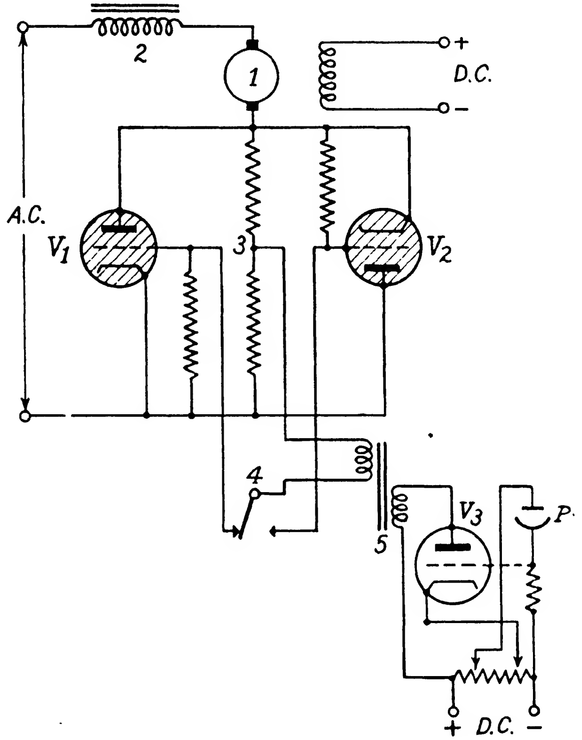


Fig. 6.7.—Photoelectric control giving speed control with preselected direction of rotation of a small separately excited motor.

By duplicating the valve with its reactor and photocell and connecting the two reactors in place of the contacts of switch 4, variable speed in either direction can be secured as a function of the differential light intensity on the two photocells. Using these principles as a basis, numerous modifications of the fundamental circuits have been employed to utilise the properties of gasfilled triodes for motor control. Reference should be made to published literature for details of some of the circuits which have been employed.[6.11, 6.12]

Auxiliary Circuits for Closer Speed Control

The amount of auxiliary protective gear for a small motor such as would be controlled by the circuits just described is very limited, but for larger machines a number of protective devices become essential and wider flexibility of control is demanded. This can be secured by employing electronic control of the field as well as the armature circuit. The full details of such circuits are quite involved, and an attempt will therefore be made to give in simplified form some of the essential features of such systems which are included in the Westinghouse Mototrol and G.E. Thymotrol systems of motor regulation.

Before describing some of these circuit auxiliaries it may be well to mention some of the factors which enter into the design of electronic control circuits for medium and large motors.

Apart from the necessity of delayed switching of the valve anode circuits, the electric supply circuit to the motor must be suitably fused to isolate a defective valve and give protection against short circuits on either the A.C. or D.C. side of the system. The highly inductive circuits of the motor field and the anode transformer require the addition of surge arresters to give protection against voltage transients which may occur if either of the valves ceases to function.

When a direct-current motor is fed from a rotary converter there is a considerable reserve of power available for peak loads by reason of the mechanical inertia of the generator and the thermal storage of the mass of material in it, so that prolonged overload within limits can be tolerated. No such similar conditions exist with a simple form of electronic control. The initial starting current of the motor must be limited generally by a resistance in series with the armature, this resistance eventually being shorted out by a contactor with a delayed closure. A thermally actuated relay in series with armature gives overload protection and a resistance may be switched automatically across the armature for rapid braking.

For the purpose of simplification, some of these devices are omitted from the circuits illustrating the following descriptions, and in some cases it will be seen that control by purely electronic means is possible. It must be remembered that where the current is obtained by rectification through gasfilled valves it is an essential characteristic of the valve that the current can pass in one direction only, and cannot reverse to return power to the line by regenerative action in the same way as if fed from D.C. mains or motor generator.

In a similar way, if the motor speed is changed from a higher to a lower one, or if an overhauling load tends to run the motor at a speed higher than that for which it is set, the terminal voltage of the motor will change and must be controlled with suitable gear.

The application of grid-controlled gasfilled valves to motor speed control differs from most A.C. to D.C. rectification circuits in that there is an opposing and variable direct voltage—viz., the back e.m.f. of the motor in the output circuit. This complicates the current wave form, and for details of the analytical and graphical treatment of such conditions reference must be made to specialised articles.[6.13]

The basic circuit for a fully automatic speed control is shown in Fig. 6.8. The following illustrations indicate the principles of some electronic circuits which have been employed for eliminating speed change for load variation, counteracting the variable voltage drop in the armature, overload protection and field control, etc.[6.14]

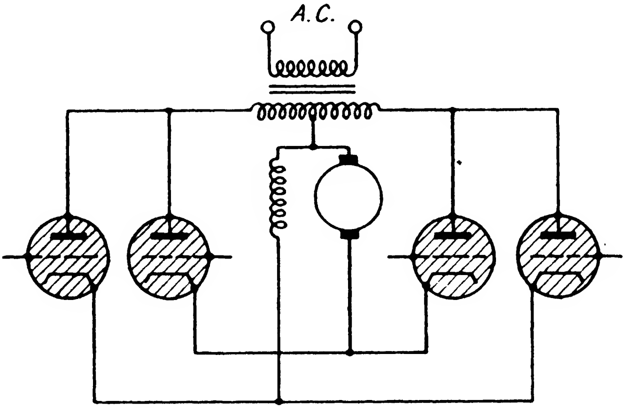


Fig. 6.8.—Basic circuit for fully automatic speed control.

Considering first the case where the field is constant, variation of speed is secured by phase change through a saturable reactor in the common grid circuit of the valves feeding the armature with rectified current. The mean anode current is thus made variable by means of a circuit independent of the field circuit. By making the number of turns of the saturating winding large, the current required in this winding can be kept small enough to be furnished by the anode circuit of a hard valve (V4, Fig. 6.9), and the iron circuit can be designed so that saturation occurs under conditions which produce a sharp voltage change in the grid voltage wave (*q.v.*). The reactor can be connected in a bridge circuit similar to that shown in Fig. 6.9 (*a*). When the direct current through the saturating winding is a maximum, the reactance is a minimum and the grid and anode voltages are almost in phase, resulting in maximum anode current through the valve. As the saturating current decreases, the phase angle changes and the mean anode current is reduced. The dotted semicircle shows the locus of the phase angle of the resultant grid voltage. In the position shown the angle of lag is large and the firing point of the valves retarded. For decreasing angles of lag, the point A moves along a semicircle anti-clockwise. The saturating direct current is provided by a small triode valve.

For the purpose of securing a stabilised and divided source of potential between the D.C. terminals required for the operation of the auxiliary electronic control gear described later a separate rectifier (not shown in Fig. 6.9 [*b*]) fed from the A.C. supply has one D.C. terminal common to the motor circuit and the other terminal

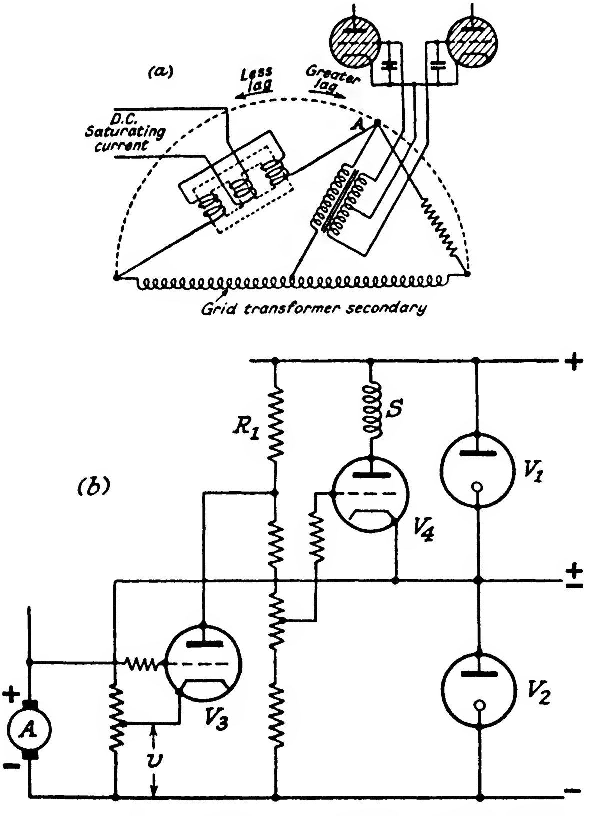


Fig. 6.9.—Compensation for supply voltage variation.

is at an intermediate potential (marked ± in Fig. 6.9 [*b*]) for the auxiliary gear. The voltages between the middle wire and the outers is stabilised by valve voltage stabilisers V1 and V2.

In Fig. 6.9 (*b*) an additional valve V3 is included in the circuit as a phase reversal device to ensure that the current change through the reactor takes place in the right direction.

Supply Voltage Variation

Suppose now the supply voltage changes so that the upper terminal of the motor becomes more positive. This increases the current through V3 and increases the voltage drop across R1. The grid of V4 therefore becomes more negative and reduces the current through the saturating winding S, increasing the phase angle of the grids of the gasfilled triodes feeding the armature of the motor and reducing the current through it. Similarly the motor speed will tend to be stabilised if the armature voltage changes in the opposite direction.

The armature will tend to maintain a voltage which is close to that existing between the cathode of valve V3 and the negative busbar, so that by an independent and preset adjustment of v (Fig. 6.9) by a potentiometer, a change in the normal motor speed level may be secured.

Variable Load

With a constant field, the back e.m.f. of the motor is a measure of its speed. The applied voltage is always equal to the back e.m.f. plus the voltage drop across the armature. Now, when the load increases the armature tends to pull up, which reduces its back e.m.f. and increases the armature voltage drop, which means an increase in the armature current.

If the speed is to be maintained unchanged under the new loading, then the applied voltage must be increased in the same ratio as the increased armature voltage drop, and this control must be provided to maintain constant speed under varying load. Such a control will also compensate for armature reaction in so far as the speed change due to armature reaction is directly proportional to the armature current.

This control can be obtained by the auxiliary circuit of Fig. 6.10. Transformer T has two primary windings, 1 and 2. These are in series respectively with the anode circuits of the two gasfilled triodes supplying the motor armature circuit. These windings are in such a direction that full-wave A.C. appears across the secondary resistance R1. T thus operates as an armature current transformer. The secondary voltage is rectified by V6 and fed through R2, the voltage across which is proportional to the armature current. If now the negative busbar is taken to a point as shown on the resistance and the lower end of the resistance R4 across the armature to a tapping on the lower end R2′ of resistance R2, two voltages will be superposed on the grid of V3: (*a*) one proportional to the armature current, previously referred to; and (*b*) one proportional to the armature voltage drop.

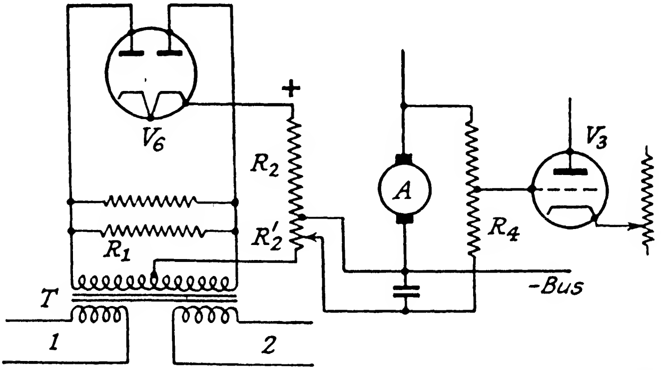


Fig. 6.10.—Auxiliary circuit for compensating for armature voltage drop variation due to varying load.

With increased load on the motor the increased IR drop across the armature makes the grid of V3 more negative so as to increase further the current supplied by the gasfilled triodes to the motor armature until the speed has increased sufficiently to bring the grid of V3 to the voltage level of the slider of the speed-control potentiometer.

Speed Control by Field Adjustment

When a wider range of speed control is demanded, adjustment of the motor field is also adopted, the field circuit being basically controlled in the same way as the armature circuit. One notable difference is that no compensation of the field is required with increasing load. The field (like the armature) is supplied by a similar but independent pair of gasfilled triodes in biphase, from which the magnitude of the current is controlled in a similar way by a saturable reactor in the valve grid circuits.

This part of the circuit is not illustrated, since the principle of operation is sufficiently analogous to that of the armature circuit already described to be understood.

The speed range of the motor can be extended by the addition of field control in this way.

If the field is weakened, the back e.m.f. of the motor is reduced so that the armature current increases to produce the extra torque required to speed up the armature until its back e.m.f. is again sufficient to limit the current to a value necessary to maintain the new speed.

When the gasfilled triodes supplying the armature are delivering maximum current and the armature voltage is a maximum as set by the A.C. anode voltage, no further speed increase is secured by reducing the field.

To prevent the possibility of these two controls, armature and field circuit adjustments overlapping, they may be ganged to one control, so that during the first half of the movement of the knob the armature voltage is progressively increased and during the second half the field is progressively reduced.

There still remains the possibility of the field being preset for high speed, so that to develop the necessary torque while accelerating under load results in excessive armature current. This condition is worst in the starting condition when the back e.m.f. is zero.

Limitation of Armature Current

A further overriding control is required to prevent excessive armature current. The circuits of Fig. 6.9 and Fig. 6.10 are combined in Fig. 6.11 with the addition of a further valve V7, which performs this function and permits the limitation of armature current to be preset so that for a given predetermined speed the armature is accelerated to that speed in the quickest time consistent with load and restriction of armature current.

Valve V7 functions in rather the same way as V5, which compensates for voltage drop in the armature.

The grid of V7 is connected to a point on resistance R2, across which the voltage drop is proportional to the armature current. The point on R2 is selected so that the voltage v_1 makes the grid of V7

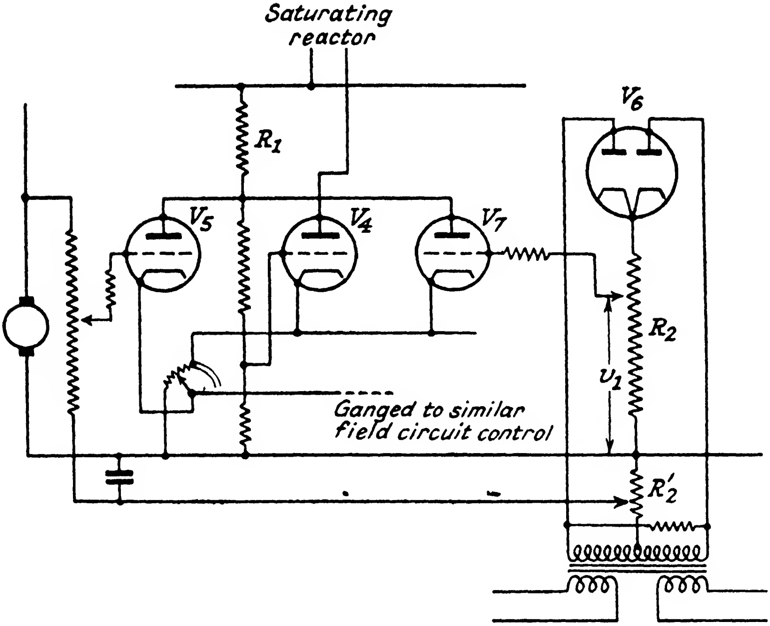


Fig. 6.11.—Overload protection for the motor.

negative to its cathode for all values of armature current below the preset limit. When the armature current exceeds this limit, the grid of V7 becomes less negative and V7 passes current. This increases the voltage across R1, making the grid of V4 more negative, so that less current passes through the saturating winding of the reactor.

The armature current is thus reduced till it is below the limiting value, when the control ceases to operate.

Since the current through the armature must obviously be established before this control can function, it will not be effective in preventing excessive current at starting when the armature current is zero, and without some further device would permit the motor to start with a sudden jolt. In addition, if the field control is set for weak field, its inductance will prevent the field control from being effective at once. Auxiliary contacts are included on the starting contactor to ensure that the gasfilled triodes are prephased in the starting position and the current limited to the preset value.

It will be noted that valves V5 and V7 have a common anode circuit through resister R1 (Fig. 6.11) and both perform the same function though actuated from different sources. Their effects are to some extent additive over a certain range, but V7 is the master control which will take over from V4 whenever the armature current becomes excessive. V4 can operate alone when V7 is inoperative.

In a similar manner the potential across part of resistor R2 (Fig. 6.11) can be communicated to another triode acting as an intermediary in the control of the field intensity, so that excessive current in the armature will also increase the field strength. In this case the controlling valve is required to produce a change in reverse direction —*i.e.*, to increase the field current for increased armature current— and the circuit must be modified to ensure this condition.

Both of these adjustments may be included in the control gear of the same motor, so that if the circuit has been preset for an ultimate speed involving a weak field, the control will force the field to full intensity during the accelerating period.

By suitable selection of the voltages applied to the intermediary valves the field intensity adjustment can be made to operate slightly in advance of the armature voltage adjustment. Consequently, with a slowly applied overload the field will at first be increased to a maximum, followed, if still uncorrected, by reduction of the armature voltage until such time as the motor speed is accommodated to the new load. At the same time this does not prevent the two controls acting simultaneously on a large or suddenly applied overload.

The flexibility of speed control is perhaps most apparent under conditions of heavy load, where the motor can with perfect safety be stalled without any danger of burning the armature out or blowing the main fuses, either or both of which may occur if a motor is stalled when driven from supply mains.

Other Features.—Besides the main control elements referred to, there are a number of auxiliary and protective devices which ensure foolproof operation and which cannot be described in detail here. Reversal of a motor is secured by means of a reversing contactor which changes the current direction through the armature. Anti-hunting circuits comprising suitably designed RC networks are included to provide time elements at certain points of the circuit, without which the high amplification of the valves would make the regulation erratic and impracticable. Voltage filter circuits are also included to avoid possible disturbances through voltage transients. Reference should be made to the published articles quoted for more detailed information.

Fig. 6.12 illustrates the Thymotrol principles of motor control utilised in this country by the B.T.H. Co., and this diagram shows all the control devices for a non-reversing motor previously outlined individually and brought together in one complete circuit.[6.15]

The armature and field circuits are biphase circuits fed respectively from gasfilled triodes TA and TF. A line contactor CR is provided for the armature circuit when closed; this completes the armature circuit through the series field coil. When open, resistance DBR across the brushes secures rapid braking.

The valves AA, BA, CA provide the various controls for the armature circuit, as previously explained. The ganged armature and field rheostats are shown here by PA and PF for presetting the motor speed, resistance variation taking place over opposite halves of these two potentiometers, so that field is not varied until a speed outside the base speed is selected. A fixed resistance between PF and contact CR " b " limits the voltage range of PF to a value suitable for the motor used. BF is the load-limiting valve for the field circuit, and the difference in connection from its armature circuit counterpart BA will be noted, since it has to operate to give current change in the reverse direction. The full-wave rectifier valve of Fig. 6.11 is here shown by valve K and the primaries of the transformer CTS are indicated by CTP.

The line contactor CR is under the control of start and stop push buttons. A field circuit relay FR has a contact FR " a" in the coil circuit of CR, and until field current is established the line contactor cannot be closed.

CR has a contact CR "b" in the circuit of rheostat PF. Since this is open at the moment of closing the contactor the field current is a maximum, since CF is then non-conducting. At the same time CR has a contact CR "e" connecting R8 to the positive terminal of the D.C. supply. Since this contact is closed at the moment of closing the contactor, the grid of BA is made positive and the armature triodes TA are cut off. When the contactor closes, therefore, the armature voltage is zero and the shunt field current a maximum. Acceleration then takes place at constant current until the speed attains the preset value.

Fig. 6.12 (*b*) shows the speed torque curves obtained from a 1 h.p. compound wound motor with and without armature voltage drop compensation. The IR drop compensation was set to give level speed compounding at 20 per cent. of the speed at normal armature voltage

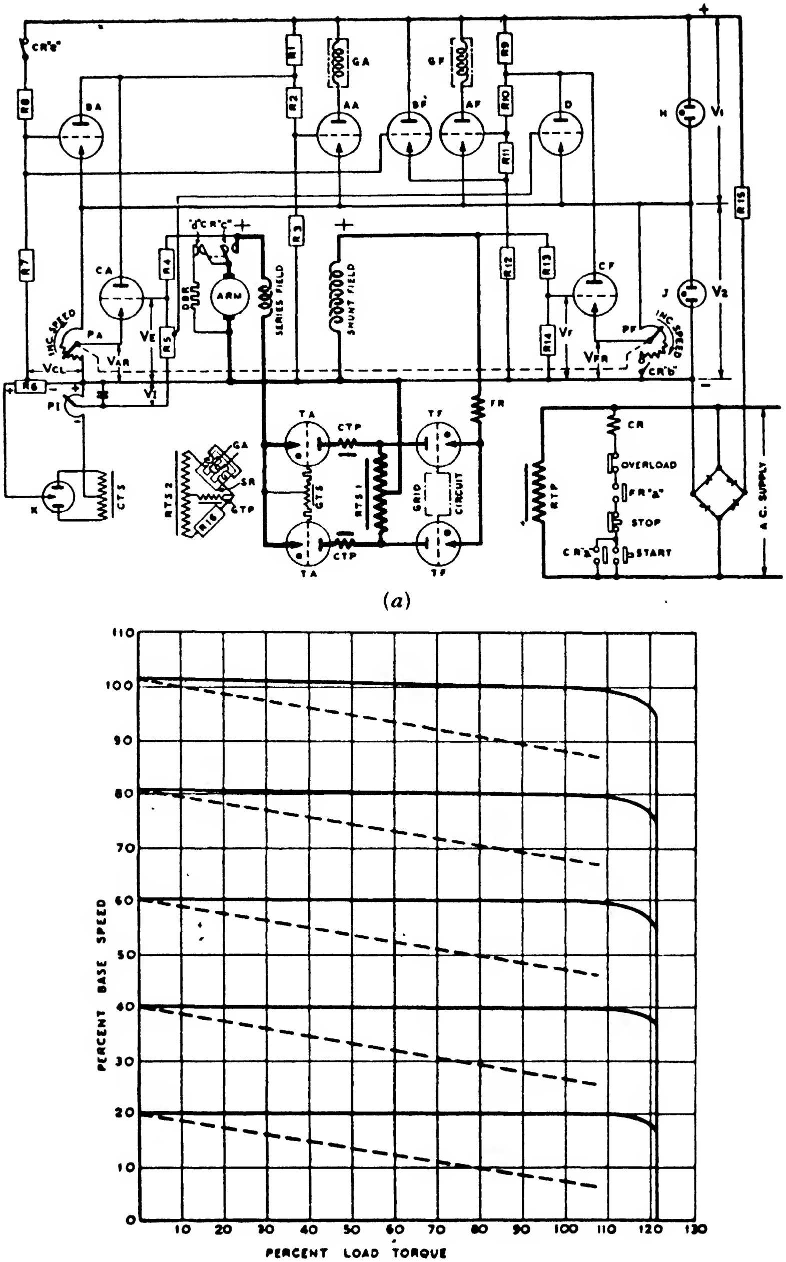


Fig. 6.12.—(*a*) Circuit diagram and (*b*) performance characteristics of the Thymotrol electronic motor control system. (B.T.H. Co.)

and field current. The size of motor which can be controlled is, of course, determined by the size of triodes which can be made available, and the method of rectification varies with the size of motor controlled. Three- and six-phase rectifier circuits are used for large motors. The principles of the auxiliary control circuits are practically the same for any size of motor, though for small ranges of speed adjustment shunt field control is dispensed with.

Motor control of the type just explained has a wide application in industry. It has been employed in the steel[6.16] industry and for automatic control of steam generators where remote control in conjunction with selsyns has been secured for the supply of fuel and water to a steam generator, enabling combustion to be adjusted automatically according to the output of the generator.[6.17] Another use in generation has been its control of a turbine governor motor according to the load, indications from frequency and line-load recorders.[6.18] "Raise" and "lower" indications are set out from the controllers at two-second intervals. Flow of current in the control circuit in one direction indicates a call for increased output and vice versa. The grid circuit of the triodes is selected by a polarised relay which distinguishes current direction and determines the direction in which the control motor, which has a double-wound series field, is driven, so that variations in the demand on the line are automatically adjusted from the generator.

Another example of the many applications of electronic motor control occurs in driving gear on winding reels for metal strip where constant tension on the wound material is required. The voltage for the motor is preset to a mean and is thereafter variable by the control to give a speed range of 4 : 1. Constant armature current is maintained in the motor, and as the size of coiled strip increases the motor slows down to provide constant tension in the metal. Reduction gearing is used in the case of slow winding speeds, and since the winding tension is determined by the mechanical friction, the control of the winding-reel motor field must be operated from a tachometer generator driven by the strip. Instead of operating as a current regulator, the equipment then functions as a speed regulator, holding the strip speed constant by slowing down the winding-reel motor as the coil diameter increases.[6.19]

Constant Speed for Small A.C. Operated Motor

Another and slightly different circuit arranged described by Whiteley[6.20] enables constancy of speed to be secured from A.C.

supply irrespective of load or voltage fluctuation over a fairly wide range (Fig. 6.13). In this respect it resembles the straightforward A.C. synchronous motor, but with the difference that the speed can be preadjusted from one constant value to another. It is of interest, inasmuch as it employs the grid control described on page 71. It constitutes a Ward Leonard set with a speed regulation and can be applied to polyphase supply if required.

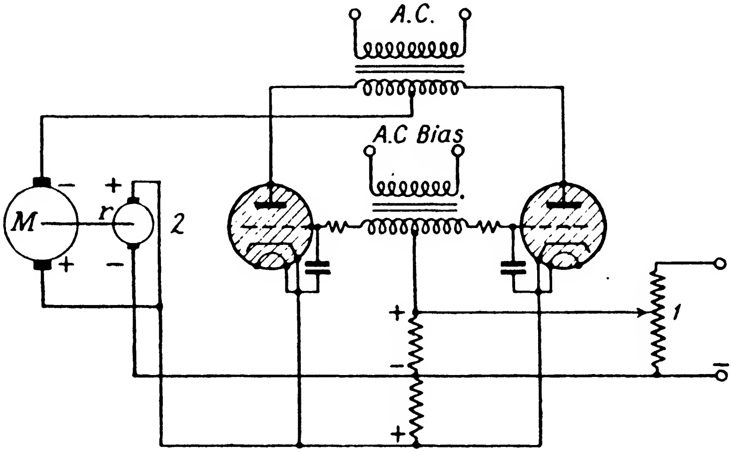


Fig. 6.13.—Another method of securing constant speed from a D.C. motor on A.C. supply.

The grid is controlled by two voltages in opposition, one from a potentiometer 1 acting as a preset speed level adjustment, and the other from a pilot generator 2 driven from the motor shaft, this voltage being proportional to the motor speed. Superposed on the grid is an alternating potential of a few volts fed through a transformer from the supply mains. The resultant direct voltage has the effect of displacing the A.C. grid voltage vertically, as shown in Fig. 3.12A, page 71, in one direction or the other. As there described, this method of control owes its effectiveness to the fact that while the A.C. grid potential is only a few volts, the voltages due to the direct-current sources are of the order of 25 or more. A 1 or 2 per cent. change in the latter voltage will thus be sufficient to change the rectified output over its whole range from zero to a maximum. The motor speed is automatically controlled at a setting of potentiometer 1, where this voltage is offset by that of the pilot generator 2. The fact that the rectifier output is smoothly adjustable over its whole range largely eliminates any tendency to hunt, which is a frequent feature of automatic control of rotary machines.

The circuit of Fig. 3.12B, page 73, has also been applied to motor speed regulation with certain modifications to secure adequate voltage regulation and other overriding safety controls.

The chief modification of Fig. 3.12B is in the grid circuit of V1, the voltage of which is made automatically adjustable to secure self-regulation.

For this purpose the valve cathode is connected to a D.C. voltage, the negative pole of which is tied to the centre point of the secondary of the anode transformer and thus constitutes a reference voltage. The grid of V1 is connected to a potentiometer across the load. If the output voltage rises, v_g also increases so that the grid of V1 becomes more positive with respect to its cathode and the firing point of the thyratrons is retarded, giving a reduction in output, and vice versa.

A full wave rectifier fed from the thyratron anode circuit provides a current proportional to the motor armature voltage drop, and this current passed through a resistance provides a signal voltage which can be injected into the grid of V1 to compensate the motor armature drop.

Further modifications limit the maximum current which the motor can take and so provide overload and maximum acceleration protection.

Current Control by Reactors

When the current feeding a load on an alternating supply system has to be varied within wide limits, the use of a grid-controlled gas-filled valve in conjunction with a saturable reactor sometimes offers an efficient alternative to the obvious method of control with adjustable series resistance. Such a case occurs with a lamp load for theatre lighting, where the illumination is required to be varied at will in imperceptible stages from darkness to full brilliancy. This is the example of such forms of reactor control most generally quoted, but the principle obviously has applications in other directions.

Control by series resistance is wasteful in power when the current is heavy and the heat developed may be difficult to dissipate with safety. If the control point is not near the load, the cables between the two must be large enough to carry the full current. The use of a tapped transformer with a load tap changing gear offers an alternative, but this again needs heavy cabling between the load and the control point.

Reactor control has the advantage that the control current can be made quite small—of the order of 5 per cent. of the load current. The general principle of the saturable reactor will be familiar from the previous references made to it as a variable inductance for securing phase shift of the grid voltage of a triode. In the case now under review the A.C. windings 1 of the reactor are in series with the load (Fig. 6.14), and the inductance in the load circuit may be reduced from a maximum to a minimum by increasing the ampere turns of the saturating winding 2. If the number of turns of the D.C. winding 2 is made large, the current required is correspondingly reduced and may conveniently be supplied by a gasfilled triode quantitatively controlled by grid phase change by methods previously referred to.

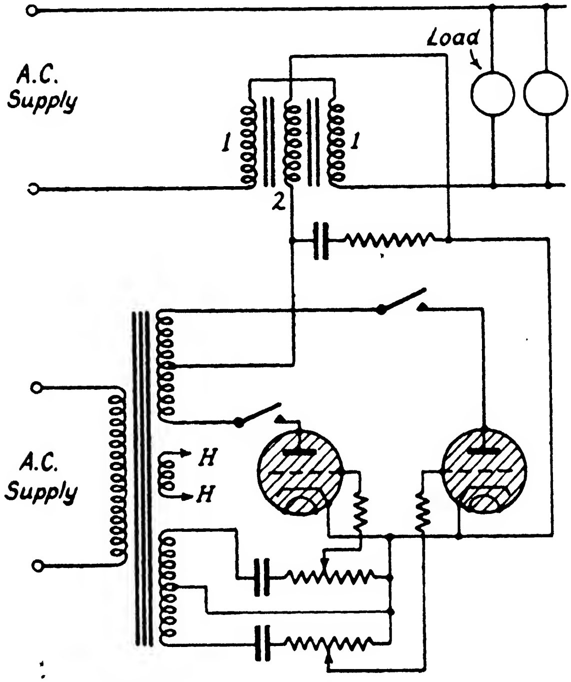


Fig. 6.14.—Two gasfilled triodes in biphase controlling an A.C. load through a saturable reactor.

A circuit in which two triodes in biphase are used for supplying the saturating winding is shown in Fig. 6.14. Several methods are possible for connecting the two A.C. coils. The coils on the outer limbs can be connected in parallel or may be divided, the two halves of each coil being parallel connected with the two limbs in series. The loading of the choke is determined by the heat produced in the coils. If the load varies widely, the choke may preferably be provided with tappings to deal with different loads. For any given number of turns on the A.C. coils there is a minimum value of load if a complete black out (lamp load) is required with no saturating current passing. When the choke is fully saturated there is a voltage drop of the order of 5 per cent. of the load voltage across the reactor.

Compensating Reactor Voltage Drop

This voltage drop can be compensated in one of several ways. One method for a lamp load is to use lamps of a voltage lower than the mains voltage, but this has the disadvantage of having possibly lamps of two different voltages on the same installation. Alternatively, the voltage may be boosted by one of the methods shown in Fig. 6.15. If the supply voltage is boosted, of course one transformer can deal with a number of chokes; but if the voltage is corrected on the load side, one transformer per circuit is required.

In the latter case, since the voltage gain depends on the voltage output of the choke, the transformer is effective only at full saturation, and at zero saturation acts simply as an additional choke. On the other hand, with this method of correction the choke is capable of handling larger loads, whereas if boosting takes place on the supply side its capacity is decreased, since more turns are required for the same minimum load voltage.

The ratio of self-inductance to resistance for the choke should be as high as possible. The saturating coil constitutes a highly inductive load on the gasfilled triode and the grid control is not at all uniform. Most change in anode current occurs when the firing point is in the 85° to 90° range after the start of the corresponding positive anode voltage.

In Fig. 6.14 the parallel resistance and condenser are added to reduce the effect of the inductance of the saturating coil.

Another method[6.21] employs a parallel connected rectifier across this winding to pass current in the reverse direction to the coil excitation current.

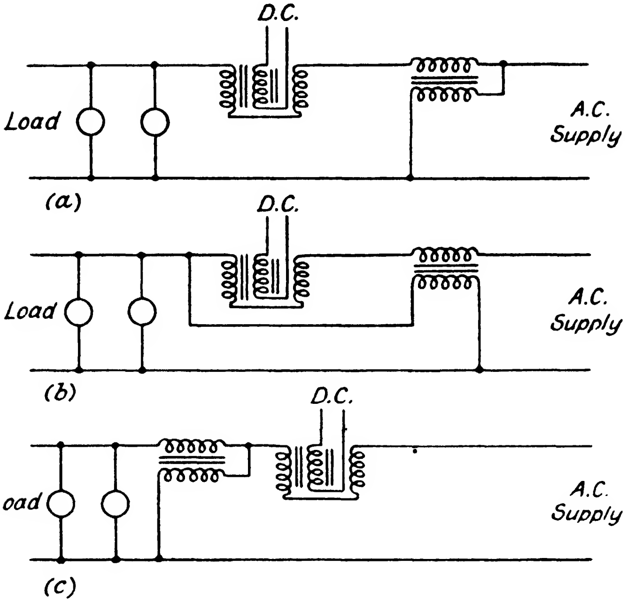


Fig. 6.15.—Alternative methods of boosting the load voltage to balance voltage drop in a reactor under saturation. (*a*) and (*b*) boosting on the supply side; (*c*) boosting on the load side of the choke.

This provides a short-circuit path to the peak reverse voltage and effectively reduces the inductance.

Other methods include winding the saturating coil on an upper former or including short-circuited windings round the D.C. iron path by connecting the A.C. windings on the outer limbs in parallel.

If the choke is tapped to handle different ranges of load, the whole A.C. winding could be used only on light loads and the outer turns can be of smaller gauge wire to reduce copper losses.

Since the reactor carries both direct and alternating currents, a strong vibrating magnetic field is produced which is most intense at the middle of the leg. This calls for particular care in construction of the choke to avoid mechanical stresses and makes it necessary to minimise the possible displacement of the conductors, which may, if allowed movement, result in abrasion of the insulation.

The use of gasfilled triodes for providing the direct current for the saturating winding is, of course, not essential for reactor control. If any alternative direct-current supply is available, this can be employed or a rectifier can be fed from the A.C. supply, in either case simple resistance adjustment of current being used. Since, however, the choke is very sensitive to current changes near its maximum inductance, the controlling resistance will need to be suitably graded and may be found to require an inconveniently large total value. A variable direct voltage is preferable, and consequently a potentiometer will be found to give more reliable adjustment.

In either case the simplicity of current control through phase change in the grid circuit of a gasfilled valve is lost.[6.22]

Voltage Pulse Generators 6.26

Means of generating Square Wave Single or Multiple Voltage Pulses.—Gasfilled triode circuits under this heading are special cases of timing circuits dealt with in Chapter 4. Typical of its class designed as a means of securing square wave single-voltage pulses is the circuit shown in Fig. 6.16. It was developed[6.23] originally for research on thermionic emission of oxide-coated valve filaments where it provided the necessary means of applying the anode voltage to a valve for a very short period. It affords an alternative method to circuits involving timed contacts where it is difficult to avoid sparking when the current exceeds about 0·5 amp., since it is effective over a wide range of current from milliamperes to many amperes determined by the size of the valves employed.

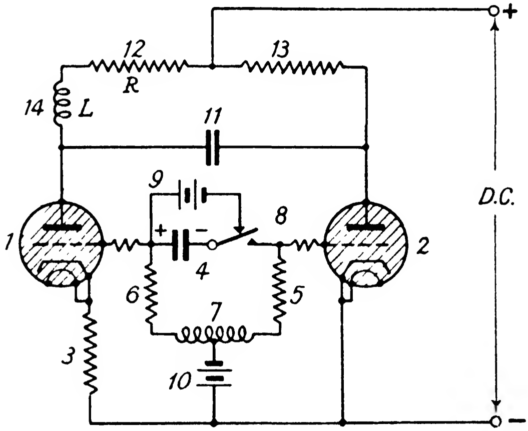


Fig. 6.16.—Generator of single square wave pulses.

This circuit is another example of the many applications of a parallel connected pair of gasfilled valves and provides a method of switching a direct current of wide range of magnitude for an accurately determined period without distortion of the wave form in the switching circuit.

The timing, which is carried out by current in one valve, is controlled by a damped oscillatory circuit which fires this valve at the start of the pulse and fires the second valve at the termination of the period, which operation also resets the first valve.

In the circuit of Fig. 6.16 valve 1 acts as the switch to start the voltage pulse. The load resistance 3 is included in the cathode lead of this valve. The oscillatory circuit consists of condenser 4, resistances 5 and 6, and inductance 7. The natural period of the generated voltage pulses is determined by the constants of this circuit.

With the switch 8 in the position shown in Fig. 6.16, condenser 4 becomes charged to the polarity shown to the full potential of battery 9 and the battery 10 applies negative bias to both valve grids so that no current passes through either of them.

When the switch 8 is moved to its lower position the positive potential on condenser 4 is applied to the grid of valve 1 and overcomes the negative bias so that this valve fires at once, while at the same time the negative bias on valve 2 is increased.

After about a quarter of the period of one oscillation the potential on condenser 4 reverses and fires valve 2, at the same time cutting off the discharge in valve 1 through the action of condenser 11, as previously explained.

If the values of the resistances 5 and 6 are suitably chosen, the damping of the oscillatory circuit is such that the grid voltage of valve 1 is not again brought below the critical negative value during subsequent oscillations, and therefore only one pulse of current passes through valve 1, though the current through valve 2 continues until its anode voltage is interrupted. A double pole switch is employed for resetting the circuit, so that the anode circuits of both valves are interrupted simultaneously, otherwise the charge on condenser 11 is liable to cause valve 1 to fire again when the current in valve 2 is cut off.

By reason of the difference in the charging and discharging currents of condenser 11 the wave forms of the voltage due to the current surges through resistances 3 and 12 are not the same.

If the inductance 14 is absent and the resistances are not inductive, the wave form of the current in the load resistance 12 is that shown in Fig. 6.17 (*a*), the termination of the exponential curve being due to the discharge of condenser 11 and its charge in the reverse direction by the current passing through valve 2 from the D.C. supply.

The wave form of the current through the cathode resistor 3 is similar to that shown in Fig. 6.17 (*b*), the initial peak being due to the charging current of condenser 11 which passes through resistance 13, valve 1 and the D.C. source. The inclusion of the inductance 14 in the anode circuit of valve 1 delays the growth of current through resistance 12 at the instant of switching. It thus produces an effect in direction and magnitude opposite to that of the condenser charging current. As a result, a square wave current pulse is produced in resistance 3, hence the reason for including the load in the cathode circuit of valve 1. The necessary condition for the operation of this circuit is that resistances 12 and 13 shall be equal and that $L=CR^2$.

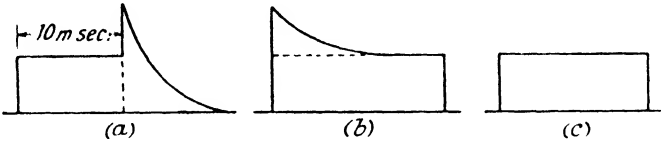


Fig. 6.17.—Current wave forms in circuit of Fig. 6.16. (*a*) Current in anode resistance 12 without inductance L. (*b*) Current in cathode resistance 3 without inductance L. (*c*) Current in cathode resistance 3 with inductance L.

Other wave forms resulting from modifications of the circuit are given in the original paper.

The author states that times of current flow down to one millisecond are readily obtainable and by an extension of the circuit, periods up to 20 secs. are possible. In the latter case, since the inductance and condenser would become inconveniently large, an alternative to the original form of damped oscillator circuit is used. This consists of a neon lamp and condenser, the latter charging from a battery through a high resistance, a conventional arrangement widely used for delayed-action and timing circuits.

This auxiliary circuit is connected so that valve 1 fires when the condenser charging circuit is closed. When the condenser potential reaches a certain point, the neon lamp flashes and the reduction in condenser voltage fires valve 2 and resets valve 1.

In some cases where circuits of this kind are used, the exact wave form may not be material; in others, the type of compensation referred to may have to be applied in varying degrees according to the precision of wave form desired.

If the grid circuit of the valves is driven by an alternating voltage in place of the oscillatory circuit, square wave pulses occurring at regular frequency and of duration equal to a half-period of the driving frequency may be secured.

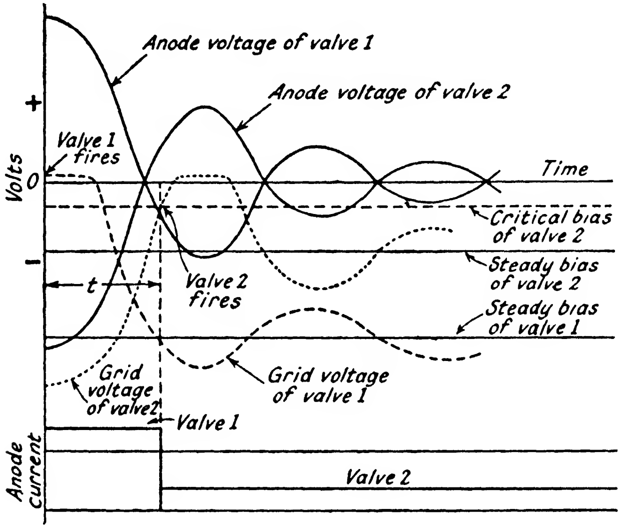


Fig. 6.18.—Wave forms in the circuit of Fig. 6.16.

One method is to superpose an alternating voltage on the negative bias of a pair of triodes so that during one half-cycle the grid potential passes the critical value and at a corresponding instant during the next half-cycle the second valve fires and resets the first. The conducting and non-conducting periods are thus constant, but are not independent of each other. They can be altered by changing the frequency, but the circuit offers some difficulty in adjustment if the output impulse is required to be variable while the driving impulse frequency is constant.

A method of securing a variable frequency source[6.24] utilises a pair of gasfilled triodes in an inverter circuit, the frequency being controlled by a potentiometer and condenser across the cathode return leads of the valves. The output of this inverter circuit is fed to the grid circuit of a further pair of triodes through the primary of a transformer which has two separate secondaries, each connected to the grid of one triode, so that the grids are always in phase opposition. A separate direct-current source provides grid bias for these valves, which do not fire in the absence of any A.C. driving impulses.

Firing impulses are thus given to each valve alternately, while the commutating condenser across the valve anodes performs the resetting operation. A meter in the cathode of one of the triodes measures the mean anode current, which is proportional to the ratio of the conducting period to the time of one complete cycle.

Peaked Voltage Generators

The necessity for producing peaked voltage pulses of short duration of the order of 1 to 100 microseconds occurs in connection with many investigations involving the measurement of short time intervals—*e.g.*, transmission and refraction of high-frequency waves in radar, ionosphere measurements, altitude meters, etc.

A circuit in which the frequency of recurrence is the same as that

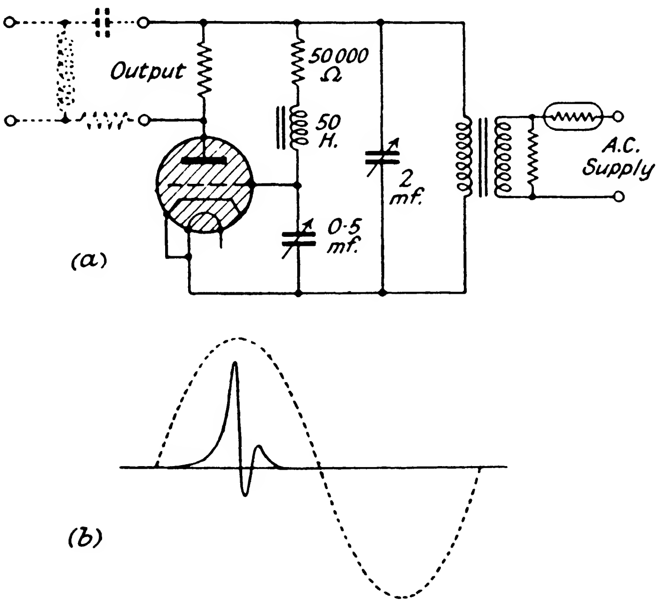


Fig. 6.19.—(*a*) Pulse generator in which the phase of the firing impulse is controlled with respect to the supply; (*b*) peaked pulse secured by addition of dotted network to output circuit.

of the driving supply frequency and in which the phase angle between grid and anode voltage is such that the valve fires at the peak of the anode voltage provides a convenient means of generating steep-fronted pulses.[6.25] The current wave form, which with a resistive anode load in the valve circuit will be approximately sine wave for the positive voltage half-cycle, is modified to produce a highly damped oscillation having a large initial amplitude giving the required voltage peak by the addition of a condenser and inductive network across the anode load, as shown in Fig. 6.19 (*b*).

Peaked voltages of this kind may be employed to initiate the oscillation of a squegger type of circuit. The voltage pulse may be fed in series with the bias to such an oscillator circuit in which the valve anode is supplied from an alternating source so that the valve fires only at the peak of the supply voltage, or a series modulator valve may be included in the anode lead to the oscillator valve, the modulator being controlled by the trigger circuit.

A more efficient method than the use of a modulator valve, since the gasfilled triode has an almost negligible voltage drop across it in the conducting condition, is to employ the valve as a switch in the anode high-voltage lead to an amplifier valve or oscillator, so that current passes in the circuit only when the gasfilled triode is fired. A

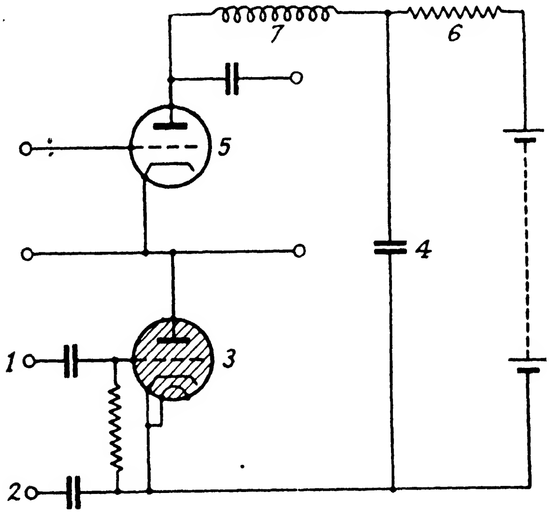


Fig. 6.20.—Thyratron control of radio frequency valve giving time adjustment of the duration of voltage pulses.

peaked voltage pulse such as that generated by the circuit of Fig. 6.19 can be fed at the required recurrent frequency to the terminals 1.2 of the gasfilled triode 3 in the circuit of Fig. 6.20, so that each time the triode 3 is fired the condenser 4 discharges through this valve and the vacuum triode 5 in series, causing the anode voltage of the gasfilled triode to drop and cut off the current through both valves. The time constant of the charging resistance 6 and condenser 4 must be such that the condenser can recharge during the period the current is cut off. The high-frequency choke 7 prevents the output terminals of the valve 5 being short circuited to current of radio frequency.

This circuit enables the duration of the voltage peaks to be varied according to the rate of condenser discharge as determined by valve 5.

More recently, study of the subject of the design of voltage pulse generators has resulted in the development of special valves for this purpose.

GENERAL REFERENCES

(*a*) *Voltage Controllers.*

(i) **Burbank**, A thyratron voltage control, *Rev. Sci. Inst.*, 7 (November, 1936), p. 427.
(ii) **Weinland**, Thyratron voltage regulator for an alternator, *Rev. Sci. Inst.*, 3 (January, 1932), pp. 9-19.
(iii) **Pinciroli** and **Francini**, Motor generator electronic control, *Alta Frequenza*, 10 (October, 1941), pp. 581-8.

(*b*) *Motor Control.*

(i) **Mayer-Delius**, Motor operation with grid-controlled mercury arc rectifiers, *V.D.E. Fachberichte* (1931), pp. 26-9.
(ii) **Lichine**, Speed control, *Comptes Rendus*, 197 (July 17, 1933), p. 223.
(iii) **Norwag**, Speed regulation by grid-controlled rectifiers, *V.D.I.*, 83 (July, 1939), pp. 827-33.
(iv) **Moyer** and **Palmer**, Thyratron motor control, *Trans. Am. I.E.E.*, 62 (November, 1943), pp. 706-12.
(v) **Leigh**, Simplified thyratron motor control, *G.E. Rev.* (September, 1946), p. 18.
(vi) **Norris**, Speed control of motors—a new thermionic motor speed regulator, *Electronics*, 8 (1935), p. 244.
(vii) **Williams**, Combined thyratron and tachometer speed control of a small motor, *Electrical Engineering*, 57 (October, 1938), p. 565.
(viii) **Tottle**, Speed control of small A.C. motors, *Electronics*, Vol. 21 (February, 1948), pp. 106-9.
(ix) **Jaeschke**, Thyratron braking for oil drilling rigs, *Electronics*, Vol. 21, No. 4 (April, 1948), p. 92.
(x) **Green** and **Jaeschke**, Reliable electronic controls for fan and stoker drives, *Elect. World* (November 23, 1946), p. 75, and (December 7, 1946), p. 96.

(*c*) *Voltage Pulse Generators.*

(i) RAJAM, A thyratron operated wave generator, *Journ. Sci. Inst.*, 13 (October, 1936), p. 331.
(ii) PEUGNET, A source of variable rectangular pulses, *Rev. Sci. Inst.*, 8 (September, 1937), pp. 340-2.
(iii) DREWELL, Operation of grid-controlled gas discharge tubes for production of oscillations, *Zeits. f. tech. Phys.*, 17, No. 8 (1936), pp. 249-62.

CHAPTER REFERENCES

6.1. GULLIKSEN, An electronic voltage regulator for D.C. generators, *Electrical Engineering*, 55 (1936), pp. 873-5.
6.2. WHITELEY, The grid-controlled rectifier or thyratron, *Journ. I.E.E.*, Vol. 78 (1936), p. 516.
6.3. WHIPPLE and JACOBSON, Thyratron regulator for an alternator, *Electrical Engineering*, 54 (June, 1935), pp. 663-7.
6.4. SPORN and LANGDON, Thyratron voltage regulator, *Electrical World*, Vol. 105 (1935), p. 1182.
6.5. *Ibid.*, Thyratron excited condensers, p. 1582.
6.6. BENSON, Electronic regulators for A.C. generators, *Electronics*, Vol. 16, No. 4 (April, 1943), p. 104.
6.7. PATCHETT, The characteristics of lamps as applied to the non-linear bridge as the indicator in voltage stabilisers, *Journ. I.E.E.*, Measurements Section, Vol. 93, Part III (September, 1946), p. 305.
6.8. BENSON and HEIDBRAK, Electronic exciter for A.C. generators, *Electronics*, Vol. 16, No. 8 (August, 1943).
6.9. RYDER, Electronic control circuits for D.C. motors, *Electronics*, 11 (December, 1938), p. 21.
6.10. GARMAN, Thyratron D.C. motor control, *ibid.*, 10 (June, 1937), p. 20.
6.11. ——, Thyratron control of D.C. motors, *G.E. Rev.*, 41 (April, 1938), p. 202.
6.12. ALEXANDERSON and MITTAG, *Electrical Engineering*, Vol. 53 (1934), p. 1517.
6.13. FLUKE, Operation of vapour tube rectifiers with opposing direct voltages, *Electronics*, Vol. 16, No. 6 (June, 1943), p. 100.
6.14. MOYER, Electronic Control of D.C. motors, *Electronics*, Vol. 16, No. 5 (May, 1943), p. 98; No. 6 (June, 1943), p. 119; No. 7 (July, 1943), p. 118; No. 9 (September, 1943), p. 133; No. 10 (October, 1943), p. 128.
6.15. FORSTER, Thyratron motor control, *B.T.H. Activities*, 19 (January, 1946), pp. 32-3.
6.16. LAWSON, Wide motor speed range with A.C. supply, *Steel* (June 21, 1943), pp. 106-8.
6.17. POTTER and others, Thyratron and selsyn control of high-pressure steam generators, *Power*, 75 (April 19, 1932), pp. 584-8.
6.18. ——, Thyratron rectifier controls steam turbines, *Electrical World*, (July 21, 1945), pp. 68-9.
6.19. HOPPER, Electronic drives on winding mills for metal strip, *Steel*, Vol. 116, No. 22 (May 28, 1945), pp. 132-5.
6.20. WHITELEY, Applications of the grid-controlled hot cathode rectifier or thyratron, *Journ. I.E.E.*, Vol. 78 (1936), p. 516.
6.21. Brit. Pat. 384,246.

6.22. SCHNEIDER, Thyratron reactor lighting control, *Trans. Am.I.E.E.* (1938), p. 328.
6.23. MADDOCK, The generation of current pulses of rectangular wave form, *Proc. Phys. Soc.*, Vol. 43, No. 239 (July, 1931), p. 371.
6.24. PRESSEY, A thyratron impulse generator, *Journ. Sci. Inst.*, Vol. 15 (1938), p. 163.
6.25. BUILDER, Wireless apparatus for the study of the ionosphere, *Journ. I.E.E.*, Vol. 73 (1933), p. 419.
6.26. VAN DEN BOSCH, Gasfilled tubes as pulse generators, *Electronic Engineering*, Vol. 17, No. 206 (April, 1945), p. 474.

CHAPTER 7

Commutating Devices

Current rectification. Filter circuits. Harmonics. The grid circuit-phase displacement. Arrangement of heater circuit. Compounding. Misfires and backfires, etc. Inverters—parallel type. Automatic switching. D.C. conversion. Series type of inverter. Voltage regulation. Large inverters. Practical applications. D.C. transmission. Commutator-less D.C. motors.

Current Rectification

SINCE the gasfilled triode is essentially a controlled current rectifier, some reference to its utility as a means of furnishing direct current from an alternating electric supply is obviously called for, though the broad principles involved in the use of these valves for such purpose will be obvious from the foregoing text. Grid control provides a means of adjusting the direct-current output from zero to a maximum by methods previously described and by the use of a control unit of almost miniature dimensions with negligible power consumption. The constant voltage drop across the valve results in increasingly higher efficiency of conversion as the size of the valve and current output are increased. Moreover, protection against overload is easily secured within a very short interval, often in the time of half a cycle of the applied alternating voltage, by suppression of the firing of the valve when the output current exceeds a specified value. Regulation of the output voltage can be secured by a method of compounding which automatically adjusts the grid firing point according to the direct-current load. The same principle can be applied to block the valve when the output becomes too large.

A particular instance of the use of grid-controlled rectifiers is for providing a high anode voltage for radio transmitting valves (7.1). Rectifier units may comprise a single valve giving half-wave rectification or a biphase connected pair giving full-wave rectification on a single-phase supply. Similar single valves or two valves in inverse parallel in each phase will provide half- or full-wave rectification on a polyphase supply. The conditions under which parallel of operation of similar valves can be employed to secure larger output with stability of operation have already been referred to on page 82. Attempts to use valves of dissimilar characteristics in parallel should be avoided, since large unbalanced loads are likely to result.

As previously explained, flexibility of control of the direct-current output can be secured by the use of a form of grid control which has both steady and alternating components. In principle any of the circuits involving valves with thermionic cathodes may be applied sometimes with certain modifications to multi-electrode valves with mercury pool cathodes, each anode of which has its corresponding control grid.

Though the controlled mercury discharge form of rectifier with thermionic cathode finds considerable application as a source of direct current up to a few amperes, much wider use is made in industry of the larger units which involve mercury pool cathodes for handling currents beyond the capacity of the thermionic cathode. The two types of rectifier have many features in common, but they have distinct fields of application, and it is proposed to deal only with those devices having thermionic cathodes and refer to certain aspects of their use more particularly on single- and three-phase circuits. Literature is already in existence in which large-power arc rectifiers have been adequately dealt with.[7.2]

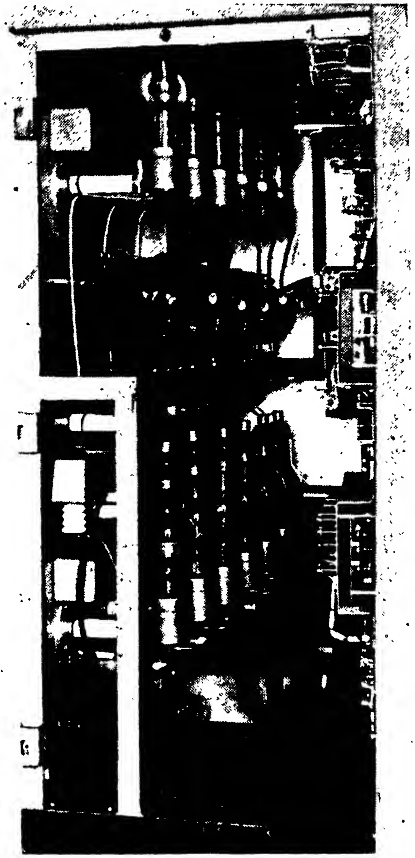


Fig. 7.1A.—Dual bank of grid controlled rectifiers for 100 kw. industrial radio frequency heating installation.
(*Westinghouse Electric Co.*)

Filter Circuits [7.3]

To give a steady voltage on the D.C. output from the rectifier a smoothing network is essential. Condenser input filters should, however, not be used owing to the high transient peak currents which occur during the condenser charging portion of the cycle. An inductive input filter (Fig. 7.1*a*) should be included, since the effect of the inductance, being opposite to that of a condenser, suppresses the peak currents, and tends to reduce the form factor of the current through the valves and transformer. Its effect, therefore, is to improve greatly the regulation of the rectifier circuit and increase its efficiency as a converter.

If the inductance is greater than a certain critical value, the flow of current, though fluctuating in magnitude, will be continuous and maintained through each valve in turn, even after the anode voltage has become negative, until the next valve takes up the discharge instead of being broken up into a series of pulses separated from each other by periods of non-conduction. The mathematical analysis of the circuit and deduction of the critical value of the inductance has been published elsewhere.[7.4, 7.5]

If the load is changed so that the filter inductance is no longer greater than the critical value for continuous conduction, one valve will be extinguished before the next one fires and the cathode voltage of the second valve changes suddenly to the potential of the positive output terminals of the rectifier. This results in the anode voltage of the second valve becoming negative to its cathode at the point where it is supposed to fire, so that this valve will either block or will fire late according to the type of circuit used and will induce transient surges in the system which may build up into sustained oscillations in the output voltage.

When the choke is greater than the critical valve the operation of, say, a biphase rectifier is as shown in Fig. 7.1 (*b*) and a three-phase half-wave rectifier as in Fig. 7.2. In the latter case Fig. 7.2 (*a*) represents the condition of maximum output where the discharge is transferred from one valve to the next at the point where their phase voltages become equal. If the point of current transfer is delayed, the delay angle a is measured from the time represented in Fig. 7.2 (*a*) by the line OY. The positive direct-line voltage is represented by the heavy line and is equal to the voltage of the particular valve which is passing current less the voltage drop across this valve, since all the cathodes are connected together and form the positive terminal of

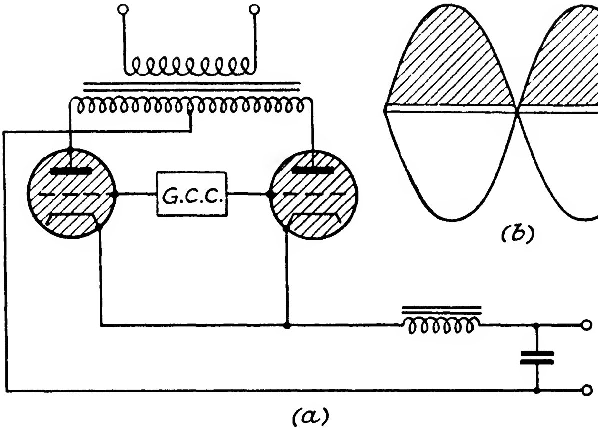


Fig. 7.1.—Biphase grid controlled rectifier with inductive input filter.

the direct-current supply. In Fig. 7.2 (*b*) $a=\frac{\pi}{6}$ and in Fig. 7.2 (*c*) $a=\frac{\pi}{3}$, indicating that each valve continues to pass current until the next one fires. In the latter case, each valve passes current during a portion of the cycle when its anode potential is more negative than the negative output terminal of the rectifier, and at the instant of firing the voltage across the valve is greater than the maximum voltage amplitude of the alternating supply.

In Fig. 7.2 (*d*) the angle a is increased to $\frac{\pi}{2}$ and the heavy curve lies as much above the axis as it does below it, so that one cathode is as much below the negative output terminal as the succeeding cathode is positive to it and the output voltage is therefore zero. In short, therefore, these latter cases represent conditions where the voltage across the valve reverses during part of the cycle, though the current is unidirectional.

It has been shown previously that with a resistive load the phase angle of the grid requires to be shifted through 180° to cover the range of no load to full load. Here we see that with an inductive load of sufficient magnitude a range of 90° is sufficient to secure the full range of control. Current passes through each valve during a time angle of $\frac{2\pi}{n}$, where n is the number of phases, and this period of current conduction is independent of the delay angle a, the effect of

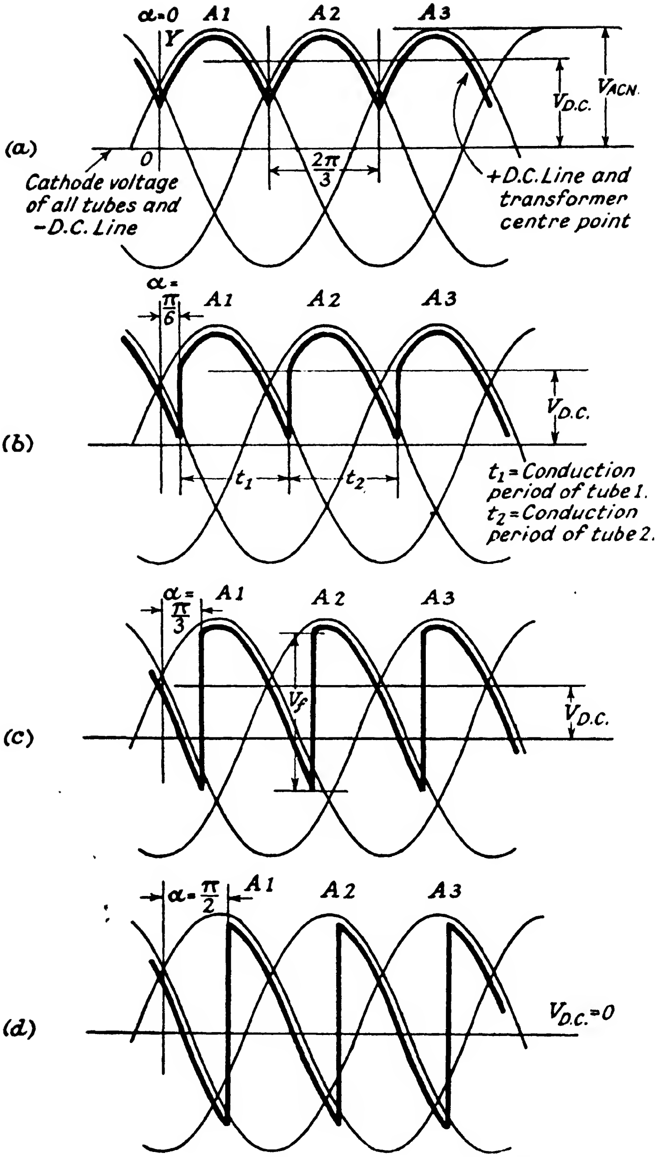


Fig. 7.2.—Output voltage of three-phase grid-controlled gasfilled rectifier with varying values of angle α. (*a*). $\alpha=0$: maximum output. (*b*) $\alpha=\frac{\pi}{6}$: decreasing D.C. voltage. (*c*). $\alpha=\frac{\pi}{3}$: decreasing D.C. voltage. (*d*). $\alpha=\frac{\pi}{2}$: output zero. D.C. voltage fluctuates with equal amplitude about zero + and —.

which is to displace the period of conduction along the time axis. The average value of the D.C. voltage for a biphase rectifier is:

$$\frac{2}{\pi} V_m \cos \alpha - v \quad . \quad . \quad . \quad . \quad \text{(i)}$$

and for a three-phase circuit:

$$\frac{3}{\pi} V_m \frac{\cos \alpha}{2} \sqrt{3} - v \quad . \quad . \quad . \quad . \quad \text{(ii)}$$

where V_m is the peak alternating voltage amplitude, v the voltage drop across the valve (practically constant), and α the delay angle of the grid.

The general case for n phases is given in the appendix. These results assume the condition that the rectifier is devoid of internal reactance. In practice the reactance gives rise to a delay in commutation and the direct voltage given by relations (i) and (ii) is reduced to two further terms, one proportional to the reactance drop per phase and the other to the reactance drop in the secondary winding.

Fig. 7.3 shows the basic circuit of a three-phase full-wave rectifier

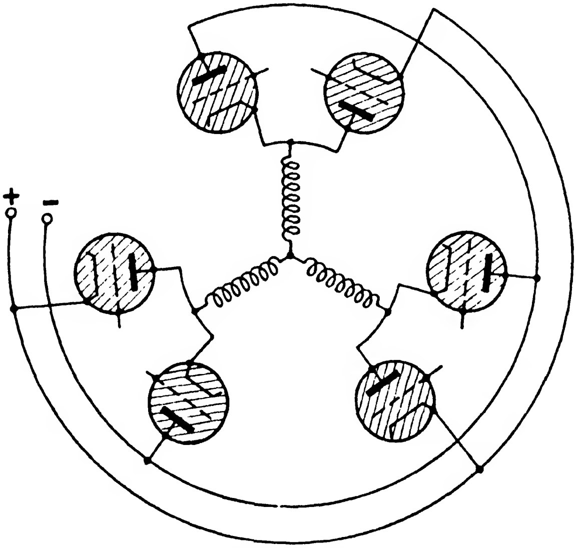


Fig. 7.3.—Corresponding arrangement of transformer secondary for three-phase full-wave rectification. (Grid circuit auxiliaries and primary winding of anode transformer omitted.)

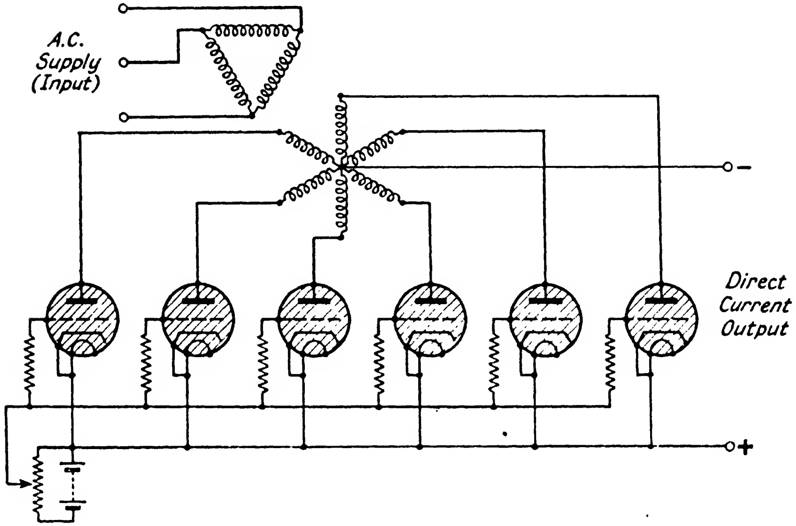


Fig. 7.4.—Grid-controlled six-phase rectifier.

where the biphase connected valves are in inverse parallel. Fig. 7.4 indicates in outline the corresponding circuit for six phases.

Harmonics

A notable difference between rectification by gasfilled and hard vacuum valves is that the ripple in the D.C. output is considerably greater in the former case, due to the fact that conduction through the valve does not follow the rise of alternating voltage from the zero of each positive half-cycle, but starts suddenly at some point during this half-cycle.

The sudden starting of the discharge results in the production of many harmonics, though many of these are of high frequency and do not offer serious difficulty to removal by filter circuits.

The existence of these harmonics should, however, be noted on account of possible disturbance they may cause in telephone or other communication services.

In mercury vapour rectifier units, somewhat elaborate filter systems are provided to eliminate ripple disturbance. Among these are: (1) small inductances in the anode leads to each valve; (2) filter circuits on the primary side of the power transformer; (3) high voltage condensers across each transformer secondary; (4) earthed metallic shielding between primary and secondary windings of the power transformer.[7,8]

As far as rectifier valves with mercury pool cathodes are concerned the circuits used are very similar, but the firing impulses are usually provided by an auxiliary thyratron. This smaller valve is in turn fired by a phase shift circuit and serves to discharge a condenser, whose charge is acquired during the non-conducting half-cycle, through the primary winding of a transformer connected in the anode circuit. The secondary winding provides a large voltage impulse for firing the main valve.

The Grid Circuit

Phase shift circuits, which include resistance, inductance and condenser networks described in Chapter 2, can be used to secure the necessary displacement of the firing point of the valve for adjustment of the current output. Alternatively the grids may be supplied through isolating transformers with alternating potentials greater in amplitude than the critical bias voltage corresponding to the peak of the applied anode voltage but adjustable in phase through a phase-shifting transformer. In the case of grid-controlled polyphase rectifiers, separate transformer feed to the grid circuit is necessary, since the cathodes and grids are at high potential to earth.

Where greater precision in determining the instant of firing and rapid isolation in case of overload is required, the grids may be maintained at a negative potential in the quiescent state, so that the current is cut off and the discharge initiated by a momentary positive impulse applied to each grid in succession, the time position of these pulses being adjusted with respect to the corresponding anode voltage to secure the required output. This method of control may employ either (1) transformers of special design with saturable reactors, or (2) impulses derived from a synchronously driven distributor, the phase of the pulses being adjustable by varying the angular position of the brushes of the distributor. The former method, involving only static components, is to be preferred. Protection against overload is attained by the inclusion of rapidly responding relays in both the A.C. and D.C. side of the system, so that the alternating voltage excitation of the grids is immediately suppressed, leaving the valves completely cut off, when the phase carrying the overload becomes so far negative that current conduction cannot be maintained, a condition which can be established in less than one cycle. After the overload has passed, the normal condition of grid excitation which existed prior to the overload is automatically restored and the rectifier continues to function and furnish the output for which it was previously adjusted. Here, again, as with motor control, safety precautions are most easily met by the use of positive drive valves while the discharge is cut off at zero grid voltage.

By a process of compounding analogous to that by which the voltage of a generator is maintained on a rising load, the output voltage of the rectifier can be kept within close limits over a wide range of current. A fixed proportion of the output current is fed back to a second winding on the peaked wave grid transformer so as to give an overriding control of the phase displacement of the firing point, and in a direction which tends to correct the change in output current.

It is essential in the case of valves with thermionic cathodes that the short-circuit current shall be limited to a value which is within the surge rating of the valve. It is usually possible with small valves to design the transformer so that its reactance is high enough to secure this condition (7.6). With larger valves on high-voltage systems the addition of chokes in series with the secondary winding may be required to secure the necessary protection.

The surge rating for short-circuit conditions usually exceeds the peak current rating frequently by two or three times. The latter indicates the maximum instantaneous current under recurrent conditions, whereas the surge rating implies non-recurrence or repetition at very widely spaced intervals.

In the case of a synchronous rotary distributor, the overload relay can be arranged to interrupt the positive supply to the distributor. With mercury pool cathodes these overload precautions do not apply, since the cathode is not damaged by overload.

Phase Displacement

Referring to Fig. 7.2, it will be noted that the maximum output occurs under conditions where $a=0$, or in the case of a three-phase rectifier when the firing point of the grid is in advance of the peak of the corresponding anode voltage by 60°. In applying the principle of peaked firing voltages as described in Chapter 3, page 76, the total angular shift of the grid firing point for circuits with inductance greater than the critical value is 90° or ±45° from the mean position. In a three-phase rectifier, therefore, the delay angle of 45° means that the firing point is still displaced 15° relative to anode voltage in advance of the position it should occupy for securing maximum output. A phase shift of this extent must therefore be introduced—most conveniently in the grid circuits—to enable the full output voltage to be secured.

A method of introducing this phase displacement is shown in Fig. 7.5. The transformer feeding the rectifier anodes is delta-star connected, and in the case of low-voltage systems, where the grids are fed direct from the supply, the grid transformer providing the firing impulses is delta-delta connected and the supply to the grids taken off from tappings approximately 20 per cent. from the end of each winding. This results in the voltage vector system shown in Fig.

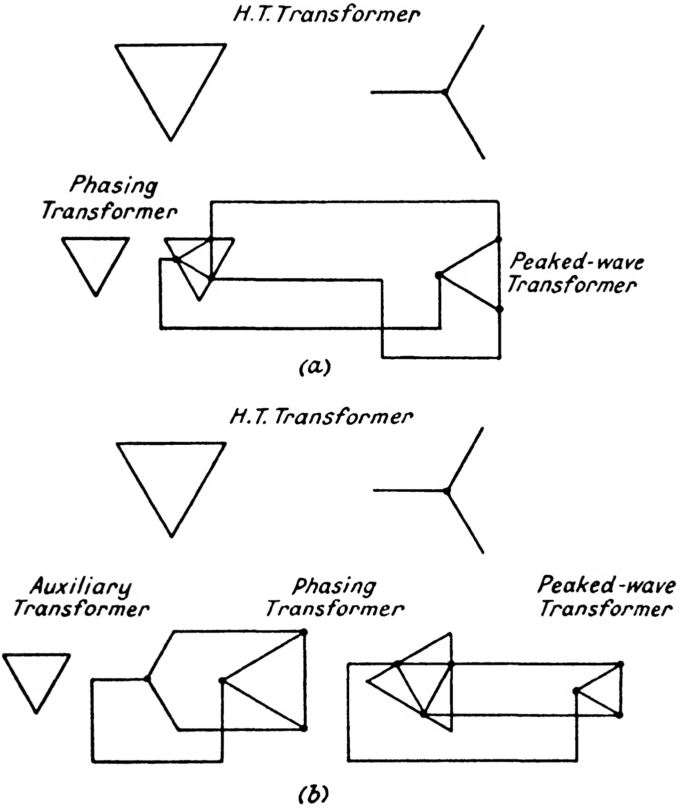


Fig. 7.5.—Phase displacement of firing point with respect to anode voltage in a three-phase grid-controlled rectifier, (*a*) with low voltage mains supply; (*b*) with high voltage mains supply.

7.5 (*a*) and indicates that the grid voltage peaks are displaced by 15° with respect to the secondary of the anode transformer. Fig. 7.5 (*b*) shows the corresponding case where a step-down voltage is required in the grid circuit.

Where the phase displacement of the firing point is large, the pulse broadens and the slope of the peak becomes flatter, and the valve may fire before the maximum grid voltage amplitude is attained, so that the conditions previously outlined may have to be modified to secure the required precision of firing.

Arrangement of Heater Circuit

To obtain an even distribution of current drawn from the valve cathodes it is desirable in the case of directly heated valves for the heater circuit voltage to be displaced 90° relative to the corresponding anodes. Fig. 7.5 (*b*) shows how this displacement is secured with respect to the anode neutral voltage, the single-phase heater transformers being connected in delta across the star output of the auxiliary transformer and the appropriate phase selected with respect to the corresponding anode voltage. Considerations other than continuity of current conduction may, of course, determine the value of the inductance used. Either freedom from resonance or elimination of ripple voltages may be the dominant factor requiring an inductance in excess of that dictated by the limiting condition of current conductance.

It should be noted that there is, in these inductive circuits, a greater tendency for arc-back to occur, since the discharge ceases when the anode voltage has reversed to a relatively high value and while a large number of positive ions are present in the valve. It is therefore essential that the valve should be operated well within the limits of its inverse voltage rating, and that the transformer reactance should not normally be less than about five times the filter inductance.

Although the general treatment of valves having mercury pool cathodes is outside the scope of this book, it may be noted that such valves exhibit a point at which the mean anode current changes suddenly from one value to another, representing a region of discontinuity over which phase control does not give smooth variation of anode current. For instance,.in the case of a polyphase rectifier used for heavy current loads such as battery charging this may introduce some difficulty. If the lower limit of the region of discontinuity is just within the rectifier rating, any adjustment to secure increased output may result in the current suddenly increasing to the upper limit, which, if outside the valve rating, may result in an overload shut-down. This phenomenon has been traced to the formation of a second hot-spot on the cathode which coincides with a reduction in arc-drop and consequent rise in current.[7.15]

The effect can be minimised by the use of high reactance transformers or the addition of anode chokes in the secondary circuit to improve the voltage regulation and restrict the discontinuity region to a narrow low-current range.

Compounding[7.9]

Fig. 7.6 shows the principle of compounding previously referred to for the purpose of making the rectifier output voltage independent of the load over its normal operating range. By feeding the grids of the valves in Fig. 7.6 from a resistance connected in the output circuit a negative bias proportional to the output current is impressed on the grids. It can be arranged that variation of this bias voltage due to change in output of the rectifier gives a control which maintains a constant output voltage independent of the load. This principle can also be used to interrupt the circuit completely by cutting off the discharge if the output current becomes excessive. The use of grids in rectifier valves having more than one anode provides a means of clearing arc-back or discharges which may take place between two

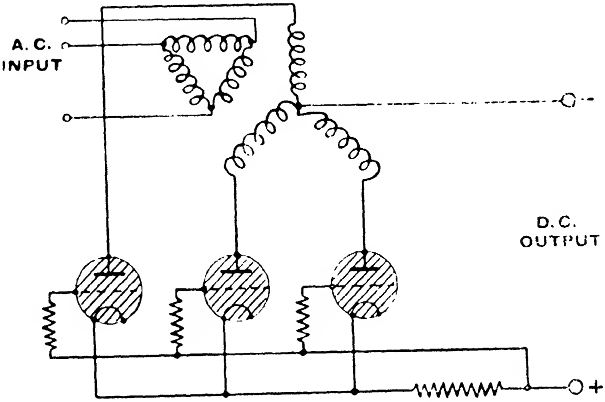


Fig. 7.6.—Automatically compensated rectifier for supplying D.C. at constant voltage.—Basic circuit.

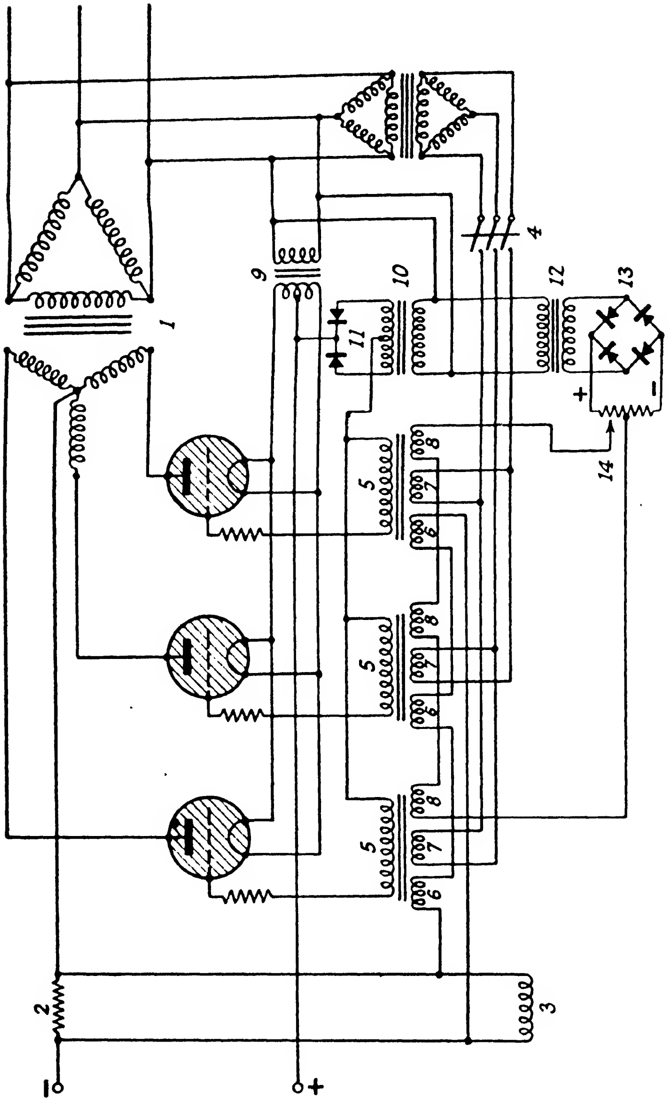


Fig. 7·7.—Grid auxiliaries added to the last illustration for securing peaked firing voltages. 1. Mains transformer. 2. Overload and compounding shunt. 3. Overload trip coil operating relay 4. 4. Relay interrupting phase transformer supply to grid. 5. Grid transformers. 6. Compounding primary winding. 7. A.C. winding. 8. D.C. saturating winding. 9. Cathode transformer. 10. and 11. Transformer and rectifier providing grid bias voltage. 12. Transformer feeding rectifier 13. 13. Rectifier providing D.C. output for saturation winding. 14. Potentiometer for adjusting current in winding 8.

anodes. When such takes place, a relay operates and imposes a negative bias on the corresponding grid or grids, so that the fault is suppressed within the period of one cycle. Fig. 7·7 shows the grid auxiliaries added to the previous circuit.

In the circuits previously described are also included a number of protective devices which have not been referred to (or shown in the diagrams). Automatic interlocking of circuits is provided with valves having thermionic cathodes, so that the anode voltage cannot be applied until the cathode has reached its full working temperature. A delayed-action switching circuit comprising a condenser and inductance is also included in the D.C. control circuit of the grid transformer, so that when the circuit is first switched on the output voltage builds up slowly to a value fixed by the setting of the grid control potentiometer, so that the surge current rating of the valve in conjunction with the filter employed is not exceeded.

Discharge Faults

Reference has already been made to an arc-back or backfire in rectifier operation.[7·7] This implies that the valve fires during the period when the valve should be cut off and when the anode is negative with respect to the cathode. This takes place when the valve fails to withstand the applied inverse voltage, and the fault is due usually to excessive inverse voltage. A defective valve or unsuspected transient voltage may be the cause. A backfire constitutes a short circuit on both A.C. and D.C. sections of the rectifier circuit and must be cleared by a suitable quick-acting relay.

If the discharge starts too early in the cycle—*i.e.*, before the point at which the grid striking voltage has been retarded—the valve is said to exhibit forward fire. No damage results, but if the process is recurrent, the rectified output voltage will be too high. A misfire takes place when the discharge occurs too late or fails to take place at all during what should be a conducting period. It is the reverse condition of the last fault and produces the opposite results—viz., if recurrent, the D.C. output voltage is too low. Finally, in multi-anode valves fault conditions may establish discharges between these electrodes.

Inverters

The dual valve circuit with condenser connected between the valve anodes, as previously discussed in connection with scaling circuits, etc., has another useful application in that it provides an efficient means of converting direct current into alternating current with static equipment devoid of all rotating or moving mechanical components, and thereby performs the inverse function of the valve rectifier.

If the common grid circuit of such a pair of triodes, whose anodes are fed from a D.C. source, is transformer coupled to a source of alternating voltage, the potentials of the grids of the two triodes, being always in phase opposition, will fire each valve in turn at the same time resetting the valve previously conducting. By replacing the anode load by the primary winding of a transformer, alternating voltages are induced in the secondary. Under the control of the alternating voltages of opposite phase applied to the triodes, current from the D.C. supply passes through each valve and each half of the transformer primary winding in turn, and each current pulse induces an A.C. voltage in the secondary. An alternating current load can thus be imposed on the secondary winding. In addition, part of the output voltage can be fed back to the grid transformer, so that the circuit becomes self-exciting. Alternatively, the grid voltage may be obtained from an independent external source of alternating current, which will then determine the frequency of the inverter. When the circuit is self-exciting, the frequency of the output will depend on the constants of the circuit.

The circuit of Fig. 7.8 is that of a typical parallel connected inverter. It differs in several respects from the scaling circuits previously referred to, notably in the grid network, and from the fact that the commutating condenser has been replaced by a symmetrical arrangement of two condensers 1, and a choke 2.

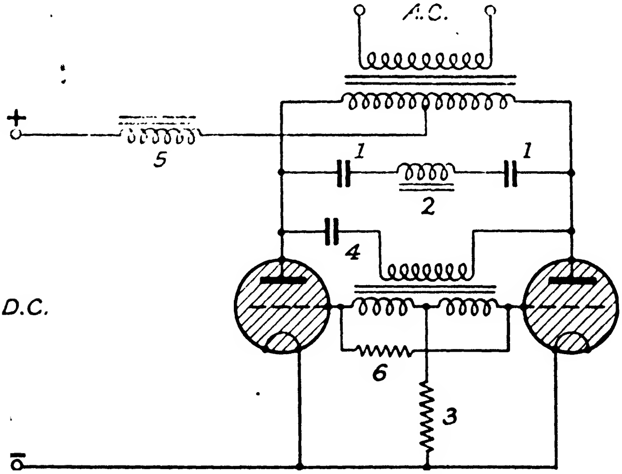


Fig. 7.8.—Typical parallel connected single-phase inverter circuit.

For the moment these latter components may be considered as a single condenser. The function of the choke 2 will be referred to later.

When the circuit of Fig. 7.8 is operating, the secondary of the grid transformer and the grid-cathode circuit of the two valves constitute a biphase half-wave rectifier, producing a unidirectional voltage across resistance 3. Superposed on this voltage which biases the valve grids negatively are alternating voltages generated in the secondary of the grid transformer which determine the instants at which the valves fire. If the resistance is large enough, the necessary condition that the grid voltage shall be more negative than the critical value before the instant at which the discharge ceases, is fulfilled. Actually the circuit of Fig. 7.8 is self-starting and the condition of existing operation for self-excitation by feed-back previously assumed is not necessary, because when the D.C. supply is connected one valve fires immediately, due to the instability of parallel connected valves previously referred to with scaling circuits. The commutating condenser then charges and the circuit functions thereafter automatically as described.

The whole power is derived from the D.C. supply, and the frequency of the A.C. output may be controlled by adjustment of the values of the condenser 1 and resistance 3. Condenser 4 is a phasing component to ensure that the phase of the grid voltage is in correct relation to that of the valve anodes.

The electrical efficiency of this method of conversion can be made very high, since the chief source of loss is the voltage drop across the values, which is constant of the order of 15 to 20 volts, and the power consumed in the heater circuit, also a constant. Consequently the percentage loss is less the higher the conversion voltage, and with high voltages a figure of 99 per cent. or more becomes possible. The single-phase circuit of Fig. 7.8 is easily modified to supply polyphase alternating current, and phase inverters of this type are shown in Figs. 7.9 and 7.10.

Further Considerations

Though the main features essential for the inversion of D.C. to A.C. have been referred to, there are several points which require further consideration in the application of these circuits to practical use.

The commutating condenser is usually an essential component of the circuit, since its function is to impress a negative voltage on the

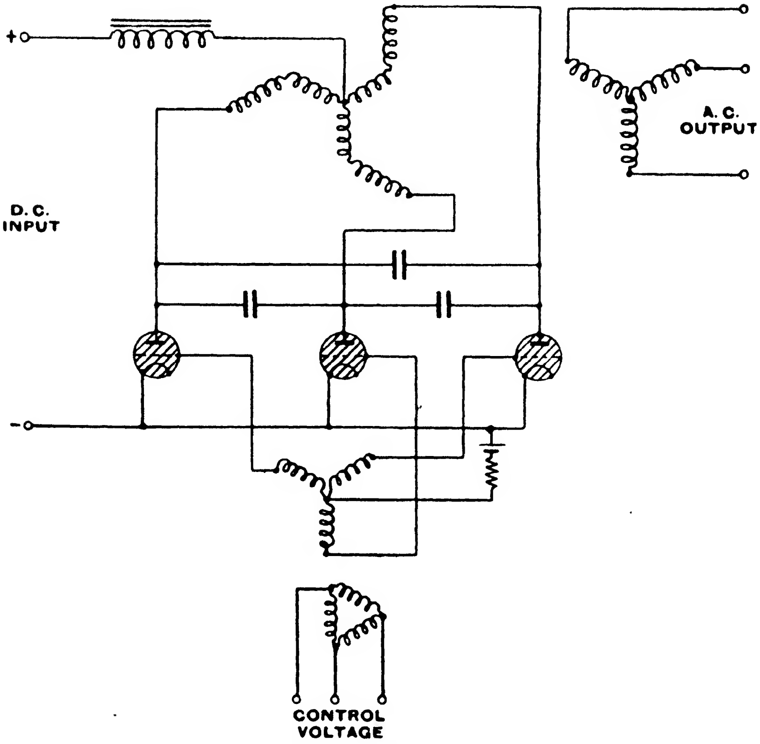


Fig. 7.9.—Three-phase inverter—simplest form.

anode of either valve to terminate its period of conduction at the instant at which the other valve fires.

The choke 5, Fig 7.8, prevents the return of alternating current into the D.C. supply.

There are two distinct conditions under which an inverter may have to work: (1) to supply alternating current to a circuit which is not fed from any other source; (2) to operate as a subsidiary generator in parallel with an existing A.C. supply feeding a common load. In the second case not only must the voltage be correct, but it must be correctly phased before it can be paralleled to the load, and the regulation must be comparable with that of the existing generators to secure stable operation. In this case the line voltage can be used to terminate the firing period of each valve, and the commutating condenser becomes unnecessary except when there is a lagging load. The wave form of an inverter is practically square. The square wave form produces one notable feature where the unit is used as a transverter of D.C.—*i.e.*, supplying a D.C. output of one voltage from a D.C. source at another voltage by inversion and rectification, the final D.C. voltage is lower than if the load is fed by current rectified from A.C. mains of the same voltage as the inverter output.

The mean voltage across the choke 5, Fig. 7.8, is zero, but since the voltage across the primary winding of that portion of the transformer feeding the conducting valve is 15 volts less than the D.C. line voltage, the potential across the non-conducting valve for a portion of one half-cycle is nearly twice the D.C. line voltage, and this falls to about 15 volts when the valve fires.

It is essential that during the commutating period the grid of each valve shall assume a value more negative than the critical value before the corresponding anode becomes positive. The commutating condenser must therefore be large enough to keep the valve anode negative for a period exceeding the deionisation time (*q.v.*, p. 59).

The primary winding of the main transformer has to carry four current components: (1) the direct input current; (2) an equivalent of the A.C. output current; (3) the magnetising current; (4) the current which passes through the grid transformer. Of these, only the first two impose any appreciable loading.

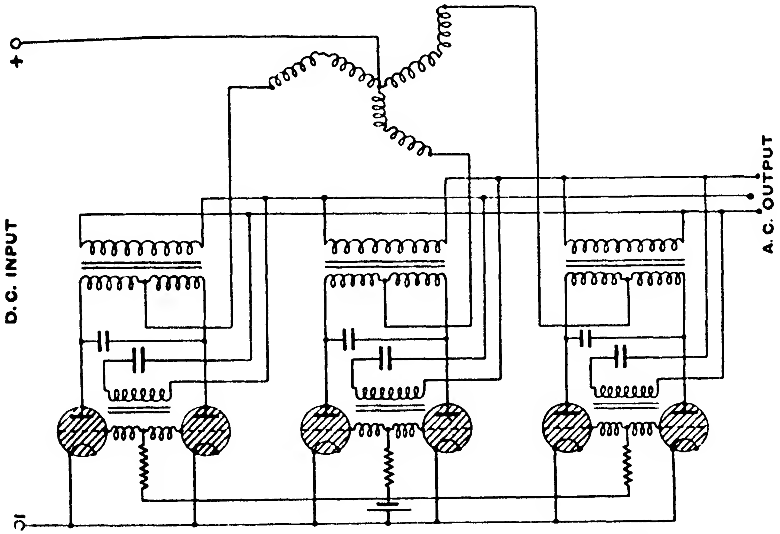


Fig. 7.10.—Three-phase parallel type inverter, with bi-phase connected triodes.

Each portion of the primary winding is in use for half the cycle, so that the KVA rating has to be $\sqrt{2}$ times that of the secondary.

Though the efficiency of the circuit depends largely on the design of the main transformer, the use of a high flux density to secure low no-load losses usually results in instability if the circuit is ever called upon to operate on low or no load.

Both output voltage and frequency usually show a falling characteristic with increasing load. If the output voltage happens to be twice the input voltage, some simplification of circuit becomes possible by using the primary winding as an autotransformer with the output leads at the two ends. The primaries then only carry D.C., but the KVA rating is less than half the rating of the corresponding transformer with a secondary winding.

The voltage across the choke 5 comprises a series of impulses of twice the inverter output frequency, and the inductance of this choke must be sufficient to prevent A.C. ripple appearing in the D.C. line, as this would be carried by and increase the main transformer losses. Since the ratio of ripple voltage to load has to be kept to a minimum, the minimum inductance necessary becomes greater at low loads.

The performance of the circuit is affected by the voltage of the secondaries of the grid transformers. If the voltage feed-back to the grid is too low, continuity of performance of the circuit under all conditions of load is not always secured. If the feed-back is too high, the frequency will change according to the magnitude of the load and the anode circuit will control the performance of the inverter. The resistance 6 across the grid transformer secondary is included to damp out any tendency to resonate.

Satisfactory operation also necessitates the value of the resistance 3 being within certain limits. The objection of a high grid resistance in any gasfilled triode has previously been referred to. The required D.C. grid bias fails to be established in the time of the cycle available if the grid resistance is too low.

So far the inductance 2 of Fig. 7.8 has been ignored. Actually its existence, though not essential for the inverter to operate, is a most important component. Its function is to retard the establishment of current in either valve at the instant of commutation, so that no appreciable current passes until the gas is ionised. Without it the full current may pass in the valve before the anode voltage has dropped appreciably, with the result that sputtering of the cathode takes place, due to positive ion bombardment due to the high voltage instantaneously across the valve in the conducting state. Though this occurs only during a small fraction of each cycle, the cumulative effect is very destructive and results in short life of the valves. In Fig. 7.8 the commutating condenser and inductance are shown symmetrically disposed.

Automatic Switching

In starting up an inverter circuit which is the sole generator for an A.C. load, the low voltage heater circuits of the valves will need to be fed initially from the D.C. supply through resistances. Since this is objectionable by reason of the heat dissipated, an arrangement must be devised to switch the heaters over to the A.C. output circuit, from which they can be fed through a step-down transformer when the inverter starts up. By means of thermally heated bimetallic strip switches the heater circuits can be closed for the required preheating time before the anode voltage is applied. These switches operate relays which perform two functions: (1) cut out the bimetallic switches after the preheating time is completed; (2) release to switch the whole circuit off if the inverter fails and prevent re-connection to the D.C. supply without going through the switching cycle afresh. In this way any possibility of switching the circuit off and then switching it on again while the valve cathodes are insufficiently heated is avoided. In addition, overload relays must be provided to protect the valves against short circuits on the D.C. supply. Fuses are too slow for this purpose, and small contactors operated by overload coils become essential.

D.C. Conversion [7.11, 7.12, 7.13]

Inverters make possible an efficient means of converting D.C. of one voltage to D.C. of any other voltage, either higher or lower, without rotary machinery. The circuit of Fig. 7.11 shows in outline such an arrangement, in which some accessory components are omitted but which will be self-explanatory. This circuit shows a mains transformer common to both inverter and rectifier, together with a second harmonic transformer, coupling the two direct-current leads and resulting in a very high efficiency of conversion. The square wave form of the inverter output enables a smooth D.C. output to be secured more easily than from a sine wave A.C. source.

While the inverter followed by a rectifier provides an efficient means of changing the voltage of a direct-current supply by the conversion DC-AC-DC, there is also the possibility of using these circuits in the reverse order, AC-DC-AC, for the purpose of providing a frequency changer where A.C. supply is available[7.16].

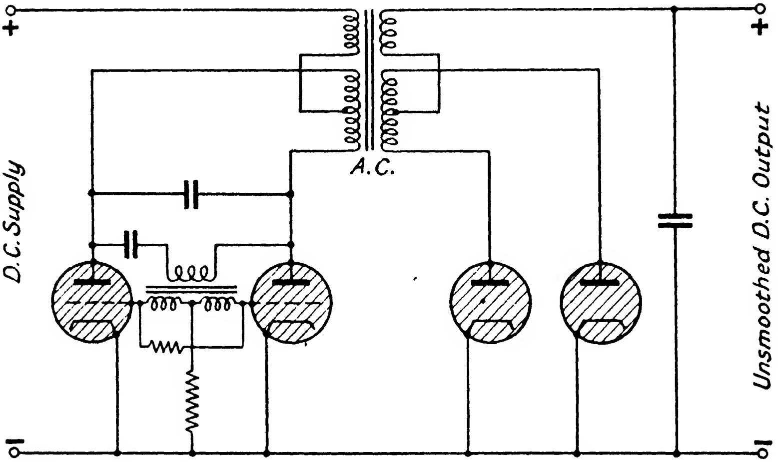


Fig. 7.11.—D.C. voltage transverter.

Series Type Inverter

A second class of inverter circuit[7.10] uses the principle of charging a condenser through one gasfilled triode and discharging it through another and similar valve, the alternating current circuit through the condenser being inductively coupled to the alternating current load circuit. Such circuits are known as series-type inverters. The valves are made alternately conducting by suitably phased impulses on their grids, and the circuit can be made self-exciting, as in the case of the parallel circuit, by coupling the grids to the A.C. output.

A direct connection between the two valves (Fig. 7.12) would entail the condition that the discharge in one valve would need to cease before the other valve fires, otherwise the direct-current supply will be short-circuited. To provide for the possibility that current may still be passing in one valve when the other fires, due to the commutating condenser not being fully charged or fully discharged, the valves are connected through a choke, the self-inductance of which prevents the occurrence of the short-circuit conditions referred to at the instant of switching from one valve to the other.

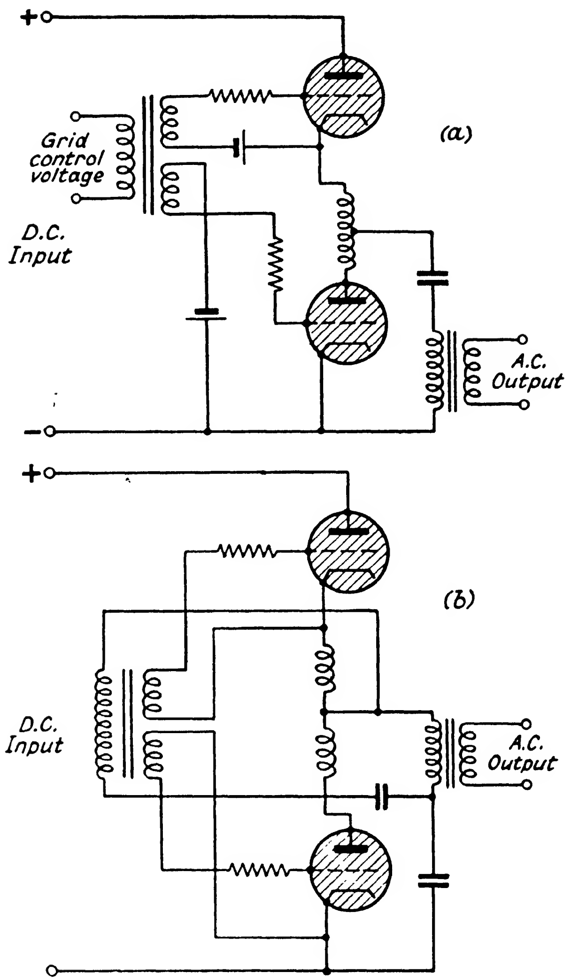


Fig. 7.12.—Series type of inverter, (*a*) separately excited; (*b*) self-excited.

The power which either type of inverter can deliver depends on the rating of the triodes and the permissible voltage which can be applied to the valve anodes, which in turn is determined by the emissivity of the cathode. Fig. 7.13 shows a three-phase series type of inverter.

Mercury-vapour tubes with thermionic hot cathodes have been made with ratings up to 100 amperes with working voltage of 1,500. For larger loads mercury pool cathodes are employed.

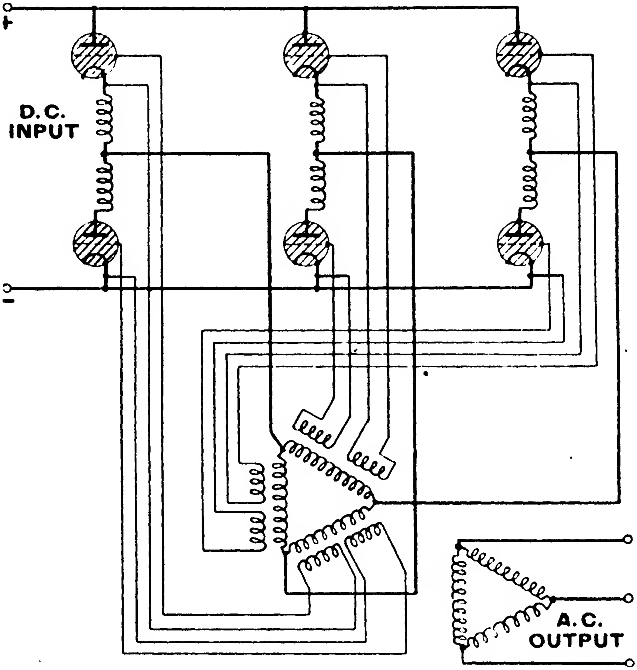


Fig. 7.13.—Three-phase series type inverter.

Voltage Regulation

If the load is a variable one, the fluctuation, if heavy, may introduce the undesirable feature of reducing the cathode temperature. It has been proposed to overcome this effect by feeding the valve heaters in series from a separate winding on the main transformer and connecting the D.C. negative to the centre point of this winding. The heater circuit is then fed from both A.C. and D.C. circuits, and as the A.C. heating decreases by increased load the D.C. component is increased and the two effects tend to neutralise.

Practical Applications

The most obvious uses for small inverters are for feeding A.C. mains radio sets and neon signs in places where only a D.C. supply can be provided. Ability to increase the frequency of the A.C. output, which the circuit provides for without great difficulty, is advantageous in producing flickerless illumination, which is also favoured by the square wave form. For feeding neon signs, iron-cored chokes are included in the circuit of each half of the main transformer to prevent the circuit from operating at a very high frequency.

To eliminate serious radio interference, the output winding on the main transformer should be screened and earthed at one point. The transformer and choke cores should also be earthed and the leads to the valve anodes kept as short as possible.

Large Inverters

Fig. 7.14 shows the arrangement of electrodes for a large mercury pool cathode inverter. This type of unit has some resemblance to the smaller sets with thermionic cathodes and to the mercury vapour rectifiers used in traction work, with the addition of grids which completely screen electrically each anode from its corresponding cathode. Since an arc is continually passing, ionisation is always present, and in consequence a relatively large current is taken by each grid in

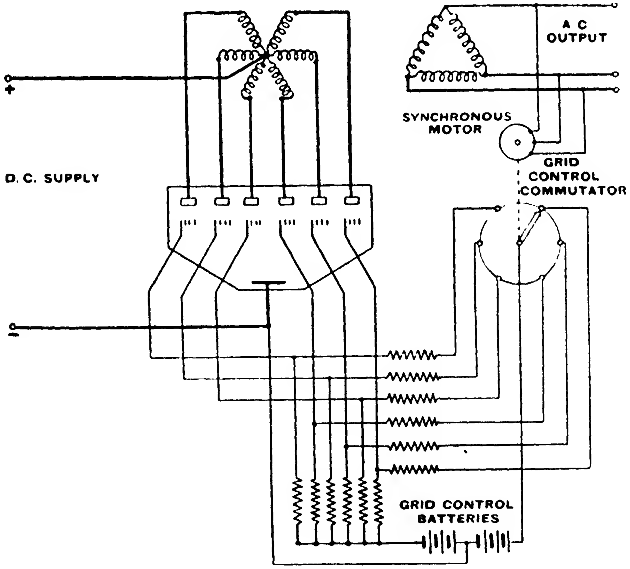


Fig. 7.14.—Large inverter, employing a mercury vapour discharge vessel with a mercury pool cathode.

restraining the discharge from passing to the corresponding anode, so that a relatively large power is required in the grid circuits of inverters using discharge tubes of this kind. The grids are usually excited from a special generator or battery through a commutator rotated in synchronism with the output voltage.

Since, unlike the thermionic coated cathodes of the smaller valves, the emission of the mercury pool is practically unlimited, the power output is restricted only by the rise in temperature of the discharge vessel. The existence of a high temperature reduces the permissible working voltage by reducing the peak inverse voltage. Currents of the order of 600 amperes per anode are possible, so that a six-phase inverter employing a bulb with twelve anodes could supply about 20,000 kilowatts.

D.C. Transmission

The combination of static inverter and mercury arc rectifier makes possible an efficient means of generating high-voltage direct current. At the time inverters were first developed there appeared to be some possibility of the adoption of such apparatus for high-voltage D.C. transmission which has a number of advantages over high-voltage A.C. Although the adoption of such means of power transmission has not materialised, the advantages remain and are of technical interest. Since the peak of an A.C. voltage exceeds the R.M. S value, the permissible working voltage on a D.C. line for a given line insulation is 1·4 times that of an A.C. line.

Capacity and power losses due to out-of-phase currents, dielectric hysteresis and eddy currents are absent, and corona losses are much lower on high-voltage D.C. Greater flexibility in operation is also secured by grid-controlled gasfilled valves in power transmission. By suitable arrangement of the grid control, inverters can be made to operate in the reverse direction, taking power from the A.C. circuit and feeding it to the D.C. Thus a means is provided for enabling power to pass in either direction according to the supply and demand of the respective circuits, so that two or more power stations generating A.C. and supplying it to local consumers may be connected by a D.C. network. The inverters enable power to be transferred in the D.C. network in either direction as the load demands, and stations may close down or start up without the need for separate synchronisation.

Uses on Traction Systems

The principles of the rectifiers previously outlined, more particularly in the case of the mercury pool type, have been employed for the purpose of supplying the armature circuits of D.C. traction motors.

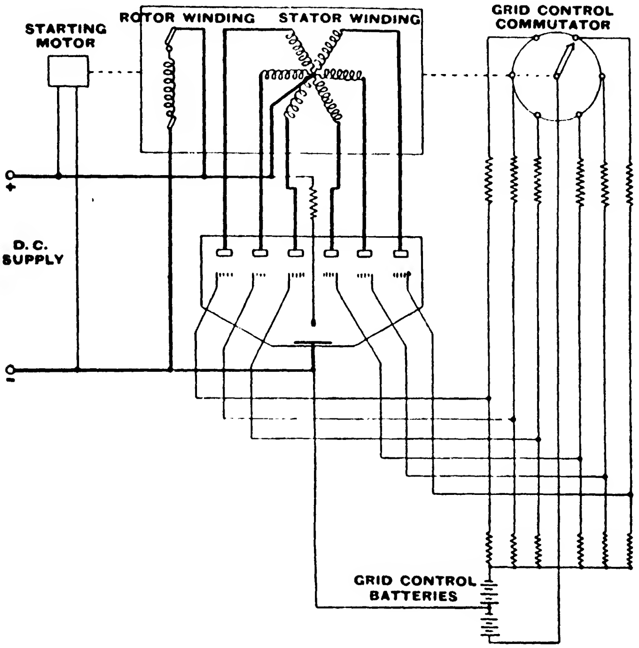


Fig. 7.15A.—Commutatorless motor driven from a D.C. supply.

Fig. 7.15A shows in outline a case where the valve performs the function of the commutator and controller of a motor driven from D.C. supply. In Fig. 7.15B, where the motor is operated from a single-phase A.C. supply, the valve performs the additional function of rectification. These circuits provide greatly improved speed characteristics and should be compared with those referred to in chapter 6.[7.14] Some of the circuits of this type can be regarded as frequency changers which enable synchronous motors to be operated at more than one speed from a constant frequency supply. Such circuits involve some of the problems associated with valve inverter circuits.

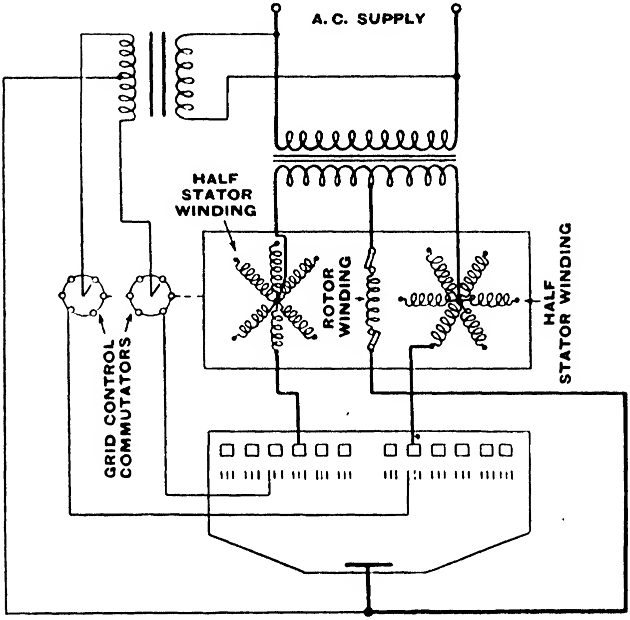


Fig. 7.15B.—Commutatorless motor driven from an A.C. supply.

GENERAL REFERENCES

Rectifiers.

(i) Klemperer; Grid-controlled rectifiers as an A.C. load, *Arch. f. Elektrot.*, 30 (October 7, 1932), pp. 710-5.

(ii) Rockwood, Thyratrons for grid-controlled rectifier service, *Am. Electrotech. Soc. Trans.*, 72 (1937), pp. 213-23.

(iii) ——, Grid-controlled rectifiers on the Bombay-Baroda Railway, *Elect. Times*, 93 (March 3, 1938), p. 313.

(iv) Bezkrovny, Use of grid-controlled mercury arc rectifiers for traction service, *Ass. Ing. El. Liège Bull.*, 18 (February-March, 1938), pp. 35-50, 69-82.

(v) Pakala and Batten, Phase occurrence in arc-backs in high-current mercury arc rectifiers, *Trans. Am. I.E.E.*, 59 (June, 1940), pp. 365-7.

(vi) Klugh, Power limitation in hot cathode mutators, *Elektrot. Zeits.*, 63. (May 7, 1942), p. 201.

Inverters.

(i) Baker and Cornell, D.C. inverter for radio receivers, *Electronics*, 3 (1934), pp. 150-4.

(ii) Wagner, Parallel inverter with resistance load, *Electrical Engineering*, 54 (1935), pp. 1225-55.

(iii) Schilling, Design of single-phase inverters, *Arch. f. Elecktrot.*, 27 (January 7, 1933), pp. 22-32.

(iv) Tomkins, Operation of a self-excited rectifier, *Electronics*, 13 (September, 1940), pp. 36-39 and 81.

(v) Stenning, Performance of commutation inverters, *Wireless Engineer*, 17 (December, 1940), p. 517.

Miscellaneous.

(i) Willis, Harmonic commutation for thyratron inverters and rectifiers, *G.E. Rev.*, 35 (December, 1932), p. 632; and *Trans. Am.I.E.E.*, 52 (June, 1933), p. 392.

(ii) Watanabe and Guti, A new inverting method using mechanical commutation and grid-controlled mercury arc rectifiers, *Electrotechnical Journal*, 3 (June, 1939), p. 133.

(iii) Willis, Study of the thyratron commutator motor, *G.E. Rev.*, 36 (February, 1933), p. 76.

(iv) Willis, Bedford and Elder, Constant-current D.C. transmission, *Electrical Engineering*, 54 (January, 1935), pp. 102-8.

CHAPTER REFERENCES

7.1. Rabuteau, Hot cathode mercury vapour high-tension supply equipment for broadcasting stations, *Electrical Communications* (October, 1936), p. 141.

7.2. Rissik, The fundamental theory of arc converters, Chapman and Hall (London, 1939).

7.3. Mariani, *Alta Frequenza*, Vol. 11 (1942), p. 67; *Philip's Transmitting News* (November, 1940).

7.4. Overbeck, Critical inductance and control rectifiers, *Proc. I.R.E.* (1939), p. 655.

7.5. Dunham, Some considerations in the design of hot cathode mercury vapour rectifier circuits, *Journ. I.E.E.*, Vol. 75 (1934), p. 278.

7.6. De Blieux, Characteristics, design and application of rectifier transformers, *G.E. Rev.*, 40 (1937), pp. 412, 481, 539, 590.

7.7. Kingdon and Lawton, The relation of residual ionisation to arc-back in thyratrons, *G.E. Rev.*, 42 (November, 1939), pp. 474-8.

7.8. Hull and Elder, The cause of high-voltage surges in rectifier circuits, *Journ. App. Physics*, 13 (June, 1942), pp. 372-7.

7.9. Goodhue and Burton Power, Self-regulated compounded rectifiers, *Elect. Eng.*, Vol. 55 (1936), pp. 1200-5.

7.10. Sabbah, Series parallel type static converters, *G.E. Rev.*, Vol. 34, No. 5 (May, 1931), p. 288; No. 10 (October, 1931), p. 580; No. 12 (December, 1931), p. 738.

7.11. Niethammer, High-tension direct-current transmission, *Elektrot. u. Maschinenbau*, Vol. 49 (April 5, 1931), pp. 261-4.

7.12. Hull, D.C. to A.C. conversion, *Nat. Acad. Sci. Proc.*, 22 (June, 1936), pp. 389-93.

7.13. Reich, Relaxation inverter and D.C. transformer, *Rev. Sci. Inst.*, 4 (March, 1933), pp. 147-51.

7.14. Alexanderson and Mittag, The thyratron commutation motor, *Electrical Engineering*, Vol. 53 (1934), p. 1517.

7.15. Wells, Mercury arc rectifiers, *Electrical Review*, Vol. 141, No. 3637 (August 8, 1947), p. 220.

7.16. Bowlus and Nims, Thyratron frequency changers, *Electronics*, Vol. 21, No. 3 (March, 1948), p. 126.

CHAPTER 8

Some Other Types of Grid-Controlled Gasfilled Valves

The ignitron. The distinction from the mercury arc rectifier. The starter or igniter electrode. Water-cooling. Applications. Welding. Non-synchronous current control. Methods of current adjustment. Dual timing circuits for steam welding. Stored energy circuits. Magnetically controlled valves. Advantages. Pulse modulators. Cold cathode tubes. The diode. The triode life. Nomenclature. The cold cathode tube as a relay. Methods of operation. Merits and disadvantages. Rectification. Relaxation oscillators. Timing circuits. Voltage stabilisers. Stabilovolt. Short-period illuminants. The stroboscope. The strobotron discharge tube. Modern forms. Neostron. Kodatron. Circuits for operation, etc.

IN this concluding chapter it is proposed to make some reference to other types of electric discharge devices which are of industrial utility and which can be classified under the heading of grid-controlled gasfilled valves.

The Ignitron

The ignitron is a high-current mercury vapour valve in which the discharge is started by a control electrode, and which combines many of the features of the thyratron with some of those of the mercury pool rectifier. Devices of this kind first made their appearance in the industrial world about 1933.[8.10] The discharge is started by an igniter electrode and the source of electrons is a mercury pool cathode. Like the thyratron, the tube is characterised by a low arc voltage drop but with much higher currents than are possible with the thermal type of cathode. In the smaller sizes such as the B.T.H. type BK22, which has a mean current of 30 amperes with a peak of 2,500 amps., the electrode system is mounted in a glass bulb, while the larger sizes, such as type BK24, with a mean current of 50 amps. and peak rating of 6,000 amps. at an inverse voltage of 300 a steel envelope is used. Continuously pumped tanks are also used. In such cases the load current can be increased relative to the size of the unit by water cooling, which is always included in the larger units, the design being such as to enable the coolant to circulate through an annular chamber between the outer case and the discharge vessel.

Small valves may rely entirely on natural air circulation, while intermediate sizes may include forced air cooling with the electrodes made to external connections specifically designed for heat radiation. Metal containers, of course, have the advantage of higher heat conduction and dissipation. Alternative methods of representation of the ignitron are shown in Fig. 8.1. That shown in Fig. 8.1 (*a*) is most usual in British literature.

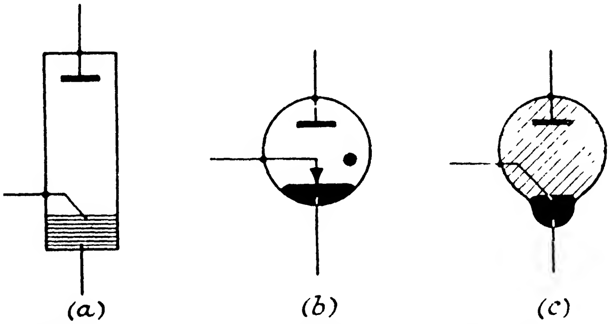

(*a*) (*b*) (*c*)

Fig. 8.1.—Conventional representation of the Ignitron.

Usually a single anode is employed, though, as in the case of specially designed grid-controlled mercury vapour rectifiers, provision may be made to accommodate two or more anodes in the same bulb.

The Ignitron Principle

The discovery of the igniter principle of initiating the arc spot on the mercury pool cathode is due to Slepian and Ludwig.[8.1] The cathode emission takes place from one or more bright spots visible on the surface of the mercury pool. The essential difference between the ignitron and the grid-controlled rectifier is in the method of starting the discharge. Both use a starting or ignition electrode, but in the rectifier this electrode is first dipped into the mercury pool and then withdrawn, trailing a small arc at the instant of breaking circuit. This forms the hot spot on the cathode surface, and if the anode is then at a sufficiently high positive potential the arc is immediately established across the valve.

In the ignitron, the ignition electrode is, with the exception of certain designs in which provision is made for adjusting the igniter, fixed in position, mounted on an insulating bushing, and permanently in contact with the mercury pool. When direct current of sufficient magnitude is passed through the cathode and the igniter electrode, the discharge starts through the formation of a hot spot at their junction. The first spot starts by a spark from the igniter, and as the current is increased it divides into other spots until at high currents there may be a number of such points each carrying current from 5 to 15 amps. according to the size of the tube.

In some designs an auxiliary anode mounted close to the igniter is provided to sustain the cathode spot when formed and to maintain it till the main anode voltage rises to a value which establishes the main arc. This auxiliary anode ceases to function as soon as the voltage cycle reaches the point where it becomes negative to the cathode pool. The auxiliary anode and igniter may be connected to a gas-tight flexible diaphragm, so that the position of the igniter can be adjusted from outside.

The igniter is a tapered electrode of a semi-conductor, the carbide of tungsten, silicon or boron being used for this purpose. It depresses but does not wet the mercury surface and imposes a resistance of the order of 20 to 400 ohms between itself and the mercury surface when the two are in contact.

There are at least two theories which endeavour to explain the process. In one[8.1] it is suggested that the electrons are ejected from the mercury surface by reason of the concentration of the lines of current flow due to the high potential gradient at the point where the igniter electrode enters the cathode. Alternatively it has been suggested that the heat produced at the point of immersion is sufficient to raise the mercury vapour pressure to a value high enough to form the cathode spot.[8.2] It is difficult, however, to understand how the temperature and vapour pressure rise can be so rapid as to give the precision of control which these valves exhibit in practice.[8.3]

Though the peak value of the current in the igniter circuit may be as much as 10 amps. or more, it really represents very small power, since it passes for only a fraction of a cycle. The cathode spot is formed in a few microseconds, and 100μ secs. is sufficient for the main discharge to be established.[8.4]

A distinctive feature of the ignitron is the reduced tendency to arc-back[8.5] except under conditions of excessive current and reverse voltage. This arises from the fact that when the anode voltage is negative there is practically no ionisation in the bulb as distinct from valves using thermal cathodes, for which special electrode design and spacing has to be adopted to reduce this tendency to arc-back.[8.6]

For satisfactory operation the temperature must be below a certain limiting value, otherwise the vapour pressure, which is determined by the coolest part of the bulb, may rise to the point where current can pass in either direction when the igniter is not energised. A valve which permits current to pass in the normal direction during what should be a non-conducting period is said to shoot through as distinct from arc-back, which implies passage of current in the reverse direction.

The cathode area must be large enough to prevent spots starting at the igniter and travelling to the envelope during a single period of conduction, otherwise metal may be sputtered from the wall of the container. The cross-section of the tube fixes the maximum peak current. Both the mean and r.m.s. current affect the electrode design. The former determines the heat generated at the anode surface and the latter the heat generated in the conducting parts of the electrode system.

In principle, many of the grid-control circuits applicable to thyratrons can also be used with ignitrons with some modification.

An essential difference between the thyratron and the ignitron is that, while the discharge is always established in the former, when the anode voltage reaches the value at which the grid control ratio is exceeded, in the ignitron the discharge cannot be established until current has passed through the igniter circuit irrespective of the anode voltage.

The most obvious way to fire the ignitron is, of course, to connect a switch between the ignitron anode and the igniter in series with a resistance to prevent a short circuit. This is known as the anode method of firing and is better performed by the use of a thyratron (Fig. 8.2 [*a*]). Besides being able to provide the high-peak igniter current, the thyratron has the advantage of suppressing the reverse current to the igniter and of extinguishing the igniter current immediately the main discharge passes.

The use of a thyratron for this purpose is not without some disadvantages. Extinction of the thyratron discharge necessitates the condition that the arc-drop across it is higher than that across the ignitron. In valves with inert gasfilling it is often difficult to secure this condition consistently with adequate life. Rectifiers, rotating contacts, and circuits involving saturable reactors[8.7] have been used

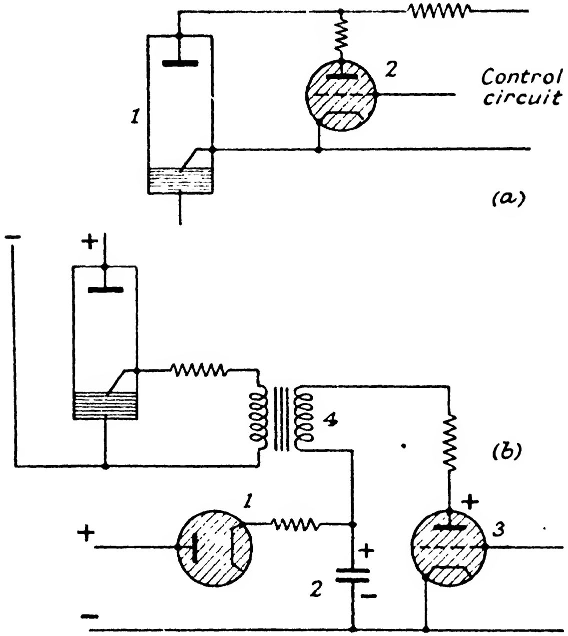


Fig. 8.2.—Usual methods of ignitron control in medium and high voltage circuits.

as alternatives. Some of these are shown in subsequent illustrations. The anode method of firing also has some limitations if the circuit contains any counter e.m.f. such as a condenser or battery, since the voltage applied to the igniter is the difference between the peak applied voltage and the back e.m.f., and if this resultant is low a relatively long time will elapse before the igniter current reaches its critical value.

With a variable counter e.m.f. intermittent delays in firing may occur. The addition of an inductance in the D.C. circuit tends to smooth out current changes and may assist in obviating this effect.

In Fig. 8.2 (*b*) is an arrangement commonly used in high-voltage circuits. Condenser 2 is maintained charged to the polarity indicated by the diode rectifier 1 during the non-conducting periods of the thyratron 3. When the latter receives a firing impulse, the condenser is suddenly discharged through the triode 3 and the transformer winding 4. The high peak current provides energy for the igniter circuit through the current transformer 4.

Fig. 8.3 shows an exploded view of the B.T.H. ignitron type BK24, indicating the components referred to. It consists of a permanently sealed-off evacuated cylinder at the bottom of which is the cathode lug integral with the cylinder end. At the upper end is the anode supported by an insulating glass seal. The igniter is supported from a glass insert at the bottom of the tube. The vessel contains

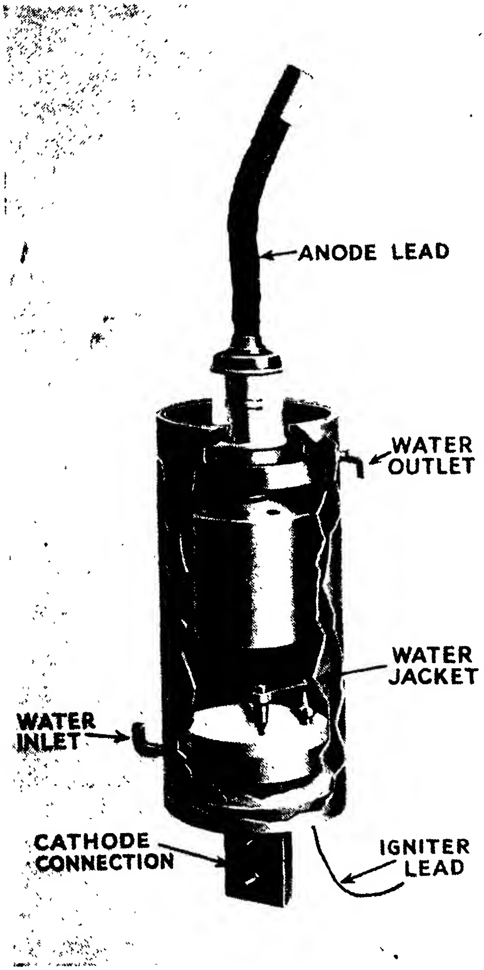


Fig. 8.3.—Exploded view of an ignitron type BK24. (*B.T.H. Co.*)

mercury vapour at the required pressure. The minimum rate of water circulation is $1\frac{1}{2}$ gallons per minute, and if the circulation falls below this rate a water switch cuts the ignition out of circuit, so that complete protection against damage is secured.

Water Cooling

Fig. 8.3 shows also a typical form of water jacket for an ignitron. Water flows upwards through the jacket, the steel tank of which is closely spaced in the discharge chamber to ensure high velocity of water circulation and prevention of air pockets. Helical baffles are provided in some forms of ignitron to direct the water flow and prevent hot spots developing.

The water-flow rating which is specified by the makers of any particular tube is usually given as maximum outlet temperature and minimum flow in gallons per unit time. Thermostatic regulation of the water flow enables the temperature to be maintained within the makers' recommended range, usually 30° to 50° C. Too low a temperature prevents adequate ionisation and the current is liable to show sudden fluctuations. Irregularity of current may also give rise to undesirable transients. Too high a temperature increases the risk of arc-back.

Interlocking devices are preferably provided to prevent the ignitron being operated without circulation of water.

The velocity of water circulation is important, because the difference in temperature between the discharge chamber and the water depends on the rate of flow of the circulating water. Consequently, with the velocity of circulation left unspecified it would be possible for the outlet water temperature to be below the rated maximum with parts of the tube at too high a temperature due to the low rate of circulation.

If two tubes are in use, it may be preferable to connect the water circulating systems in series to prevent the possibility of overheating due to unequal division of the circulating water. Protective and interlocking devices should be designed to avoid interruption of their operation through accumulation of scale or silt.

Corrosion is prevented by suitable chemical treatment of the water, and if an adequate supply is not available some form of heat exchanger will be required to permit of continuous recirculation.

Steel of suitable composition must be used for the ignitron tube. It is possible for hydrogen-ion diffusion to take place through the walls of the tube and render the valve inoperative if steel of suitable chemical composition is not employed. Stainless steel has been used successfully in overcoming this effect.

Applications of the Ignitron

With the distinctive characteristics previously outlined in mind, the ignitron, for the majority of industrial applications, can be regarded as a large edition of the thyratron to be employed where currents of very high peak values are involved.

Consequently, its most extensive use has been in the realm of precision welding. The use of electronic control has greatly extended the practical utility of welding processes, and welding is now established as a distinct and separate branch of engineering.

It is obviously impossible, therefore, to do more than give an outline of some of the ways in which the ignitron is employed in welding control. For further information a specialised treatise on the subject should be consulted.[8.8]

Welding Control

The general principles involved in the timing of the period of current application for welding operations have been already referred to in Chapter 4. The ignitron, by reason of its much higher current rating, extends the principle of control beyond the range of loading possible with the thyratron and its thermionic cathode. In large welds the high currents necessary to ensure adequate rise of temperature at the point of junction also necessitates rapid rise and fall of temperature, to prevent heat travelling appreciably into the surrounding metal and each point of weld is surrounded by an area of relatively cool material, so that oxidation and deformation are minimised.

As distinct from the circuits shown in Chapter 5 involving thyratrons wherein the discharge through the triode serves to vary the impedance of the spot-welding transformer, ignitrons are nearly all used connected in pairs in inverse parallel and directly in series with the primary winding of the welding transformer, the discharge through the valve providing the current for the primary winding, to produce high current pulses in the secondard. Fig. 8.4 shows the interior view of an ignitron contactor, including a pair of ignitrons in circuit with the welding transformer in the same way as an electromagnetic contactor would be used. The igniter control circuit is brought out to terminals, and when these are bridged the ignitrons pass current in turn on alternator half-voltage cycles and continue to do so as long as the control circuit is closed.

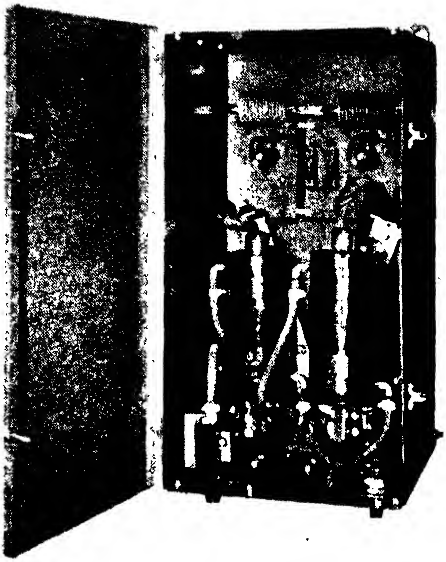


Fig. 8.4.—Ignitron contactor panel FW224A (internal view). (*B.T.H. Co.*)

Non-Synchronous Control

It will be seen from the circuit diagram of Fig. 8.5 that each igniter and its protective resistance is shunted by a metal rectifier, the object of which is to provide an easy path for reverse current and to prevent it passing through the igniter. Now, referring to Fig. 8.5 and assuming an instant at which the anode of ignitron 1 is positive, as soon as the control circuit is closed current passes from the anode of ignitron 1 through the external connection to cathode 2. Here the current divides and the greater portion passes through the metal rectifier 8 in the forward direction and only a small portion passing as reverse current through the igniter and its resistance 6. Current flow continues through fuse 10 and timing circuit 12 (not shown), water flow switch 11 and fuse 9. The current then divides again, and in this case, owing to the direction of flow, most of it passes through resistance 5 and the igniter of ignitron 1. Thus the igniter of ignitron 1 receives a heavy current impulse which fires the main discharge. Immediately the main discharge is set up the igniter circuit is shorted and its current extinguished.

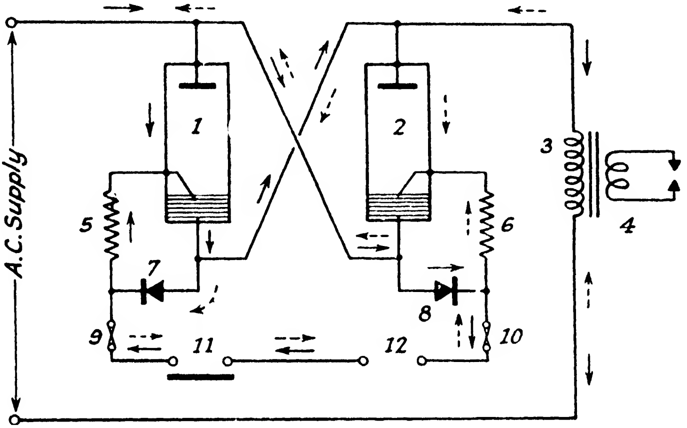


Fig. 8.5.—Circuit of ignitron contactor shown in Fig. 8.4, a typical non-synchronous type of control. (Full and dotted arrows show current paths on alternate half-cycles.)

Owing to the inductive nature of the circuit, the current through ignitron 1 will persist into the following half-cycle of voltage and will cease when the anode of ignitron 2 has become positive. The discharge is then established in the second ignitron in the same way as in the previous case, the direction of current in the auxiliary control circuit being the reverse of that previously described. In Fig. 8.5 the full and dotted arrows indicate the direction of current in successive half-cycles of the supply voltage. Thus each ignitron fires in turn as long as the control circuit is closed, and heavy pulses of current alternating in direction pass through the primary of the welding transformer 3, resulting in still higher currents in the secondary winding 4.

Since the existence of current through the igniter is an essential condition before the discharge can start, it follows that the ignitron cannot fire near the zero point of supply voltage, where current transients in the power circuit will be most destructive. Thus the ignitron type of control has a further advantage over a contactor in producing more uniform welds. The magnetic contactor can close the power circuit near the zero voltage point in the first half-cycle of any weld.

It will be noted that the circuit of Fig. 8.5 is not shown with any timing control. Any suitable timing device, according to the time range to be covered, can be included in the control circuit, and if a magnetic contactor is being replaced by an ignitron.

This is a typical example of a non-synchronous control applicable to spot welding and projection welding, in which the circuit, though timed for a period of current application in the weld, cannot control the precise instant in the positive half-voltage cycle at which the current starts. For welding times exceeding, say, half a dozen cycles the error is not important, but for shorter periods the inaccuracy of fixing the instant of starting becomes an appreciable portion of the whole time of current passage. Hence, to secure the accuracy required for short-time welding the circuit must be modified to give synchronous control.

The inverse parallel arrangement of ignitrons is retained, but each is fired by a control thyratron whose grid circuit is normally negatively biased and fired by a peak voltage impulse at the instant corresponding to zero current in the power circuit.

Synchronous control overcomes what may be an undesirable feature in some welding applications, particularly in seam welding, where both the period of current passage and the interval between successive applications of the current are short and not more than a few cycles.

If the ignitron is not fired at the instant corresponding to the normal current zero in the power circuit, a surge is produced, and although this damps out after a few cycles and is therefore of relatively less importance if the current passes for any appreciable period, it is obviously of importance if the current passes only for the short time during which the surge lasts. Since the configuration of the surge depends greatly on the deviation of the point of firing from the optimum point, it is clear that non-synchronous control may result in some variation in the heat produced by successive welds due to small variations in the instant at which the first ignitron starts to conduct.

Current Adjustment

The current required for different thicknesses of metal can be adjustably preset either by the use of suitable tappings on the transformer or by means of an autotransformer between the supply and the welder. The additional circuit component is a disadvantage in the latter case, whereas high transformer efficiency in the former case cannot be maintained for widely varying loads. Hence the advantage of phase-shift methods of control.

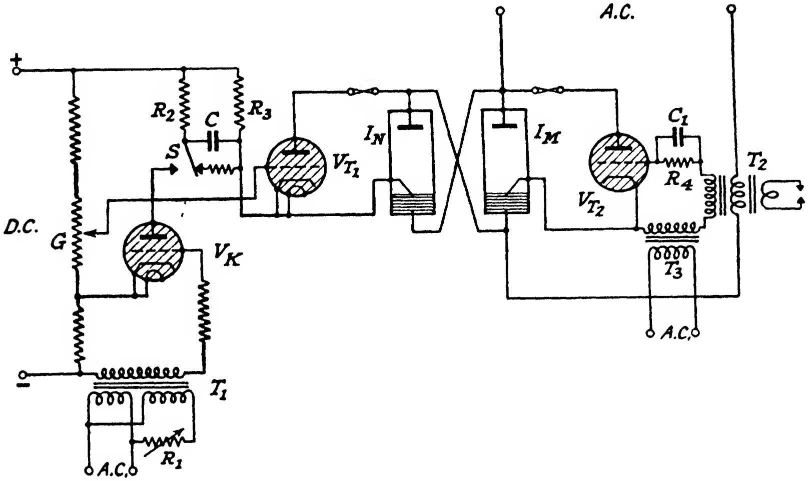


Fig. 8.6A.—Synchronous control on one valve with phase shift and timing circuit, the second valve operating as a trailer.

An example of this is shown in the circuit of Fig. 8.6A. The anode method of firing is applied through an auxiliary thyratron for each ignitron with a keying tube as a means of presetting the firing point. Transformer T1 has a double primary, an adjustable resistance in one winding serving to vary the phase angle at which the peak firing voltage occurs.

With switch S in the position shown, the cathode of thyratron V_{T1} is maintained positive to its grid, so that no discharge passes. Moving S to the left completes the anode circuit of triode VK, which fires at once. The left-hand terminal of condenser C receives a voltage pulse due to the decrease in positive voltage through the drop across R2, and VT1 fires and the discharge passes through I_{N}. Since the condenser does not charge instantly, a time period determined by the value of C and R3 elapses before the cathode of VT1 again becomes sufficiently positive to cut off the ignitron discharge. A second ignitron I_{M} which acts as a trailer to I_{N}, has its own thyratron control (VT2) normally held non-conducting by an A.C. grid voltage applied through T3, 180° out of place with the anode voltage of VT2. A small D.C. component smoothed by C1 and R4 is also applied to the grid of this valve.

As soon as current passes through the primary of T2 when 1_N fires, an impulse is fed back to the control circuit of VT2, firing 1_M on the next half-cycle; 1_M and 1_N thereafter continue to fire in turn until the expiry of the preset timing period.

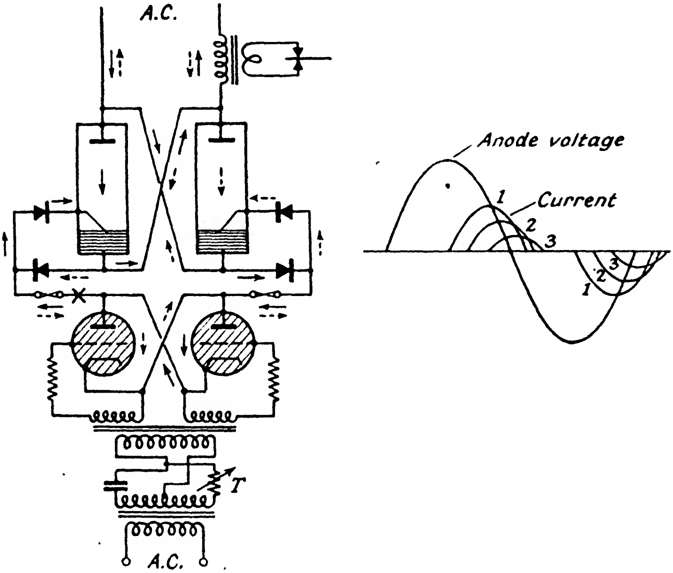


Fig. 8.6B.—Fully synchronous control with phase shift on both valves. (Full and dotted arrows show current paths on alternate half-cycles.)

In this type of circuit there is direct synchronising control only on the first ignitron. Also, since the cathodes of the two control thyratrons are at different potentials, they cannot be directly connected to the same timing circuit.

It should be noted that the possibility of using the second ignitron as a trailer depends on the existence of circuit inductance, which enables the current to persist into the following half-cycle of anode voltage when the anode of the second ignitron becomes positive and this valve is in a condition to conduct. A trailer circuit of this type also has the advantage that it avoids the possibility of conduction for an odd number of half-cycles and the existence of a direct-current component in the welding transformer, with consequent magnetic saturation.

Rotary commutators and impulse generators have been employed as alternative controllers. Also the grids of the two controlling thyratrons may be coupled to the arms of a phase-shifting bridge so that each ignitron receives a firing impulse displaced by 180° from the firing impulse of its partner. Fig. 8.6B shows a fully synchronous control applied to both ignitrons with current adjustment through phase shift in the transformer T.

Dual Timing Circuits

Resistance seam welding involves a succession of spaced spot welds for the purpose of securing a gastight joint between two sheets of metal. To secure uniformity in the seam the welding current must be applied for an accurately measured time interval and then cut off for a further definite period, the on and off periods being regularly recurrent.

Consequently, two independently adjustable timing circuits are required, one for the "on" and one for the "off" period. Electronically this may be attained by the use of two RC circuits, the operation of one of which prepares the circuit of the other. Alternatively a circuit analogous to a two-thyratron flip-flop or inverter can be used in which the circuit constants are chosen so that the times of conduction in the two control valves are unequal. Furthermore, for pulsation welding, where the welder is required to lock out after a preset number of such cycles, each operation of the welding circuit may be arranged to transfer a fixed charge to another condenser, which in turn will render the whole installation inoperative as soon as its potential reaches a preset value.

For details of these circuits and a number of other special auxiliary devices which are utilised in welding control circuits the general references under this heading should be consulted.

Stored Energy Welders

The use of high peak current loads may result in some unbalance on a three-phase system. Consequently in cases where, for instance, the welding of light alloys demands very high peak currents it may be preferable to employ a circuit in which the energy required for welding is stored in a condenser or an inductance. Where this can be done, the energy required is taken from the line in the storage system at a much lower rate over a longer period.

Storage welders cannot give continuous operation, since a period is necessary for the energy to build up in the storage system after each discharge.

Fig. 8.7 shows one circuit of this type in outline. Here a three-phase rectifier 1 maintains the charge on condenser 2, which may be several thousand microfarads at a potential of several kilovolts through a charging resistance 3. In the grid circuit of the control thyratron there is a similar condenser charging circuit. When starting switch 4 is closed, condenser 5 discharges through the transformer primary 6 firing the ignitron. Condenser 2 then discharges a heavy current surge through the welding transformer.

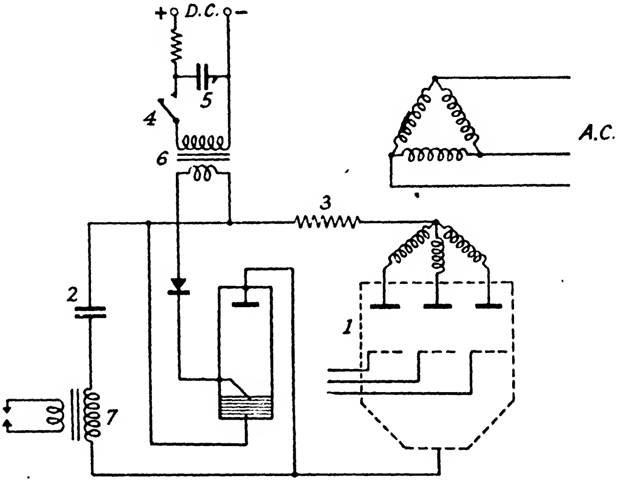


Fig. 8.7.—Storage type of welder.

The magnitude of the current surge can be adjusted by altering the condenser charging voltage, while limited control of the wave form may be obtained by varying the condenser capacitance and/or transformer tappings.

Magnetic types of storage welder involve the use of a high inductance reactor which forms part of the welding transformer circuit.

The magnetic field of this reactor is built up prior to the welding period by an auxiliary igniter which prevents the welding circuit operating during this time. At the instant of welding the main ignitrons are fired and the induced current due to the collapse of the reactor magnetic field passes through the primary of the welding transformer.

The ignitron thus performs the function of a low-resistance switch to trigger the stored energy at the correct instant and suppress the reverse current since a condenser discharge is normally oscillatory. For the latter purpose an additional shunt-connected ignitron is often employed, and fires by the induced voltage which appears when the energy of the welding transformer begins to fall. To prevent saturation of the transformer core, means are generally provided for reversing either the condenser polarity or the polarity of the primary leads at successive operations. For more complete information on the application of discharge tubes to electric welding reference should be made to specialised works.[8.8, 8.14]

Magnetically Controlled Valves

An electron stream can be deflected by a magnetic field (*e.g.*, cathode-ray tube), so that it would appear almost self-evident that some control over the discharge of a gasfilled valve could be effected by a suitably disposed externally applied magnetic field. Such devices have been developed and used industrially. To make such a control effective necessitates certain structural alterations in the electrode design of the voltage-controlled valve. Certain designs of voltage-controlled valves lend themselves to magnetic control and were, in fact, the original types on which magnetic control was experimentally investigated.

Magnetically controlled mercury vapour valves were marketed in America under the name of Permatron by the Raytheon Co. about ten years ago, but do not appear to have acquired any importance in industry. Consequently, although they are of technical interest, it is not proposed to deal with them here in detail, and the reader is recommended to consult the appropriate references for further information of their historical background.[8.11, 8.12]

The original permatron consisted of a tubular bulb with the heated cathode mounted at one end and the metal anode at the other end. This tube contained a cylindrical electrode known as the collector mounted with its axis down the centre of the tube. The coils which provide the magnetic control encircle the tubular bulb in the region where the electron velocity is low and have a common axis with the bulb. There is no grid. When the magnetic field is applied, electrons emitted from the cathode are deflected towards and impact on the collector, and are thus prevented from attaining sufficient velocity to produce cumulative ionisation. The formation of positive ions is, in consequence, prevented and the discharge cannot start. If the magnetic field is removed or reduced below a certain intensity, the valve fires and continues to do so until the anode voltage is reduced below the ionising potential, as in the case of the grid-controlled valve. The permatron thus bears considerable resemblance to the triode in that there is, for every value of anode current, a critical minimum magnetic field which will restrain the discharge.

Some adjustment of the performance is possible by applying a bias voltage to the collector so that the tube thereby becomes analogous to a tetrode. Phase shift in the magnetic circuit can be employed to secure quantitative control of the mean anode current when the anode voltage is alternating by varying the point in the anode voltage cycle at which the valve fires. Variation of the magnetic reluctance provides a further means of adjusting the mean anode current and enables synchronisation of the discharge with some rotating part of a machine to be secured.

The power consumption in the control circuit is small, and though it increases with the size of valve it is relatively smaller the larger the valve. About one watt is sufficient to control about 200 kw. Alloys, graphite and low-permeability nickel steel are employed in the electrode construction, since it is necessary to exclude magnetic material from any area where it might adversely affect the flux distribution of the controlling field, though in some designs iron is intentionally introduced in order to confine the magnetic field in the desired direction.

Advantages

Magnetically controlled valves have the merit that the control circuit is entirely separated from the discharge path and can be earthed without reference to the cathode or anode potential. As distinct from the triode, the operation is not complicated by the existence of grid current which has no parallel feature in the magnetic tube.

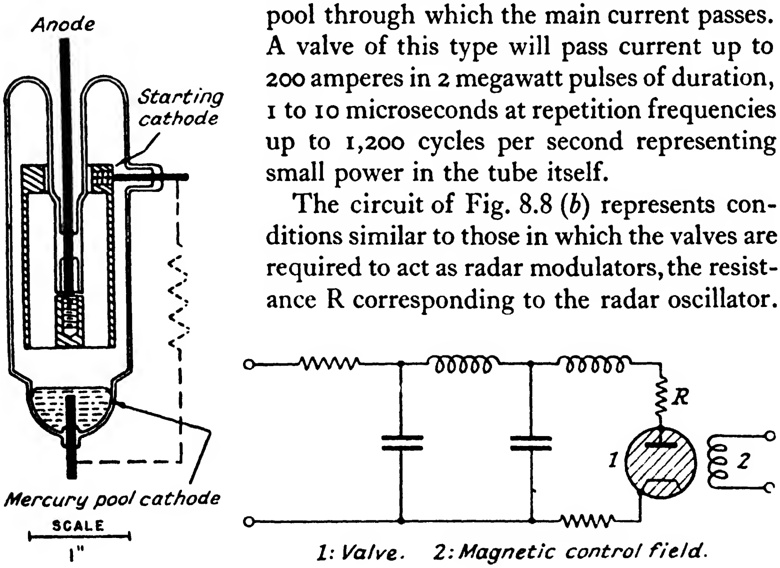
Though these factors enable a certain degree of simplification to be secured in some problems, there has been no general adoption of magnetic tubes of this type, and as far as is known none have ever been made on a commercial basis in this country. In the great majority of cases control by magnetic field has no advantage over potential control on a grid, and there is the additional necessity of a field coil and the space it occupies and a source of current to excite the magnetic field.

During the last war there was some revival of interest in the magnetic tube, and as in the case of many other special devices with little or no industrial tradition, a modified form of this valve found service in accessory equipment for defence or destruction.

Pulse Modulation

As pulse modulators for magnetrons in radar equipment, designs of tube in which the discharge can be started by the sudden application of magnetic field were developed.[8.13] In the type shown in Fig. 8.8 (*a*) there are two co-axial cylindrical electrodes with a mercury pool as an auxiliary cathode. A glow discharge in the mercury vapour between the cylinders is initiated by a magnetic pulse of about 350 oersted, and bombardment of the pool by ions from this glow discharge produces an arc spot on the pool through which the main current passes. A valve of this type will pass current up to 200 amperes in 2 megawatt pulses of duration, 1 to 10 microseconds at repetition frequencies up to 1,200 cycles per second representing small power in the tube itself.

The circuit of Fig. 8.8 (*b*) represents conditions similar to those in which the valves are required to act as radar modulators, the resistance R corresponding to the radar oscillator.



(*a*) (*b*)

Fig. 8.8.—Magnetically controlled valve and circuit representing conditions of use as a pulse modulator in radar equipment.

Cold Cathode Tubes

Like its hot cathode counterpart, the cold cathode grid-controlled triode is by no means a new device. Prior to the war its manufacture was practically confined to America and Germany, and although tubes of foreign manufacture were obtainable in this country, usually under the name of grid glow tubes, there was insufficient industrial demand for them to encourage British manufacturers to take up their production seriously. During the war there arose demands from the combatant services for triggering devices which had to be employed under conditions where the provision of an electric supply for heating the cathode could not be tolerated, notably for proximity fuses for explosive missiles, and interest in the grid glow tube was in consequence forcibly resurrected. Study of the shortcomings of some of the pre-war tubes resulted in the evolution of units of greatly improved performance, and since the war attempts have been made to popularise the use of these devices for industrial use, since for some purposes they have decided advantages.

The absence of any source of power for heating the cathode with the attendant need for preheating which is characteristic of the hot cathode triode is, of course, a desirable feature. In some instances it may be a most important one provided it can be secured without seriously restricting other desirable characteristics which the problem in hand may require, otherwise the existence of a cold cathode will not be all pure advantage.

It should be noted that functionally the thyratron, the grid glow tube and the ignitron have many features in common. In each there is a pair of electrodes, between which the current passes to the external circuit, and a control element whose purpose is to determine the instant of initiation of the discharge between the main electrodes. In each case a critical relation exists between the condition of the control element and that of the main electrodes which is just sufficient to prevent the valve from firing, and once the discharge has been established the control element has no further power to influence either its magnitude or its duration. In each case the potential across the main electrodes when the discharge has been established is practically constant and independent of the current, which is determined by the total circuit resistance. But apart from marked differences in other operational characteristics, the magnitude of the current is of a totally different order in the three cases, so that the practical applications do not greatly overlap even though considerable similarity can be recognised in some of the circuits in which all these discharge devices are used.

The Cold Cathode Diode

We will consider first the operation of a cold cathode gasfilled diode. Devices of this type have been in common use in industry for many years as low-level illuminants and live-circuit indicators. Neon or an admixture of neon and argon at low pressure constitutes the gasfilling. In illuminants the pressure is of the order of 10 mm., but in triodes employed for relays, voltage regulators or rectifiers, for which purposes they are mainly employed, a pressure of 30 to 40 mm. is often used. Consider a unidirectional voltage applied to the electrodes. Unlike the case of the hot cathode tube, there is no source of thermions inside the bulb to provide means of current transfer between the electrodes. A few ions, however, are always present in gas under reduced pressure due to various causes, such as cosmic radiation, which is universal, minute quantities of radioactive elements, etc. We need not here enquire further into the source of these ions; suffice it to admit that a few ions do exist. These will be directed by application of the potential difference between the electrodes to move towards the positive pole.

The current represented by this movement of ions is extremely small, at the best possibly of the order of a microampere. For many practical purposes it may be considered that there is no current under these conditions, and the power taken from the voltage source is zero.

If the voltage between the electrodes is increased, the ionic velocity increases until a potential is reached at which some of these ions produce others by disruptive collisions, and if this process is increased, cumulative ionisation results, positive ions are driven back on to the cathode and produce a limited supply of electrons. Breakdown of the path between the electrodes thus takes place and the gas in the tube becomes a conducting medium.

The unheated cathode is, however, not a copious source of electrons, and its emissivity is relatively low. Consequently the current through the valve is of a lower order compared with that in a gasfilled triode.

The passage of current between the electrodes when the valve fires is visible as a coloured glow characteristic of the particular gas present. The position of the visible glow depends on the electrode geometry and the gas pressure. In the case of small neon tubes employed as indicators the glow appears localised near the surface of the negative pole when the voltage applied is unidirectional, and such devices are known as negative glow tubes. This feature enables them to be used as polarity indicators on direct-current supply or to identify an unknown supply as being direct or alternating, according to whether the glow appears at one or both electrodes.

In tubes with wider electrode spacing the visible discharge may extend from the positive pole. In very small tubes the electrode system may be so compact as to render it difficult to decide by inspection on the precise location of the glow.

For more detailed information on the physics of the glow discharge and its relation to gas pressure, as well as the influence of the latter factor on the firing voltage (Paschen's Law), reference should be made to publications dealing with the physics of electric discharges in gases.[8.15]

The voltage at which the discharge is established is known as the striking or firing voltage, and at the instant the current is established the voltage across the triode drops to a lower value known as the sustaining voltage. The current is then practically independent of the voltage across the valve and limited only by the total resistance in circuit (Fig. 8.9).

After the discharge has been established, current will continue to pass between the electrodes even when the voltage is reduced below the point at which the discharge started. If the voltage is reduced considerably (30 to 50 volts lower, according to the design of the tube), a point will be reached at which ionisation can no longer be maintained and the discharge is suddenly extinguished.

The voltages referred to, of course, vary widely according to the electrode design, spacing, composition and pressure of the gas, etc., and there is likely to be appreciable variation between individual specimens of the same nominal rating due to manufacturing tolerances which it may not be possible to control closely. For instance, a diode which has a striking voltage of 170 volts may have an extinction voltage in the region of 130.

Of course, diodes can be made to operate at much lower voltages, but in all cases the extinction voltage is high compared with the voltage necessary to maintain the arc in a thyratron or an ignitron, and the voltage range between the striking and extinction voltage is a characteristic of the cold cathode tube.

The current which can pass without disintegration of the electrodes through overheating is limited by the permissible energy dissipation at the cathode. Since the cathode has no external source to draw upon to maintain its emissivity, this energy is quite small. When the cathode current density exceeds about 20 ma. per sq. cm. the cathode surface is rapidly disintegrated by positive ion bombardment. Since large-area cathodes are impracticable, the total current is usually limited to something less than 100 ma. As with the thyratron, the discharge path has negative resistance characteristics, and an external resistance to limit the current is essential if the device is not to have a very short life.

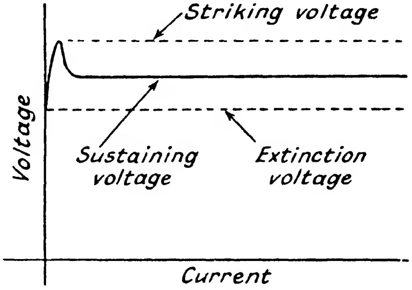


Fig. 8.9.—Voltage/current curve of a typical cold cathode discharge tube.

In some commercial neon lamps used as illuminants there is sufficient space available to accommodate the necessary resistance in the end of the cap.

If, in our hypothetical tube, the electrodes are identical in size and shape, then obviously either can function as the cathode, and if alternating voltage is applied between the electrodes, current will pass in both directions during those periods when the voltage has exceeded the striking voltage, but has not fallen to the extinction value. If the electrodes are unequal in area, current will pass more readily in the direction in which the larger electrode is the negative pole, and by making the electrodes widely different in size incomplete rectification is secured due to the asymmetrical current characteristic.

Rectification is further assisted by suitable preparation of the cathode to produce a surface of relatively low work function.

Triodes.—Many instances have in the past been described in which a commercial form of diode has been converted into a triode by the addition of the control element as a wire wrapped round the bulb in a suitable position or as a layer of tinfoil stuck to the external surface of the glass, but such arrangements are usually makeshifts and cannot, of course, be expected to operate as well as electrode systems designed specifically as relay triggering devices.

A common form of cathode is of nickel coated with barium or strontium formed by reduction of these metals from their oxides by positive ion bombardment.

The control electrode or grid is set relatively close to the cathode. If the voltage between anode and cathode is greater than the extinction voltage, but less than the striking voltage, the function of the grid is to initiate the discharge between the main electrodes through a sudden voltage impulse from the external circuit, which causes a change in the voltage gradient inside the tube sufficient to break down the path between cathode and anode.

The control grid is always positive to the cathode and, unlike the case of the thyratron, is not greatly different in voltage from the anode.

Like the thyratron, the control grid normally has no ability to stop or vary the discharge when once the tube has fired, and the current through the tube can be extinguished only by introducing into the circuit a condition which reduces the anode voltage below the extinction value. Resetting is performed in one of several ways precisely analogous to the case of the hot cathode tube—viz., by opening the circuit, by injection of a reverse voltage into the circuit, by the discharge of a condenser, or by the use of an alternating supply when the current automatically ceases, when the voltage passes through the zero.

Providing no restriction is placed on the polarity of the voltages applied to the electrodes, there are six different ways in which a discharge can pass between two electrodes in a cold cathode triode. These are obviously the permutations of the three electrodes in pairs. Such effects are, of course, only involved when departure from the normal procedure of firing the triode by a positive grid voltage rather less than the anode voltage takes place. Fig. 8.10 shows the conditions under which a discharge can pass between the electrodes of a typical cold cathode tube, in this case the R.C.A. type OA4G. These are indicated by the lettering AB grid to anode, BC cathode to anode, CD cathode to grid, DE anode to grid, EF anode to cathode, FA grid to cathode. The closed figure embraced by these limiting conditions indicates an area of non-conduction, since any point within the figure represents conditions where the potentials applied do not enable the valve to fire.

Life.—The life of a cold cathode tube depends on what takes place during the time current passes through it. It is in no way affected by the time during which the device is connected to the supply but passing no current.

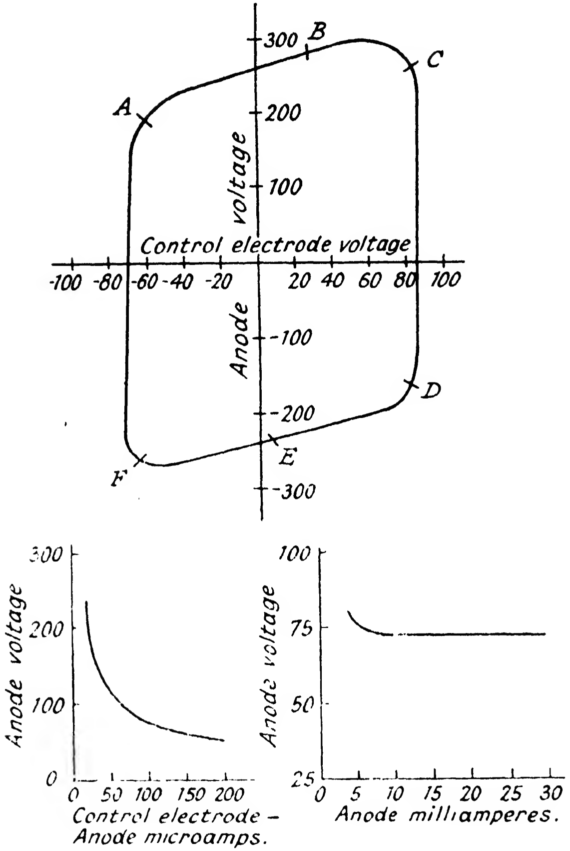


Fig. 8.10.—Conditions of discharge in a cold cathode triode. (*R.C.A.*)

A small amount of active material proportional to the current and its duration is removed from the cathode surface each time the tube fires.

The useful life terminates when either (1) the cathode has become so deprived of active material that the tube ceases to fire, or (2) partial clean up of the gas takes place, resulting in a progressive rise in striking voltage.

The life is normally specified in milliampere hours, so that with a tube having a life of, say, 400 ma. hours, if the current and duration are kept down to a minimum, this may represent several hundred thousand flashes, or if the tube is fired intermittently the life may be almost unlimited.

Notation.—There appears to be no universal nomenclature for cold cathode tubes. Fig. 8.11 (*a*), (*b*) and (*c*) show diagrams common in American literature. The reason for the wide difference in representation of the hot cathode tube in the case of the first two is not clear. Fig. 8.11 (*d*) and (*e*) occur in English literature. Fig. 8.11 (*e*) is rather a compromise mixture of accepted British representation of a triode and American symbolism for a gasfilled tube. Since the most fundamental difference from the hot cathode tube is the cathode itself, it seems logical to retain the symbolism of the anode, grid and gasfilling, with a distinctive symbol for the cathode. This has been adopted in Fig. 8.11 (*f*), which will hereafter be retained except in the case of some special devices, for which a distinctive method of representation has already been adopted.

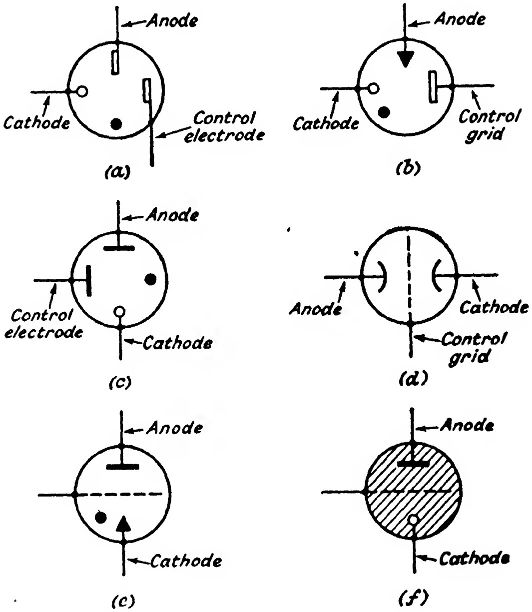


Fig. 8.11.—Methods of representing cold cathode triodes.

Cold Cathode Triode as a Relay

Fig. 8.12 shows a typical arrangement for using the cold cathode triode as relay. The sudden application of a potential between the control electrode and the cathode exceeding the breakdown voltage will start the main discharge, providing the potential between anode and cathode exceeds the extinction voltage. The current in the gap between the control grid and the cathode may be referred to as the grid or transfer current, and does not greatly exceed the current which passes between the main electrodes before the main discharge is established, but this current becomes large at the striking voltage of the main gap. The grid current depends greatly on the composition of the gasfilling. Neon has the smallest transfer current and lowest striking voltage. Admixture with argon increases both. Both the duration and the amplitude of the firing signal have their influence on whether the discharge will start or not, and the effect of one is roughly inversely proportional to the other. For neon the deionisation time is of the order of 10 millisecs., and is therefore roughly 100 times that of the hot cathode valve. In general the introduction of argon reduces the deionisation time but increases the grid current, so that the device becomes less sensitive.

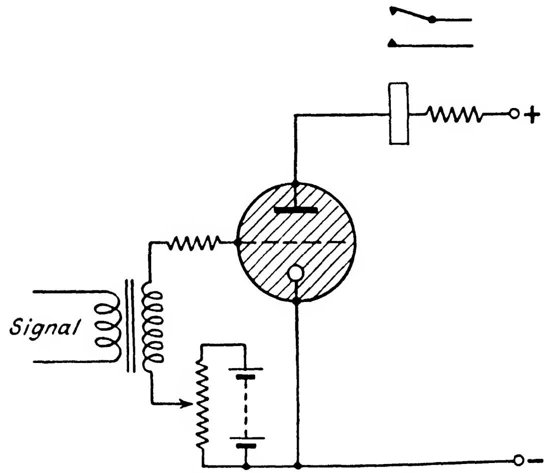


Fig. 8.12.—The cold cathode triode as a relay.

The switching on of the anode circuit can cause premature starting of the discharge, and a surge-limiting resistance is frequently included in the anode lead to obviate this if the anode circuit is subject to a separate switching control. Usually the grid current determines the triggering action of the main discharge. The grid to cathode voltage drop remains sensibly independent of the current over a wide range. The voltage required to trigger the discharge consists of this constant drop plus the voltage drop in the grid resistance at the current value which causes the valve to fire.

Methods of Operation

It would appear that there are two methods of operating a cold cathode triode.

In the first, the resistance in the control grid circuit is so low that when the voltage on this electrode reaches the point where it initiates the main discharge, a relatively large current flows in the grid circuit and the discharge will always start. In this case the disadvantage is that the constancy of triggering is dependent on the constancy of the grid starting voltage, which is usually the least dependable characteristic in this type of tube. In addition, a large current may pass in the grid circuit if the grid voltage rises much above the striking voltage.

The second method is to include a high resistance (10 megohms) in the grid circuit so that at the grid starting voltage the current passed is insufficient to cause the main discharge to start, and consequently the grid voltage must be raised further before the tube fires. The grid current is a more important factor in determining the triggering condition than any figure for voltage.

Before the main discharge passes, the grid current is determinable with much less accuracy than in the case of a hot cathode valve, since the starting of the discharge is affected by the surface condition of the electrodes, and this is subject to change after each discharge has been established, resulting in some variation in starting voltage. There is also some evidence that over a certain range of current the discharge is not stable, and oscillations may be produced at the instant of firing whatever the value of the external resistance.

In many circuits where cold cathode tubes are employed the triode often has only the advantage that it enables the main discharge to pass at a lower voltage between the main electrodes than would be possible if the grid were not present. Consequently, a triode is often of no particular merit and the circuit will function equally well with a diode, though at somewhat higher applied voltage, which is not always a disadvantage.

Most cold cathode tubes exhibit feeble photoelectric properties, usually insufficient in magnitude or regularity to enable the tube to be used as a photoelectric cell, but sufficient to cause irregular performance if an attempt is made to secure repetition accuracy of performance under varying conditions of illumination—*i.e.*, daylight and darkness. The tubes are therefore best operated in a light-tight enclosure.

The merits and disadvantages of the cold cathode triode can thus be summarised:

Advantages:

(1) No power consumption in the quiescent state.
(2) Can be used immediately the circuit is completed with any preswitching of the cathode.
(3) Indefinitely long life under infrequent operation.
(4) Unaffected by normal temperature changes.
(5) Accessory circuit equipment is a minimum.

Disadvantages:

(1) Characteristics much less uniform than those of the hot cathode tube.
(2) Limited current-carrying capacity.
(3) Affected by external electrostatic fields.
(4) Ionisation and deionisation periods considerably longer than in the case of the hot cathode valve.

Some cold cathode triodes are designed to work into a high impedance circuit, consequently a thermionic valve is required in the output circuit and the most attractive feature of the conventional trigger tube circuit—viz., the absence of devices involving heated cathodes—is consequently lost, though the advantage of the need for any preheating time and the switching controls to secure it remains.

The cold cathode triode in some instances provides a convenient means of securing a frequency selective relay circuit. Where a large number of such circuits have to be switched on or off by an injected alternating signal of specified frequency, the absence of any power-consuming device in the control circuit during the quiescent state is a considerable advantage. In the circuit of Fig. 8.13 (*a*) the valve will fire and actuate relay A at a single frequency—viz., that at which the LC circuit is resonant. Before the signal frequency is injected into the line the steady voltage is insufficient to cause the valve to fire. A modified circuit is shown of Fig. 8.13 (*b*), the variation from the previous case producing higher sensitivity with a certain degree of adjustment by means of a variable condenser. C2 is about 20 per cent. larger than C1, and a frequency within the range of 200 to 500 Kc is employed for the triggering signal to permit of the use of convenient sizes for the inductance and capacitance.

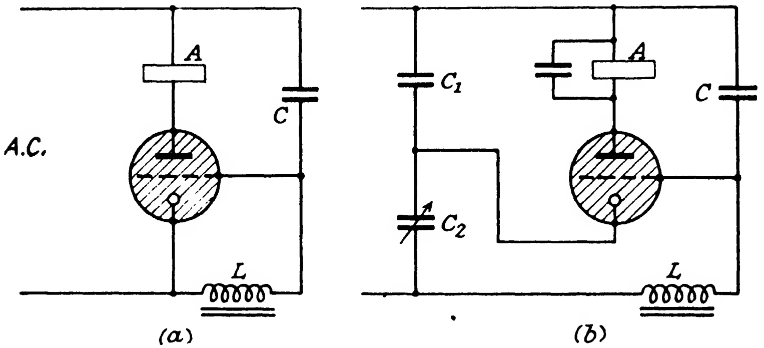


Fig. 8.13.—(*a*) A cold cathode discharge valve in a frequency selective circuit. (*b*) Modification of (*a*) to secure higher sensitivity.

Another case arises in the possible application to the remote switching of radio receivers, or in fact any similar type of equipment, by the use of a radio-frequency switching signal, so that the triode is fired when the peak radio-frequency voltage exceeds considerably the voltage required to cause breakdown of the control gap.[8.16]

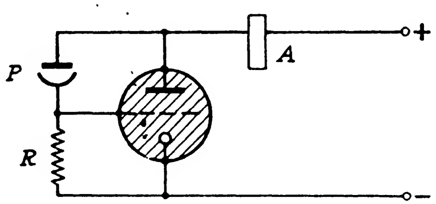


Fig. 8.14.—Photoelectric relay control. Suitable adjustment of the voltage enables the valve to fire and actuate relay A when the light on photocell P is suddenly increased.

Another method of using the tube as a relay is to employ the circuit of Fig. 8.15, which is referred to later.

Fig. 8.14 shows the tube adapted to a simple photoelectrically controlled circuit. The applied voltage is adjusted so as to be just below the striking voltage. A sudden increase of light on the photocell makes the control sufficiently positive to initiate the main discharge.

The circuit is exactly analogous to the corresponding circuit employing the hot cathode valve. Operation in the reverse direction—*i.e.*, when the light on the photocell is suddenly reduced—can be obtained by reversing the position of the photocell P and the resistance R. The voltage adjustment to secure the most sensitive condition will probably not be the same in the two cases.

A special application of the cold cathode triode for relay circuits comprises a recording arrangement which indicates when the load on an electrical circuit exceeds a preset maximum. Here again its merit lies in the fact that it is not a power-consuming device. For instance, if it is required to record when the load on a motor exceeds its maximum rating, a cold cathode triode such as the Ferranti K3

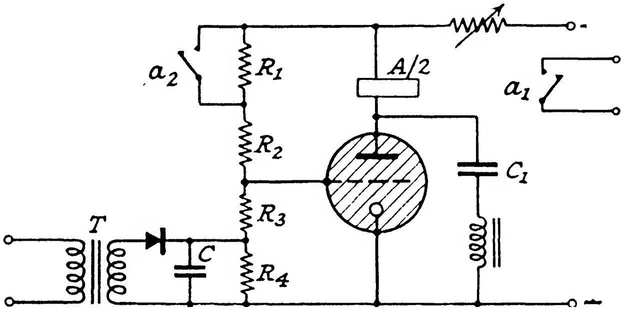


Fig. 8.15.—Relaying circuit for recording purposes.

may be used in a circuit like that of Fig. 8.15. The grid of the triode is adjusted by suitable disposition of the resistances R1 – R4, so that its voltage is normally insufficient to start the discharge. The signal circuit is coupled to the relay by the transformer T. If the controlling factor is a voltage change, it will be fed direct to the transformer primary; if a current change, the transformer primary will be a shunt to the current circuit. In either case condenser C will receive a charge, the voltage of which will be proportional to the peak signal voltage and the polarity such as to increase the tendency for the triode to fire. The point of firing is thus preset by adjustment of the resistances R1 —R4 and the signal input circuit.

When the triode fires, relay A/2 closes and completes the recording circuit through a_1. Contact a_2 shorts the resistance of R1 and raises still further the triode grid voltage, producing a condition which still further conduces to firing the tube and secures positive operation. The discharge of C1 resets the triode.

This circuit involves the same principles as those already referred to in Fig. 3.2, page 57, with one notable difference. Since the permissible peak current through any cold cathode tube is relatively low, C1 can be a much smaller condenser. Consequently the rate of charge and discharge of C1 will be much higher. In general, therefore, the grid impulse will give rise to several discharges, so that current through the tube will persist at least as long as the grid impulse. For relay operation the circuit constant should be such that this cycling frequency is not low enough to cause the relay to chatter, nor high enough for the grid to lose control. Thirty to 50 cycles per sec. is generally suitable.

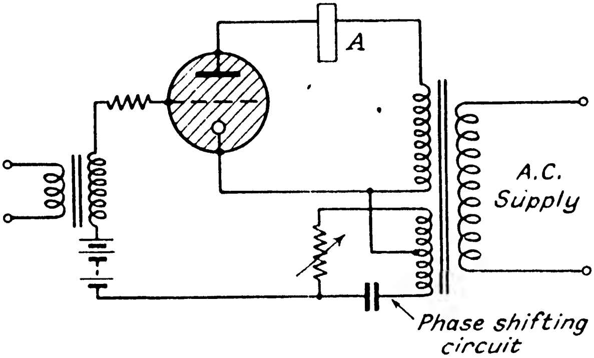


Fig. 8.16.—Mean current through the triode adjusted by phase control of the grid voltage.

As with a thyratron, phase control circuits may also be applied to the cold cathode tube (Fig. 8.16).

By feeding the anodes of two similar cold cathode tubes from a common direct-current source, the anodes being interconnected by a commutating condenser and each anode coupled to the control grid of the other triode through a small condenser, a square wave oscillator circuit can be formed. The mode of operation is again exactly analogous to the same type of circuit using hot cathode triodes, but since the power output is necessarily small and the operating voltage range of the valves restricted, the use of cold cathode tubes for this purpose is very limited.

The circuits just referred to can, in the same way, be extended to scaling counter-circuits, using a chain of valves in which each impulse fires one valve, prepares the next, and resets the previous one, so that each impulse advances the condition of conduction through the series of triodes. As the firing impulse required is higher and the ionisation and deionisation periods longer, with a corresponding lower limit of operating frequency, the hot cathode tube is usually preferred for counting circuits of this type.

Rectification

The possibility of a cold cathode tube acting as a rectifier on alternating supply depends on the existence of asymmetrical current characteristics (Fig. 8.17) in the two directions, a condition which is favoured by the use of a cathode of large area with a surface coating of a substance of low work function. In view of the limited current which the tube will pass, it is little used primarily as a rectifier. But it may have indirect applications as a polarity indicator, giving visual indication by the disposition of the discharge relative to the electrodes or by operation of an indicator by its function as a polarised relay.

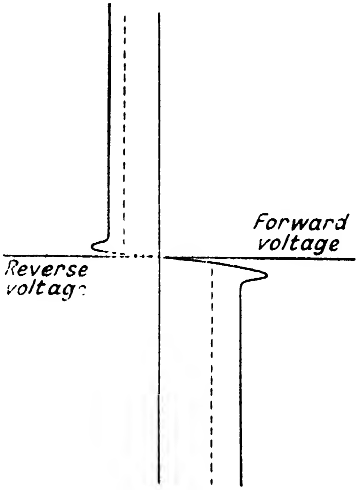


Fig. 8.17.—Rectification by cold cathode diode due to asymmetrical voltage/current curve.

The function of the control electrodes in such cases is to assist the firing of the discharge in the required direction. An instance of such an application has been described for selective ringing on communication circuits.[8.17] The arrangement is shown diagrammatically in Fig. 8.18, where two ringing circuits are shown. The signal operating the ringers consists of A.C. with superposed D.C. On each local circuit the triode operates as a rectifier, and since the local circuits are connected between either main and earth, the polarity of the D.C. signal will determine which ringing circuits are operated.

In this instance there is the advantage that the absence of current flow during the non-operate period prevents noise in the communication circuits.

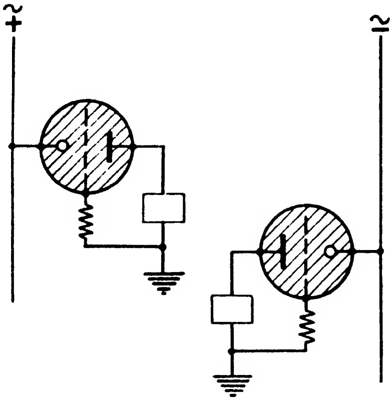


Fig. 8.18.—Selective ringing circuits.

Relaxation Oscillators

Recurrent discharges through the triode to produce a source of regularly timed impulses are easily secured by a circuit of the type shown in Fig. 8.19. Resistance R is of the order of megohms and is high enough to prevent a discharge from the direct-current supply passing through the triode. Condenser C, however, gradually acquires a charge until the potential across its terminal is sufficient to fire the triode. The function of the inductance is to maintain current through the triode until the condenser voltage falls below the striking voltage of the valve, at which point the discharge is extinguished and the condenser starts to recharge and repeat the cycle. The oscillation period is determined by the values of the condenser, resistance and inductance. The control grid is shown dotted in Fig. 8.19 and connected through a resistance to the anode. Here again, if the supply voltage is high enough, the circuit will function without the use of the control grid, and circuits of this kind, using the discharge tube as a diode, are used more for timing circuits than as relaxation oscillators, the condenser and charging resistance being chosen in value

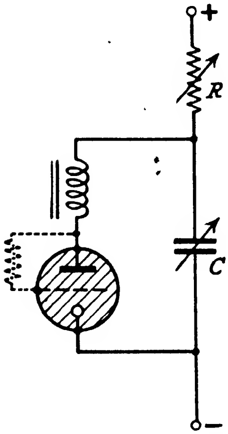


Fig. 8.19.—The cold cathode valve in a relaxation oscillator circuit.

to secure a repetition cycle of anything up to, say, 30 or 40 seconds.

With suitably selected components this arrangement can also be employed as a relay circuit, differing from the usual form of triggering circuit by the fact that the grid potential determines both the starting and stopping of the discharge, because the arc is extinguished and restrikes each time the condenser potential goes through its voltage cycle. Therefore in this case the relaying action persists as long as the control electrode voltage is favourable to the starting of the discharge. In such a circuit the relay coil takes the place of the inductance of Fig. 8.19. The frequency of oscillation will be selected so that it is not too low to permit the relay contacts to chatter nor too high to be outside the range of grid control. A frequency of 30 to 40 per sec. would probably be suitable, though the final selection will depend on the characteristics of the relay.

Timing Circuits

Typical circuits for securing a delayed switching operation are shown in Figs. 8.20 (*a*) and 8.20 (*b*). In Fig. 8.20 (*a*) the circuit functions in the same way as the oscillatory arrangement of Fig. 8.19. The charging resistance R1 is of the order of megohms. The time period starts when switch S is closed. As soon as the voltage across condenser C reaches the striking voltage of the valve, a discharge

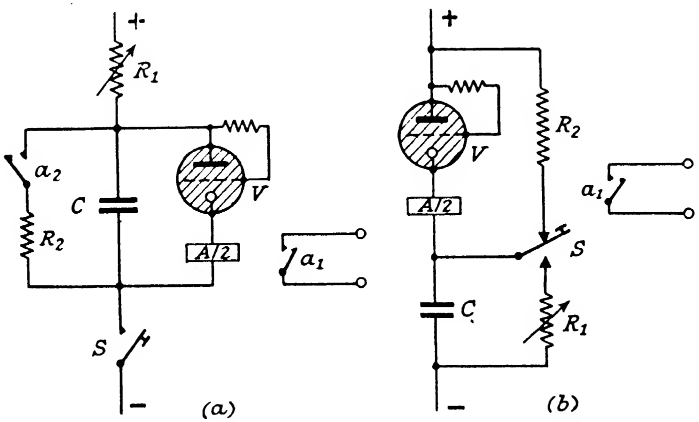


Fig. 8.20.—(*a*) Parallel connection of condenser and cold cathode valve to secure time delay; (*b*) series connection of condenser and cold cathode valve.

passes through it and impulses the relay A/2. The condenser voltage then falls below the valve extinction potential and the discharge ceases. Thereafter, condenser C starts to recharge and the circuit repeats the cycle. Each discharge therefore produces a momentary closure of relay A/2, which actuates some further controlled device through contact a_2.

The object of contact a_1 is to short circuit the condenser where the relay A/2 closes, so that the condenser always starts to charge from zero. Since the extinction voltage of the cold cathode valve is only some 30 to 50 volts below its striking voltage, the condenser C would otherwise be left with a residual charge at an indefinite potential, which would introduce a variable into the timing period. Resistance R2 is included to limit the short-circuit current of the condenser and protect contact a_2 from damage. Relay A/2 must, of course, have characteristics suitable for responding to the short current pulse from the condenser discharge. The time period is determined by the value of the resistance R1 and the condenser C, the time constant CR1 being the time required for the condenser to acquire 0·63 of its final potential.

About 1 mF. is the practical lower limit for the condenser capacitance, otherwise the energy of the discharge is too small to impulse a robust form of relay. If the time period is extended beyond about 60 seconds, leakage of the condenser, which is unavoidable, causes the time period to become less consistent as the time is increased.

If the supply voltage is not greatly in excess of the striking voltage of the valve, the rate at which the condenser voltage rises near the firing potential will be relatively slow and the discharge point less sharply defined. In order to secure satisfactory repetition consistency in the timing period, the charging voltage should be at least 100 volts in excess of the striking voltage of the valve.

The inclusion of a small half-wave dry-plate rectifier in the charging circuit enables operation to be secured when the supply is alternating. In this circuit the condenser C starts the timing period in the uncharged condition, so that if switch S is closed and then opened before the valve fires, the condenser, assuming loss by leakage is negligible, will partially charge and then continue to charge when the switch S is again closed. If the switch closure is intermittent, the timing period for which the circuit is set indicates the total time during which switch S has been closed.

A timing period can also be secured by the circuit of Fig. 8.20 (*b*), in which the valve and condenser are series connected. This circuit utilises the discharging time of the condenser, and the period starts with the condenser fully charged to the supply voltage. When the switch S is moved from its upper to its lower contact, condenser C starts to discharge through resistance R1. The condenser potential then falls, while that across the valve rises until the striking voltage is reached, when a momentary current pulse through the valve recharges the condenser, which then begins to discharge and repeat the cycle. In this instance, returning the switch to its upper contact cancels the time period which has elapsed since the valve last fired, providing it remains long enough in this position to enable C to recharge completely.

If switch S is moved intermittently from one position to the other, relay A/1 operates only when switch S has closed on the lower contact for an uninterrupted period equal to the period for which the circuit is set. This circuit can therefore be used to indicate when a contact closure persists for more than a specified time.

In both these circuits, if the operating switch remains closed, the relay is impulsed by the valve continuously at the preset frequency.

If it is required to give one delay period only, as, for instance, where the switching of a controlled circuit is desired, the relay can be made to lock in through a separate retaining contact so that the valve gives one flash only and then isolates the timing circuit. If the timing and the controlled circuit are fed through a common switch, the switching-off operation automatically isolates both circuits and the timing period comes in only at the switching-on.

When the period desired exceeds about a minute, a stepper switch operated by the relay A/2 should be added so that the controlled circuit is brought in at some predetermined contact of the stepper switch. It is then only a matter of making the timing circuit to have a period which is some submultiple of the total time required. Periods up to an hour can be easily measured off in this way.

The principles of these arrangements can be extended to a number of more elaborate circuits which are widely used in industry. For instance, a cycle of several time periods each of different duration can be devised by making the stepper switch alter the value of the condenser charging resistance R1 of Fig. 8.20 at each impulse.[8.18]

Voltage Stabilisation

Referring again to Fig. 8.9, the fact that as soon as the discharge starts across the main electrodes the voltage falls to a lower value, and is then practically independent of the current, enables the tube to be employed as a voltage stabiliser for small currents. This is analogous to the thyratron the voltage across which is constant when the discharge passes and independent of the current. The normal arrangement is that shown in Fig. 8.21. It is, of course, a condition of stabilisation that the discharge shall be established through the triode. In Fig. 8.21, if the output voltage tends to fall due to an increased load, the potential across the triode remains constant, the difference in voltage due to the change in the output circuit appearing across the series resistor R. Diodes are frequently used to secure the same conditions of stabilisation, and series connection of such units is possible to secure regulation at higher voltages or on more than one circuit.

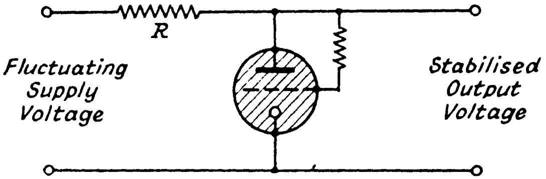


Fig. 8.21.—Voltage stabilisation with a cold cathode tube.

Stabilovolt Tube

An example of such a device is the Marconi stabilovolt,[8.19] which consists of an assembly of several cup-shaped electrodes mounted concentrically inside one another and supported from a glass pinch inside the gasfilled bulb. It thus consists of several discharge paths in series, the outer electrode being normally connected to the most negative point of the electrical system (Fig. 8.22 [*a*]). A barretter is frequently included in one supply lead to the stabilovolt, since it provides conditions which facilitate the striking of the discharge. A barretter passes a relatively high current at the instant of switching which enables the stabilovolt to fire. As in the case of all discharge tube stabilising devices, a current-limiting resistance of some type is essential on the main side of the stabilovolt to prevent the current reaching a high value.

The rating of the barretter should be chosen so that about one-third of the applied voltage drop occurs across it when fully loaded, with the remaining two-thirds across the stabilovolt. Thus a supply voltage considerably in excess of that demanded on the stabilised circuit is essential.

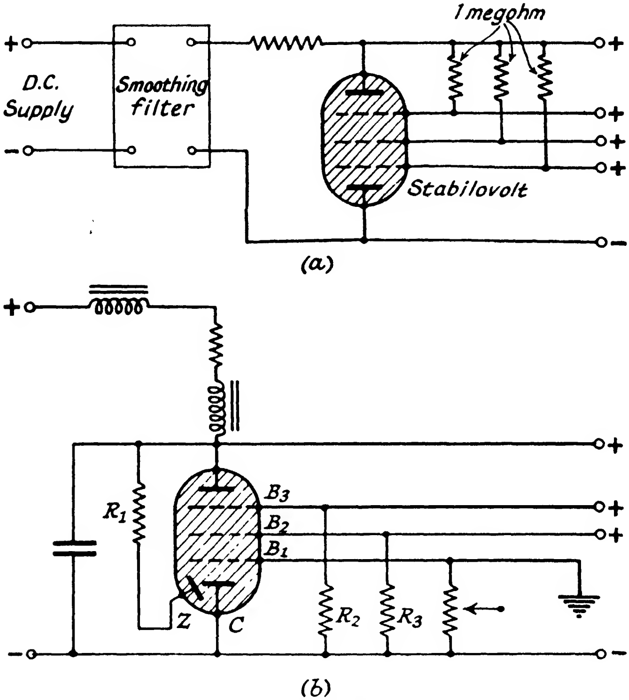


Fig. 8.22.—(*a*) Circuit incorporating Stabilovolt type STV280/40 for securing several different stabilised voltages; (*b*) circuit incorporating a Stabilovolt with auxiliary starting electrode.

If all the gaps are not required, those not in use should be short circuited. Greater stability than is possible with one unit may be obtained by connecting a further stabilovolt across the output of the first tube. In such a case the grids of the first tube are connected through separate resistances to the negative line. In this cascade form of connection the second stabilovolt must be preceded by its own current-limiting resistance. The increased stability thus secured is obtained at the expense of higher power consumption and lower output voltage.

Two or more stabilovolts can be connected in series when it is required to stabilise a voltage higher than the maximum voltage rating of the tube.

When used for the purpose of providing a steady supply for the h.t. circuits of a radio receiver, the last grid is frequently earthed so that the adjacent plate is negative to earth and can therefore provide grid-voltage bias.

Close adjustment of this bias voltage is obtained by connecting a potentiometer across the last gap. Since in a multivalve receiver the anode current of all the valves passes through the last gap and its associated potentiometer, the resistance of the latter must be low, otherwise the gap will take too much current and overload. The use of a low-resistance potentiometer to secure this condition may result in the voltage across the gap becoming too low to initiate the discharge. To overcome this an additional grid, Z in Fig. 8.22 (*b*), encloses the adjacent anode which is perforated at various points on its surface. With the arrangement then set out as in Fig. 8.22 (*b*), the effect is to make each gap fire in turn instead of all the gaps firing at the same moment.

These stabilovolts with auxiliary ignition electrodes have a much wider field of application, since they can also be used like the standard form of tube with the auxiliary electrode free when it is not required.

Stabilovolt tubes are also employed on alternating voltage supplies to secure a stabilised peak output voltage. If the supply voltage is sine wave, the output voltage has a square-topped wave form. As the discharge is then extinguished twice in each voltage cycle, the mode of operation is not quite as simple as in the case of direct-voltage operation.

Multi-gap discharge tubes of this kind have many applications for control and measuring circuits, and by including the secondary of a transformer with a potentiometer across the last gap it is possible to use the device as a relay and to start or stop the discharge according to the direction of the coil winding by impulses received on the transformer primary.

Short-Period Illuminants

Possibly the most useful practical application of the cold cathode triode is that of a short-period illuminant principally in connection with stroboscopic observations and for photography of rapidly moving objects.

Stroboscopes.—Portable stroboscopes are becoming widely used in industry, and some description of the principles involved in their operation seems necessary. They are best understood by considering a motor shaft rotating at a constant speed and carrying a white disc with a black mark near one edge (Fig. 8.23 [*a*]). Under conditions of steady illumination, when the disc is rotating the position of the mark cannot, unless the speed is very low, be identified, and persistence of vision indicates its existence only as a slightly dark ring on a white background (Fig. 8.23 [*b*]). The outline of the mark can, however, be seen if the disc is intermittently illuminated, and the position in which it appears will depend on the instant at which the flash of light reaches the disc.

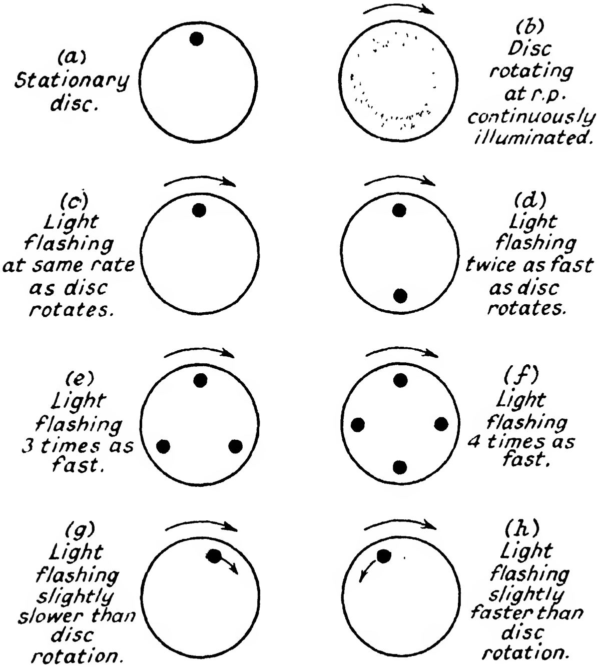


Fig. 8.23.—Stroboscopic images.

For the purpose of illustration it will be assumed that the disc carries a black dot and is driven round in the direction of the arrow at a speed of 72 revs. per sec., also that the light flashes at the same rate and that the duration of the flash is instantaneous. Suppose that the light flash takes place when the disc is in the position shown in Fig. 8.23 (*a*), so that the spot appears in this position. Before the next flash takes place the disc makes one complete revolution and arrives at the same point in step with the illumination. The disc is thus always illuminated at this instant only and appears at rest in this position.

The same visual appearance results if the lamp flashes at half this rate—*i.e.*, 36 per sec.—since the disc will then be illuminated when the spot is in the same position, but at every alternate revolution. Similarly if the rate of light flashing is $72/n$ per sec., where n is any whole number, the black spot will always be seen in the same position, being illuminated at every *n*th revolution. If $72/n$ is less than about 25, the rate at which the visual impressions are received becomes too slow to produce continuity and flicker appears.

The existence of a stationary image does not therefore necessarily indicate a frequency of movement identical with that of the light source. The object illuminated may be moving at some speed which is a multiple of the frequency of the light incidence.

Now consider the reverse case, where the light incidence is more rapid than that of the revolution of the disc. Suppose it is twice as fast—viz., in the example quoted 144 flashes per second with the disc running at the original speed of 72 revs. per sec. In this case it is clear that the light illuminates the disc twice during each revolution, so that two images of the spot appear at diametrically opposite points. This is, however, not the only case where two such images appear. Whenever the disc makes an odd number of half-revolutions between each light flash the spot will be alternately at opposite ends of a diameter when the light reaches it.

Similarly, if the light flashes exactly three times as fast as the disc revolves there will be three stationary images spaced at 120° to each other, and there will in the same way be a number of multiple speeds at which this triple pattern will appear. A stationary pattern therefore indicates the same frequency of cyclic motion as that of the light source or some multiple or sub-multiple of it.

In making observations which involve deduction of speed, therefore, possible confusion between multiples of a fundamental frequency must be obviated. For inspection purposes the differentiation of one frequency from another may not matter.

There is yet another condition which should be mentioned. So far reference has been made to cases where the two frequencies are exactly the same or exact multiples one of the other. If the frequencies are not equal, but differ by small amounts, another effect is produced.

Suppose that the light flashes at the rate of 72 per sec. while the disc rotates at 72·1 revs. per minute. If at one instant the spot appears at the point indicated in Fig. 8.23 (*a*), then after 10 secs. the disc will have made 721 revs. and the spot will coincide with the light flash in the same position. In the interim the spot will be observed to take up all intermediate positions round the disc and will appear to move slowly round the disc in the direction of motion (Fig. 8.23 [*g*]) at the rate of 1 rev. in 10 secs.

(*General Radio.*)

Fig. 8.24.—Stroboscope in use for examining valve springs in rapid motion.

Similarly, if the disc is running slightly slower than the rate of light flashing, the spot will appear to travel slowly in the reverse direction. Thus a means is provided of viewing the progress of the disc in slow motion.

Now, in applying these principles to practical use there are obviously two essentials: (1) sufficient illumination to enable the disc to be seen with comfort; (2) a short duration for the light flash, otherwise the spot will appear to move while it is illuminated and a blurred image will result, so that accurate determination of frequency coincidence will be impossible.

A regular intermittent illumination can be secured by (*a*) a steady illumination with a mechanically operated shutter, (*b*) an electric discharge.

The former has the disadvantage that the shutter restricts the amount of light and the frequency of mechanical operations is limited, whereas the discharge lamp permits of wide frequency range and very high intensity short-period flashing—a few microseconds.

Used as a measuring or observational instrument, the stroboscope, being completely isolated from the object under view, can measure speeds of low inertia masses, since no load is imposed on the moving object and it can be employed to view inaccessible positions.

In the General Radio strobotac the circuit operates from A.C. mains and a small metal reed vibrating at twice the mains frequency is mounted below the lamp. Since the lamp illuminates the reed, a stationary image is formed when the reed frequency is equal to, or some multiple of, the lamp.

Before using the instrument the scale is set at the supply frequency and the control adjusted till the reed appears at rest. Additional checks can be made at other parts of the scale.

The accuracy is, of course, limited to that of the supply frequency, and where a controlled frequency is not available alternative means of precalibration must be used.

Among the many applications of the stroboscope are the detection of vibration in moving mechanisms, checking on constancy of speed, examination of printed designs on paper moving at high speed, and motion study of machine tools, vacuum cleaners, fans, motor commutators, aircraft propellers, etc.

The Strobotron

The passage of a momentary discharge through a cold cathode tube is accompanied by a flash of light. Consequently, any such device capable of regular recurrent flashing can in principle be used as a stroboscope, though in many tubes designed for relay or indicator use the light intensity is too low and inconveniently disposed for satisfactory performance. A tube of special design is necessary to furnish the required high peak current with adequate life. Conversely, any stroboscopic discharge tube can operate as a relaying device provided circuit components to suit its characteristics are available.

Some of the circuits employed in stroboscopes are rather unconventional, and nearly all utilise the principle of discharging a condenser to produce a high peak current of short duration.

Cold cathode tubes for this purpose were developed under the name of strobotron in America by Germeshausen and Edgerton (8.20), and they are frequently referred to as Edgerton tubes. The name strobotron is also frequently applied to the many modifications of the original tubes which have been used for short-period illumination. This type of tube, which was the forerunner of the modern flash tubes, has two grids, though not all the circuits in which it is included involve the use of both of them. The minor grid may be connected to the cathode through a resister, or the two grids may be strapped together to one common terminal. The glass bulb housing the electrode system is filled to a pressure of about 1·5 cm. Hg with neon. Argon has been used, but has been found to yield lower visibility. When the discharge is established, a column of light about 8 mm. in diameter is formed between the cathode and the anode.

The cathode is roughened to produce an irregular surface and is treated with a cæsium compound so as to facilitate the formation of a cathode spot. The inner grid is supported by a ceramic insulator which surrounds the cathode and concentrates the discharge on the active portion of the cathode surface. The surface of the inner grid receives a deposit of active cathode material during manufacture, and this facilitates the starting of the discharge by reduction of the voltage on the control grid. Both cathode and anode are effectively shrouded by the outer grid. As distinct from the inner grid, this electrode is made of graphite, so that the breakdown voltage between the outer grid and the anode may not be materially affected by the surface of the electrode.

The anode is carried on a vertical glass insulator, the plate being mounted above and axially central with the two grids.

These two grids, which act as electrostatic shields, serve as starting electrodes, since the current between cathode and anode, which passes as an arc when the valve fires, is first set up as a discharge between inner and outer grids. With about 300 volts on the anode and the outer grid about 100 volts positive to the inner grid a discharge starts with the inner grid as cathode, and if this current exceeds a certain minimum the discharge is at once transferred to the cathode and anode.

Alternatively, if the potential of the outer grid is made about the same extent negative to the inner grid, a discharge will pass in the reverse direction with the outer grid as cathode, and will again, if intense enough, establish the main discharge. In both cases the initial current must produce sufficient ions in the interelectrode space, otherwise the main discharge cannot start.

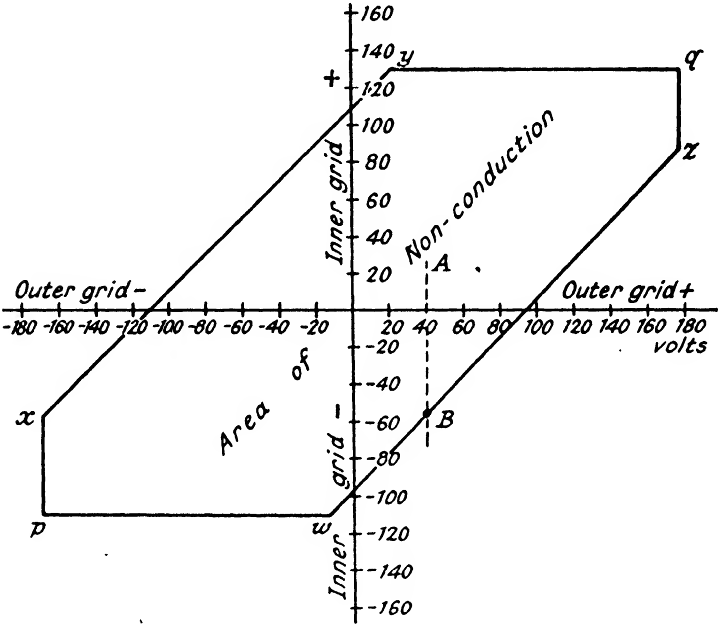


Fig. 8.25.—Characteristic loop of Strobotron indicating region of 40v. conduction with a fixed anode voltage. Potentials are relative to the cathode.

The interdependence of the voltage of the auxiliary electrodes on the firing of the valve is interesting. It has been shown[8.21] that the condition of non-conduction for a given anode voltage can be represented by the area embraced by the closed figure of Fig. 8.25, where the voltages of the inner grid with respect to the cathode are plotted as ordinates against the outer grid potentials as abscissæ.

Suppose that the closed curve of Fig. 8.25 is drawn for 350 volts on the anode and consider the ordinate AB representing a condition of +40 volts on the outer grid. Conduction is established in the valve if the inner grid is more negative than − 55 volts, the point B representing the condition of transition from the non-conducting to the conducting state with fixed anode potential of 350 volts and +40 volts on the outer grid.

A feature of the double-grid cold cathode valve is its application to circuits which require the simultaneous action of two independent potentials to establish the discharge.

The magnitude of the grid current at the instant of firing is of importance when the valve is to be operated by an emission type of photocell or any other low-current source of high resistance.

The relatively high instantaneous current required to complete the discharge between the main electrodes, and which exists for only a matter of microseconds, may be provided by the connection of a small condenser between the grids or between grid and cathode according to the circuit being used, this condenser being charged by successive operations of the tube. Alternatively, when the double grid control is used and a trigger action is to be secured, the grid current can be greatly reduced by suitable choice of the portion of the characteristic on which the valve is to operate. In Fig. 8.25 the line *zw* represents a condition of minimum grid current under the conditions of operation. The passage of the operating point across the vertical portion *zq* results in the completion of the discharge in two stages: first between the two grids, and finally between cathode and anode under conditions of minimum grid current.

A simple circuit which produces one flash per cycle of the supply voltage is shown in Fig. 8.26. The condenser C is charged from the supply during one half of the supply voltage. During the following half-cycle the condenser C maintains the anode potential, but the signal grid is driven negative and fires the tube.

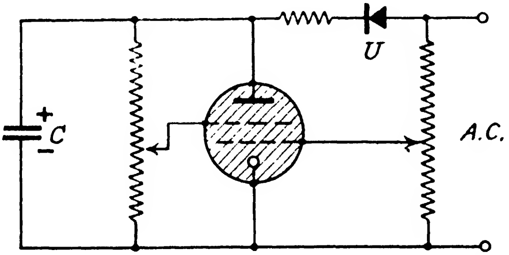


Fig. 8.26.—A simple circuit producing one flash per cycle of the supply voltage.

This circuit permits of no variation in the rate of flashing, which is fixed by the constancy of the supply voltage. In the circuit of Fig. 8.27, which shows the arrangement adopted in the General Radio strobotac, the frequency is under some control. As before, the flash results from a condenser discharge through the valve, but is here actuated by a triggering impulse from the variable frequency relaxation oscillator shown in the lower part of the diagram.

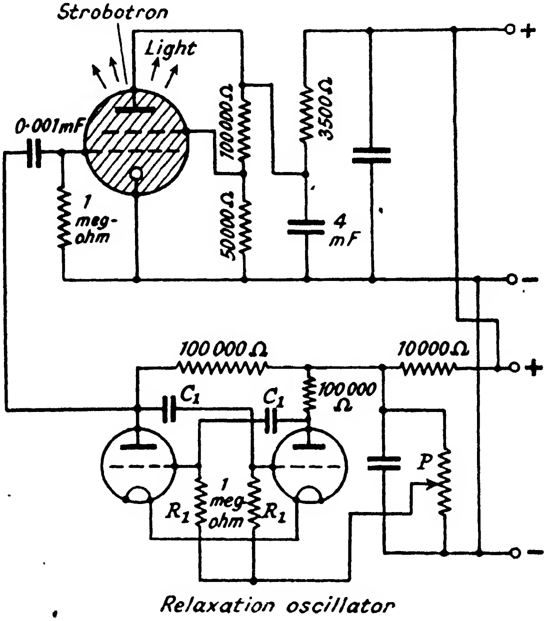


Fig. 8.27.—Circuit of the variable frequency stroboscope using a strobotron in the General Radio Strobotac.

At the instant at which the left-hand valve of the oscillator begins to conduct in each cycle a negative potential is impressed on the inner grid of the tube, and at this instant the potential difference between the inner and outer grids exceeds the starting voltage and the valve fires. The potentiometer P serves as an adjustment for frequency control over the separate ranges provided by varying the values of condenser C1 and resistance R1. With C1 = 0·02 μF the frequency range is about 10 to 60 cycles per sec. and C1 = 0·005 about 40 to 240 cycles per sec.

Modern Stroboscopic Tetrodes

The electrode system of a modern form of stroboscope tetrode, which is an evolution of the earlier types previously described, is shown in Fig. 8.28.

The electrode system of this device is mounted on a glass stem and comprises a hollow cæsium-activated cathode, a signal grid which passes up the centre and projects above the cathode, an outer grid or shield which covers the cathode and which is perforated with a small hole through which the main discharge passes, and an anode. The anode is a small disc about an inch above the top of the screen. Glass sheathing completely covers the electrode supports and the lower portion of the grid cathode assembly, so as to ensure that the discharge passes only through the screen aperture.

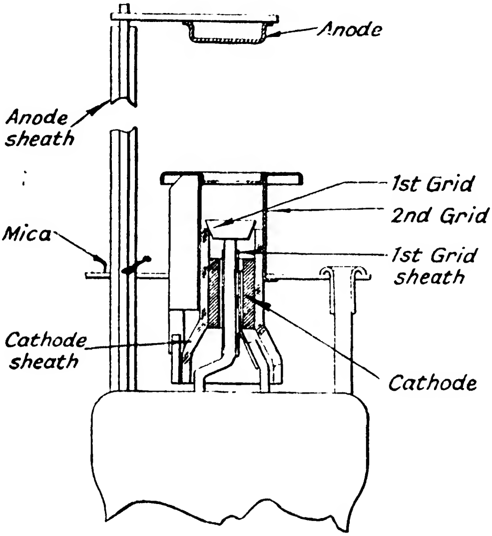


Fig. 8.28.—Electrode assembly details of Ferranti N.S.P.I.

The signal grid is activated by a cæsium deposit during manufacture, and this reduces the magnitude of the impulse required to trigger the tube. The shield grid is carbonised to minimise electron emission and to prevent anode-screen breakdown.

The tube requires an anode voltage positive to the cathode with a positive bias on the screen. A glow discharge between screen and grid is then initiated by a negative impulse on the signal grid. Ions produced in the cathode-anode space result in bombardment of the cathode and breakdown of the main discharge path. Less usual methods of firing the valve consist either of starting a discharge between grid and cathode with a positive screen bias or between grid and screen by an impulse applied to the screen.

Closed curves indicating the region of non-conductance similar to that shown in Fig. 8.25 can be drawn for this tube.

The initial glow discharge must exceed a critical minimum value depending on the anode voltage before the main discharge can be established. This minimum current varies from about 30 ma. with an anode voltage of 400 to about ten times this value at 200 volts on the anode.

The duration of the firing signal, though not critical, is reduced as the initial glow current is raised above its minimum value, and where high precision of firing is required microsecond pulses of high peak energy from a multi-vibrator and differentiating circuit can be used. The firing pulse must not be so long as to permit the discharge to be restarted during the condenser charging period. The cathode is designed for pulse operation and capable of passing peak currents between 5 amps. and 250 amps., but the mean anode current must not exceed 40 to 100 ma. The maximum recommended flashing frequency is about 300 per sec. The neostron type of tube can be also used in relay circuits.

High Intensity Flash Tubes for Photography

The recording of single high-speed photographs is a requirement which arises in many research investigations into the mechanism of objects moving at high speed and calls for two main essentials in the illuminant: (1) a short-duration light flash so that the illuminated object does not move appreciably while illuminated; (2) adequate light intensity to enable the photograph to be recorded on the film in the short time available.

The discharge of a condenser across a spark gap ensures a flash of very short duration, but scarcely of adequate intensity except for close-up views.

Compared with the early devices, modern flash tubes are characterised by their very high peak power rating and intense short period luminosity. Small tubes with a peak power of 500 watt-seconds corresponding to a light output of some 15,000 lumen-seconds are commercially available and tubes of much higher rating up to 600,000 lumen-seconds have been produced.

The luminous energy of the flash is proportional to the stored energy of the condenser. If the charging voltage is E_1 and the condenser capacitance C (mF.) is discharged to a residual voltage E_2, the energy of the discharge is:

$$C(E_1^2 - E_2^2) \times 10^{-6}/2$$

watt-seconds, and if there are n flashes per second, the average power is:

$$nC(E_1^2 - E_2^2) \times 10^{-6}/2 \text{ watts.}$$

Thus if $E_1=1{,}500$ volts, $E_2=100$ volts, $C=50$ mF., the energy of the flash is 56 watt-seconds and with one flash per minute the watt consumption is 56/60 or about 0·9 watt.

If the tube is flashed 10 times per second, the watts consumption will be $10 \times 56 = 560$ or more than 600 times as great.

If, therefore, the rate of flashing is increased, the condenser capacitance must be reduced to maintain the same wattage, otherwise the lamp may be severely overloaded and may conduct continuously or the temperature rise may be excessive and may soften the glass of the bulb.

The flash through the tube is established by ionising the gasfilling, the firing impulse being a grid impulse applied to an electrode incorporated in the tube, a high voltage spark from an induction coil or the high frequency discharge of a Tesla coil applied to a few turns of wire wrapped round the bulb, according to the design of the tube, and initiated by a switch, microphone, light cell or some other signal source.

Nature of the Flash

The duration of the flash is proportional approximately to the condenser capacitance. It also increases, though at a much lower rate, with increase of charging voltage. For a given energy in the discharge, the shortest flash is secured with a low capacitance charged to a high voltage. The design of the tube greatly influences the duration of the flash. In some lamps it is 1 or 2 microseconds; in others, and particularly if the circuit is not devoid of inductance, it may reach 1,500 microseconds and the discharge may be oscillatory.

Tubes with small bore are most suitable for rapid recurrent flashing, since the construction favours rapid de-ionisation.

The spectral characteristics are dependent on the current density and the colour rendering properties of the flash are improved as the current density increases.

Argon, Argon-hydrogen, argon-nitrogen and xenon have been used as gasfilling. Xenon gives a spectrum most nearly approximating to natural daylight.

In the available commercial forms of discharge tubes used as illuminants, the light is neither sufficiently intense nor suitably disposed to be fully exploited. A special design of discharge tube is therefore required. One type of such a source is the kodotron speed lamp (Fig. 8.29), which provides a relatively concentrated source of high actinic brilliancy.

Fig. 8.29 shows the tube with its protective glass cover removed. The coiled glass tube which constitutes the discharge path enables the source to be made more concentrated and permits the use of a reflector, so that as an illuminant it becomes something between a spotlight and a floodlight. Mounted near the centre of the coil for the purpose of providing sufficient light for setting up and making preliminary tests is a small projector lamp of the tungsten filament type.

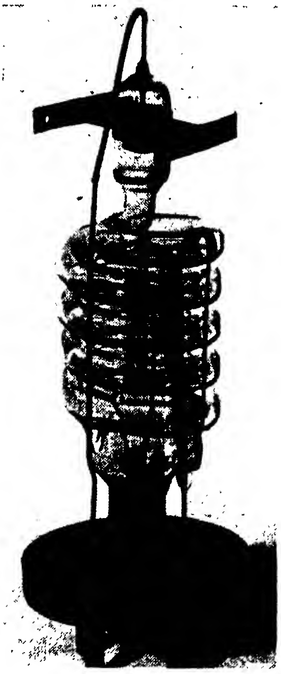


Fig. 8.29.—Internal construction of the kodotron lamp. (*Kodak Ltd.*)

The control panel of the case in which the kodotron is fitted carries three manual controls for adjustment, namely: the tungsten lamp, the power feed to the kodotron, and the trip contact for firing the discharge, though connections are also provided for firing to be remotely controlled from an external point. A pilot lamp is also provided to indicate that the unit has been connected to the electric supply and that the circuit is alive.

The electrical circuit of the lamp is shown in Fig. 8.30. A half-wave valve rectifier of the usual type forms part of the equipment providing a D.C. supply of 1,850 volts; this power section is not shown in Fig. 8.30. Resistances R1, R2 constitute a voltage divider for securing a lower voltage for the cathode in the non-conducting state, and the voltage across R1 is still further subdivided by R3, R4 to secure a lower potential for the control grid of V1. Condenser C1 constitutes a smoothing device to eliminate surge voltages across R1. Condenser C is of large capacitance 112 mF., and is charged to the full D.C. voltage. Normally the voltage output of the rectifier is insufficient to initiate the discharge while the circuit is maintained in the condition of Fig. 8.30. V1 is a strobotron type of discharge tube.

On closing the switch S the grid potential is increased in the positive direction to the point where current is established through V1. The current through the primary of the transformer T produces a large voltage on the secondary which fires the kodotron V2 and short-circuits the condenser C, so that the energy of the discharge into a luminous flash is of very high brilliancy.

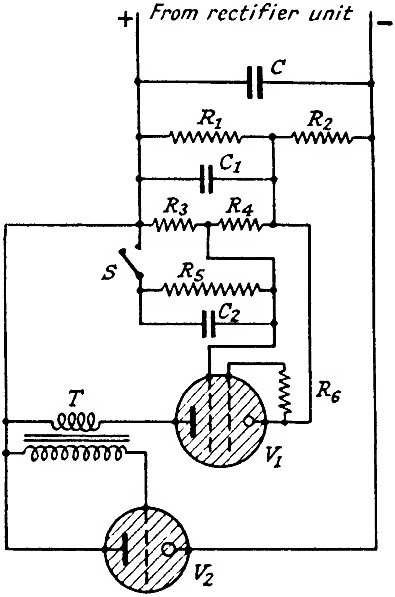


Fig. 8.30.—Flashing circuit of Kodak kodotron lamp.

The time delay between closing the switch S and firing the kodotron is probably less than a microsecond.

The time-intensity characteristic of the lamp shown in Fig. 8.31 indicates that the relatively long decay period shown by the right-hand side of the curve imposes a limitation on the definition of the duration of the discharge, since it must be decided first where the luminosity of the flash is considered to terminate.

Messrs. Kodak supply two types of kodotron tube with different characteristics. No. 1 tube is filled with a krypton-xenon mixture and is rich in blue rays with a certain proportion of red and infra-red, but less green. No. 2 type has a higher luminous output in red and green.

By means of suitable filters good colour photographs can be secured with either type of tube by using film of the appropriate spectral response.

Owing to the very short duration of the light flash the most important factor in its operation to secure a clear stationary picture of a rapidly moving object is the accuracy with which it is possible to synchronise the tripping switch with movement of the object.

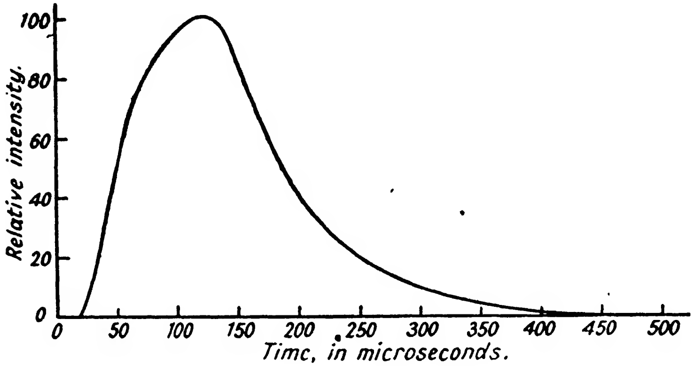
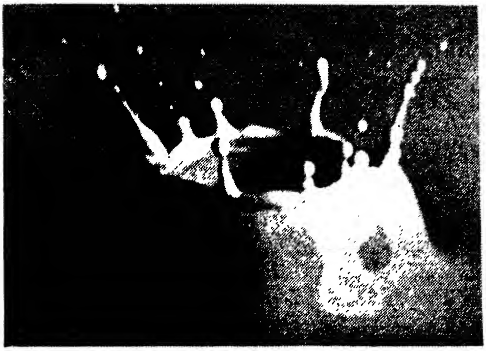


Fig. 8.31.—Kodak kodotron lamp. Time/Luminous intensity characteristic.

When synchronised with a camera shutter, the time delay between the start of the discharge and the peak of the luminosity of the flash may be of the order of 50-100 microseconds and the flash becomes effective as an illuminant earlier still. The flash will normally occur, therefore, before the camera shutter opens. This is the reverse of the conditions which are present with the foil type of photo flash bulb in which the ignition of the foil is relatively long in starting and the lamp circuit must be completed before the shutter is opened (8.24).

In most cases the moving object itself will directly or indirectly perform the synchronisation. Fig. 8.32 shows the wave form produced on the surface of a liquid when a solid object is dropped into it. Here the rising crest of the wave performed the switching operation and completed the tripping circuit through the stationary contact which can be seen on the left. By varying the position of this contact the time of the light flash can be adjusted so that a series of photographs showing progressive stages in the wave formation can be secured.

The foregoing treatment deals with some of the more interesting types of cold cathode gasfilled triodes and their uses. A number of



(*Kodak Ltd.*)

Fig. 8.32.—Typical high-speed photograph showing the character of a splash at the surface of a liquid.

other devices which function in a similar manner, and which therefore do not call for separate description, are also in general use. In most cases the grid functions as a means of reducing the voltage necessary to start the discharge—*e.g.*, recording tubes for impressing a sound record on a film.

GENERAL REFERENCES

Ignitrons.

COX and JONES, Ignitrons for the transportation industry, *Trans. Am.I.E.E.*, 58 (December, 1939), pp. 618-22.

THWAITES, Ignitron rectifiers for war industries, *Journ. Eng. Inst. of Canada*, 24 (January, 1941), pp. 4-7.

NOMOTO, Ignition mechanism of the ignitron, *Electrotech. Journ.* (Tokyo), 4 (November, 1940), pp. 252-5.

WARMOLTZ, Potential distribution at the igniter of a relay valve with mercury cathode, *Philips Tech. Rev.*, Vol. 8 (November, 1946), pp. 346-52.

Application to Welding.

PALMER, Electronic welding control, *Electronics* (August, 1942), p. 36.

BIVENS, The applications of ignitron to resistance welding control, *Trans. Am.I.E.E.*, 60 (1941), pp. 471-8.

——, Seam and pulsation welding controls, *ibid.* (September, 1942), p. 55.

——, Special welding controls, *ibid.* (October, 1942), p. 62.

DAWSON, New developments in ignitron welding controls, *Electrical Engineering*, 55 (December, 1936), pp. 1371-7.

Cold Cathode Tubes.

HILLIARD, Gaseous discharge tubes and their applications, *Electronics*, 19, No. 3 (March, 1946), p. 122.

KNOWLES, The theory of the grid glow tube, *Electric Journal*, 27 (1930), pp. 116, 232.

GOSSFORD, Neon-filled grid-glow tube, *Electric Journal*, 29 (July, 1932), p. 351.

ANON., Cold cathode counter control, *Electronic Engineering* (June, 1945).

CHAPTER REFERENCES

8.1. SLEPIAN and LUDWIG, A new method of starting an arc, *Electrical Engineering*, 52 (September, 1933), p. 605.

8.2. MIERDEL, Ignition of the mercury vapour arc in the ignitron, *Wiss. Veroff. a.d. Siemens Werken*, 15, 2 (1936), p. 35.

8.3. CAGE, Theory of the immersion mercury arc rectifier, *G.E. Rev.*, 38, No. 10 (October, 1935), p. 464.

8.4. DOW and POWERS, Firing time of igniter type of mercury arc rectifier, *Electrical Engineering*, 54 (September, 1935), p. 942.

8.5. WATANABE and others, Back current in ignitrons, *Electrotech. Journ.* (Tokyo), 1 (November, 1937), pp. 180-6.

8.6. PACKARD and HUTCHINGS, Sealed-off ignitrons for resistance welding control, *G.E. Rev.* (February, 1937).

8.7. KLEMPERER, A new ignitron firing circuit, *Electronics* (December, 1939), p. 12.

8.8. CHUTE, Electronic control of resistance welding, McGraw Hill (N.Y.), (1946).

8.9. KLEMPERER, Dielectric ignitors for mercury pool cathodes, *Electronics* (November, 1941), p. 38.

8.10. KNOWLES, The ignitron, *Electronics* (June, 1933), p. 164.

8.11. OVERBECK, The Permatron and its application in industry, *Electronics*, (April, 1939), p. 25.

8.12. MCARTHUR, Magnetic control of thyratrons, *Electronics*, 8 (January, 1935), dp. 12, 26.

8.13. MACKINSON and others, *Journal of App. Physics* (July, 1946).

8.14. BISCHEL and HUGHES, Improved electronic control for capacitor discharge resistance welding, *Trans. Am.I.E.E.*, Vol. 63 (December, 1944), pp. 1150-6.

8.15. CROWTHER, Ions, electrons and ionising radiations, Arnold, 7th ed. (1942).

8.16. KIMBALL, Remote control, *R.C.A. Rev.* (January, 1938), p. 303.

8.17. STACY, Vacuum tube improves selectivity ringing, *Bell Lab. Record*, 36, p. 111.

8.18. MYLES, Cold cathode timing devices, *Electronic Industries*, Vol. 3, No. 7 (July, 1944), p. 98.

8.19. *Marconi Review*, No. 44-5 (1933).

8.20. GERMESHAUSEN and EDGERTON, A cold cathode arc discharge tube, *Electrical Engineering*, Vol. 55 (July, 1936), p. 790.

8.21. GERMESHAUSEN and EDGERTON, The strobotron, Part I, *Electronics*, Vol. 10, No. 2 (February, 1937), p. 12; ditto, Part II, *ibid.* (March, 1937), p. 18.

8.22. HARRISON, Automatic measurement reduction and recording of wave lengths for spectrograms, *Journal Optical Soc. of America*, Vol. 25, No. 6 (June, 1935).

8.23. GRAY and NOTTINGHAM, Half-cycle spot-welder control, *Rev. Sci. Inst.*, Vol. 8 (February, 1937), p. 65.

8.24. BICKNELL, The applications of modern flash discharge tubes, *Trans. Illum. Eng. Soc.*, Vol. 13, No. 1 (1948), p. 1.

General References

(A) Books

1. Cobine. *Gaseous Conductors.* New York (McGraw Hill). 1941.
2. Cockrell. *Industrial Electronic Control.* New York (McGraw Hill). 1944.
3. Chute. *Electronics in Industry.* New York (McGraw Hill). 1946.
4. Crowther. *Ions, Electrons and Ionising Radiations.* (Arnold). 1942.
5. Dow. *Fundamentals of Engineering Electronics.* New York (Wiley). 1937.
6. Fink. *Engineering Electronics.* New York (McGraw Hill). 1938.
7. Gulliksen and Vedder. *Industrial Electronics.* New York (Wiley). 1935.
8. Henney. *Electron Tubes in Industry.* New York (McGraw Hill). 1934.
9. Kloeffler. *Principles of Electronics.* New York (Wiley). 1942.
10. Koller. *The Physics of Electron Tubes.* New York (Wiley). 1937.
11. McArthur. *Electrons and Electron Tubes.* New York (Wiley). 1936.
12. Manfield and Benedict. *Theory of Gaseous Conduction and Electronics* New York (McGraw Hill). 1941.
13. Millman and Seely. *Electronics.* New York (McGraw Hill). 1941.
14. Reich. *Principles of Electron Tubes.* New York (Wiley). 1942.
15. Wheatcroft. *Gaseous Electrical Conductors.* New York (McGraw Hill). 1939.

(B) General Paper References to Gasfilled Triodes

1. Alexanderson, Thyratrons and their uses, *Electronics,* 11 (February, 1938), pp. 9-12.
2. Chin, Gasfilled rectifier circuits, *Electronics,* 18 (April, 1945), pp. 138-43; (May, 1945), pp. 132-7.
3. Hauffer, Industrial applications of grid-controlled rectifiers, *V.D.I.,* 79 (December 7, 1935), pp. 1475-8.
4. Havens, Electron tubes in industry, *G.E. Rev.,* 34 (December, 1931), pp. 714-21.
5. Hoogenhout and Alberts, Valve rectifiers and thyratrons, *S. Africa I.E.E. Trans.,* 22 (December, 1931), pp. 307-20.
6. Hull, Gasfilled thermionic tubes, *Journ. Am.I.E.E.,* 47 (November, 1928), p. 798.
7. Hull, Hot cathode thyratrons, *G.E. Rev.,* 32 (April, 1929), p. 213.
8. Hull, Thyratrons, *Physics,* 4 (February, 1933), pp. 66-75.
9. Klemperer, Mercury vapour triodes, *Arch. f. Elektrot.,* 27 (May 2, 1933), pp. 322-8.
10. Kluge and Briebreche, Circuit combinations of photocells and thyratrons, *E.T.Z.* 56 (June 27, 1935), pp. 731-35.
11. Kluge, High voltage hot cathode mercury vapour valves, *E.T.Z.,* 57 (March 12, 1936), pp. 301-4, and (March 19), pp. 333-4.
12. Lewer and Dunham, Gasfilled relays, *G.E.C. Journal,* 3 (May, 1932), p. 67, and (August, 1932), p. 119.
13. Maddock, Some useful circuits employing thyratrons and ignitrons, *Journal Sci. Inst.,* 20 (March, 1943), pp. 37-46.

14. McArthur, An indexed bibliography of electron tubes and their applications, *G.E. Rev.* (October, 1938), p. 455.
15. Petit, Hot cathode thyratrons, *Revue générale d'Electricité*, 36 (October 20, 1934), pp. 533-8.
16. Slummard, Some electronic switching circuits, *Electrical Engineering*, 57 (May, 1938), pp. 209-20.
17. Steiner and others, Engineering features of gasfilled tubes, *Electrical Engineering*, 51 (May, 1932), p. 312.
18. Strelzoff, Mercury vapour grid-controlled rectifiers, *Journ. Frank. Inst.*, 224 (July, 1937), pp. 55-75, and (August, 1937), pp. 191-215.
19. Ulrey, New electron tubes and their uses, *Physics*, 7 (March, 1936), pp. 97-105.
20. Whiteley, Applications of hot cathode grid-controlled rectifiers or thyratrons, *Journ. I.E.E.*, 78 (May, 1936), p. 516 *et seq.*

APPENDIX A

Mean Anode Current at Phase Angle θ of Grid-Firing Voltage

If I_p is the instantaneous peak value of the anode current corresponding to peak anode voltage and i the instantaneous current at any instant, the mean anode current I_m when grid and anode voltage are in place is:

$$I_m = \frac{1}{2\pi}\int_0^{\pi} i\,d\,(wt) = \frac{1}{2\pi}\int_0^{\pi} I_p \sin wt\,d\,(wt) = \frac{I_p}{\pi}$$

If the point of firing of the discharge is retarded by an angle θ due to grid phase change:

$$I_{m\theta} = \frac{1}{2\pi}\int_{-\theta}^{\pi} I_p \sin wt\,d\,(wt) = \frac{I_p}{2\pi}\,(1+\cos\theta)\,\frac{I_p}{\pi}\cos^2\frac{\theta}{2}$$

So that

$$\frac{I_{m\theta}}{I_m} = \cos^2\frac{\theta}{2} \qquad \text{(see Fig. A.1)}$$

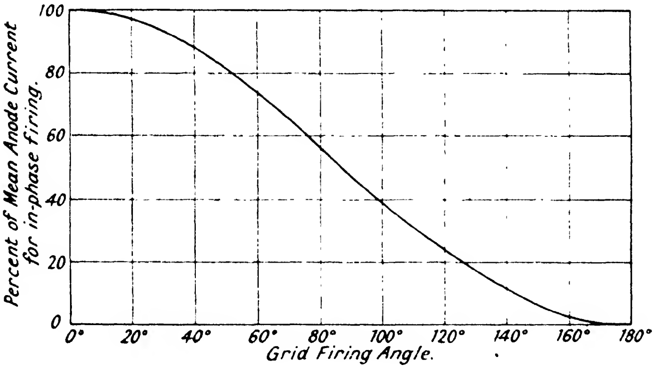


Fig. A.1.

APPENDIX B

Inductive Load. Single-Phase Half-Wave Circuit. Theoretical Deduction of Mean Anode Current

THE following deductions are due to C. R. Dunham. Suppose a sinusoidal voltage E sin wt is applied to the anode circuit which includes a resistance R and an inductance L and is switched on at the instant $wt=0$. During that portion of the cycle of applied alternating voltage in which the current flows we have:

$$\mathrm{E}\sin wt=\mathrm{R}\,i+\mathrm{L}\frac{di}{dt} \quad . \quad . \quad . \quad . \quad . \quad \text{(i)}$$

where i is the instantaneous value of the current. The solution of this equation is:

$$i=\mathrm{A}\sin(wt-a)+\mathrm{B}e^{-wt/\tan a} \quad . \quad . \quad . \quad \text{(ii)}$$

where

$$\mathrm{A}=\frac{\mathrm{E}}{\sqrt{\mathrm{R}^2+\mathrm{L}^2w^2}} \text{ and } \tan a=\frac{\mathrm{L}w}{\mathrm{R}}$$

The current can be made to start at any instant during the positive half-cycle of anode voltage by suitably adjusting the phase of the grid voltage. When once started, the current continues to the end of the positive half-voltage cycle and thereafter starts again at the same point in succeeding positive half-cycles.

If the current starts at the instant $wt=\beta$, equation (ii) takes the form:

$$i=\mathrm{A}\sin(wt-a)-\mathrm{A}\sin(\beta-a)e^{(-wt-\beta)/\tan a} \quad . \quad . \quad \text{(iii)}$$

The current is next zero when $wt=\gamma$, where

$$\mathrm{O}=\mathrm{A}\sin(\gamma-a)-\mathrm{A}\sin(\beta-a)e^{(-\gamma-a)/\tan a} \quad . \quad . \quad \text{(iv)}$$

The mean current in the load is therefore:

$$\frac{1}{2\pi}\int_{\beta}^{\gamma} i\,.\,d\,(wt)$$

or

$$\frac{\mathrm{A}}{2\pi}[\mathrm{Cos}\,(\beta-a)-\cos(\gamma-a)+\sin(\beta-a)\tan a.\ e^{(-\gamma-\beta)/\tan a}-\sin(\beta-a)\tan a]$$

Substituting the value of $e^{(-\gamma-\beta)/\tan a}$ from equation (iv), this becomes:

$$\frac{\mathrm{A}}{2\pi}[\cos(\beta-a)-\cos(\gamma-a)+\sin(\gamma-a)\tan a-\sin(\beta-a)\tan a)$$

$$=\frac{\mathrm{A}}{2\pi\cos a}(\cos\beta-\cos\gamma) \quad . \quad . \quad . \quad . \quad \text{(v)}$$

Alternatively this result can be deduced from the fact that the mean current is equal to the mean voltage divided by the resistance of the load, so that

$$\text{Mean current} = \frac{E}{2\pi R}\int_{\beta}^{\gamma} \sin wt \,.\, d\,(wt) = \frac{E}{2\pi R}\,[\cos\beta - \cos\gamma] \quad . \qquad \text{(vi)}$$

To evaluate the mean current it is first necessary to find the value of γ from equation (iv). This is done graphically by finding the intersection of the curves:

$$y = \frac{\sin(\gamma - \alpha)}{\sin(\beta - \alpha)} \text{ and } y = \varepsilon^{(-\gamma-\beta)/\tan\alpha}$$

The mean anode current is then calculated for various values of the load phase angle α and the grid ignition angle β, giving a set of curves as shown in Fig. B.1, each curve representing a given load phase angle.

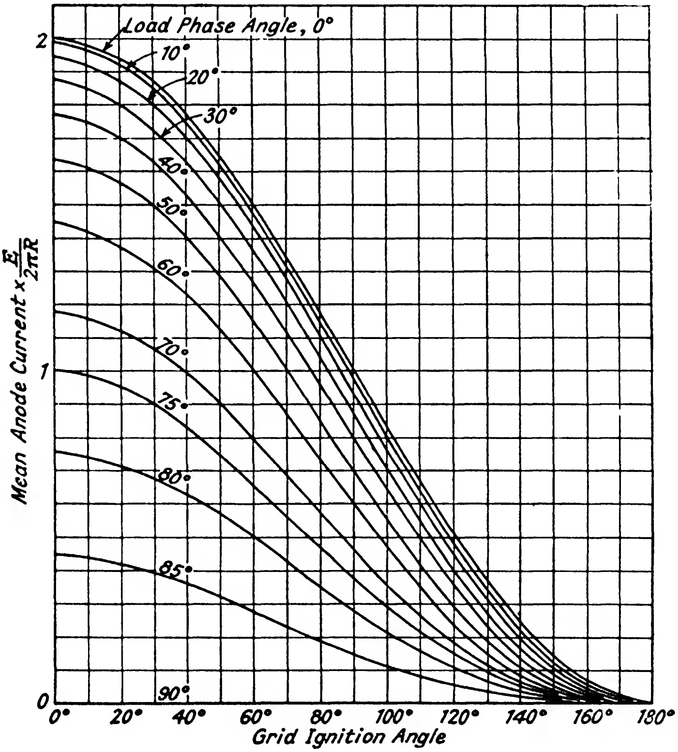


Fig. B.1.

Biphase Circuits

In the case of a biphase half-wave circuit where two sinusoidal voltages L sin wt and L sin $(wt-\pi)$ are applied to an inductive load through two grid-controlled rectifiers, two conditions of current flow may occur according to whether or not the ignition of either valve takes place before the current through the other has ceased.

In the first case, where the current starts in one valve after it ceases in the other, the current through the load starts and ceases every half-cycle, but in the second case the current through the load is continuous and is transferred backwards and forwards between the two anodes. In the case where the load current is discontinuous each half-cycle can be treated separately and the mean anode current in each is:

$$\frac{E}{\pi R}[\cos\beta-\cos\gamma] \quad . \quad . \quad . \quad . \quad (vii)$$

The condition that the current should be discontinuous is that

$$\gamma<\beta+\pi \quad . \quad . \quad . \quad . \quad . \quad (viii)$$

which gives on substitution in equation (iv)

$$\text{Sin}\{(\beta-a)+\pi\}<\sin(\beta-a)\, e^{(-\gamma-\beta)/\tan a}$$

which is satisfied if $\beta>a$.

In the second case, where the currents overlap, the discharge passes through one valve from the time $wt=\beta$ when it is fired until the time $wt=\beta+\pi$, when the other valve fires. The voltage applied to the load is then E sin wt from $w=\beta$ to $\beta+\pi$ and E sin $(wt-\pi)$ from $wt=\beta+\pi$ to β.

The mean voltage is, therefore:

$$\frac{1}{\pi}\int_{\beta}^{\beta+\pi} E\sin wt\, d(wt)=\frac{2E}{\pi}\cos\beta \quad . \quad . \quad . \quad (ix)$$

and the mean load current:

$$\frac{2E}{\pi R}\cos\beta \quad . \quad . \quad . \quad . \quad . \quad (x)$$

which is independent of the load inductance. If, therefore, $\beta<a$ the load current is continuous and independent of the load inductance.

Three-Phase Half-Wave Circuit

In a three-phase half-wave. circuit there are three sinusoidal voltages: E sin wt, E sin $\left(wt-\frac{2\pi}{3}\right)$ and E sin $\left(wt-\frac{4\pi}{3}\right)$ applied to the load through the rectifying valves and the positive half-voltage cycles overlap each other by $\frac{\pi}{3}$. Without grid control, current is transferred from one valve to the next at the mid-point of these overlaps when the difference in voltage between the two phases changes sign. Grid control will therefore be ineffective in changing the mean current output unless the ignition point is delayed beyond the mid-point of the overlaps—*i.e.*, for $\beta<\frac{\pi}{6}$ the mean output current is constant and equal to:

$$\frac{3E}{2\pi R}\int_{\pi/6}^{5\pi/6} \sin wt \, d\,(wt)=\frac{3\sqrt{3}}{2\pi}\frac{E}{R} \quad . \quad . \quad . \quad \text{(xi)}$$

As before, when $\beta>\frac{\pi}{6}$, two conditions of current flow may occur: the load current may be continuous or it may start and stop every one-third cycle.

In the discontinuous case the extinction angle can be found from the tabulated values of load phase angle and grid ignition angle found from the relations following equation (vi). The mean output current is:

$$\frac{3E}{2\pi R}\int_{\beta}^{\gamma} \sin wt \, d\,(wt)=\frac{3E}{2\pi R}\,[\cos\beta-\cos\gamma] \quad . \quad . \quad \text{(xii)}$$

and the condition for discontinuity is

$$\gamma<\left(\beta+\frac{2\pi}{3}\right)$$

In the continuous case, the mean output current is:

$$\frac{3E}{2\pi R}\int_{\beta}^{\beta+2\pi/3} \sin wt \, d\,(wt)=\frac{3E}{2\pi R}\sqrt{3}\cos\left(\beta-\frac{\pi}{6}\right) \quad . \quad . \quad \text{(xiii)}$$

Six-Phase Half-Wave Circuit

In a similar way it can be shown that in a six-phase half-wave circuit for $\beta<\frac{\pi}{3}$ the mean load current is constant and equal to:

$$\frac{6E}{2\pi R} \quad . \quad . \quad . \quad . \quad . \quad . \quad \text{(xiv)}$$

for $\beta>\frac{\pi}{3}$ and $\gamma>\beta+\frac{\pi}{3}$ the load current is continuous and has a mean value:

$$\frac{6E}{2\pi}\cos\left(\beta-\frac{\pi}{3}\right) \quad . \quad . \quad . \quad . \quad . \quad \text{(xv)}$$

and for $\beta > \frac{\pi}{3}$ and $\gamma < \beta + \frac{\pi}{3}$ the load current starts and stops six times per cycle and has a mean value $\frac{6E}{2\pi R}(\cos\beta - \cos\gamma)$.

Twelve-Phase Half-Wave circuit

For twelve-wave circuits the corresponding relations are:

For $\beta < \frac{5\pi}{12}$ the mean current is constant at the value:

$$\frac{12E}{2\pi R}\sqrt{2-\sqrt{3}} \qquad . \quad . \quad . \quad . \qquad \text{(xvi)}$$

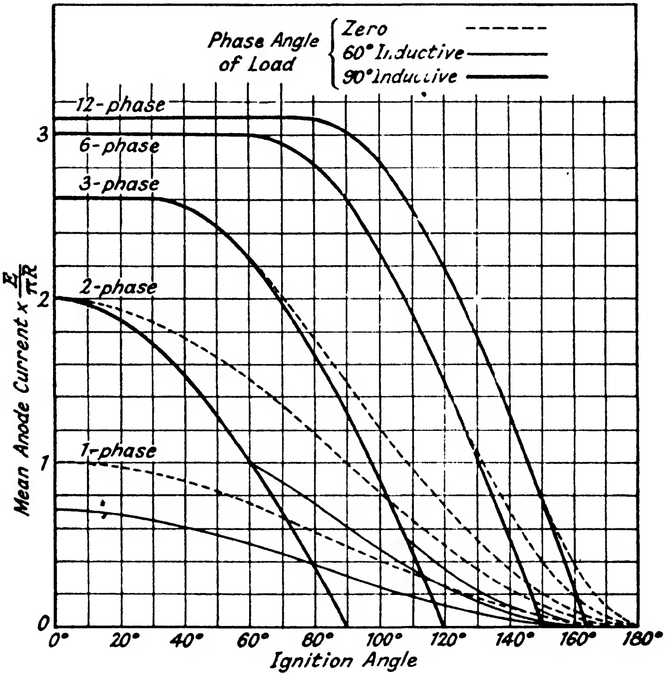


Fig. B.2.

For $\beta > \frac{5\pi}{12}$ and $\gamma > \beta + \frac{\pi}{6}$ the load current is continuous and has a mean value of:

$$\frac{12E}{2\pi R}\sqrt{2-\sqrt{3}}\cos\left(\beta - \frac{5\pi}{6}\right) \qquad . \quad . \quad . \qquad \textbf{(xvii)}$$

and for $\beta > \frac{5\pi}{12}$ with $\gamma < \beta + \frac{\pi}{6}$ the load current starts and stops twelve times per cycle and its mean value is:

$$\frac{12E}{2\pi R}(\cos\beta - \cos\gamma) \quad . \quad . \quad . \quad . \quad \text{(xviii)}$$

Fig. B.2 shows all these cases drawn to the same current scale, enabling a comparison to be made of the effect of grid control between single- and multi-phase circuits for resistive and inductive loads.

APPENDIX C

General Case of n-*Phase Half-Wave Grid-Controlled Rectifier* (*Fig. C.*1)

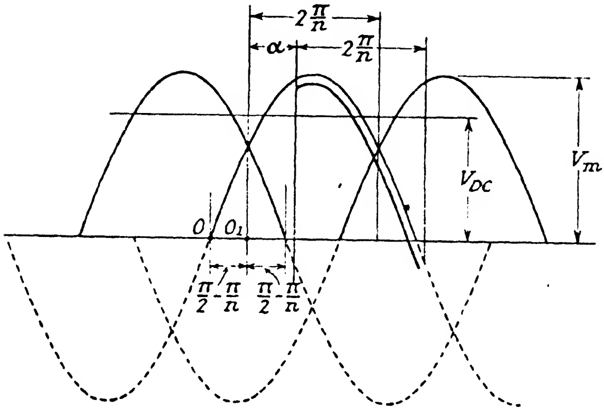


Fig. C.1.

Assuming the A.C. phase voltage is sinusoidal and equal to $V_m \sin wt$, then, since the delay angle is reckoned from the point O, by transferring the origin of co-ordinates from O to O_1 the instantaneous value of the A.C. voltage is $=V_m \sin\left(wt+\frac{\pi}{2}-\frac{\pi}{n}\right)$. If the delay angle of firing of each tube is a, then, since each tube conducts through an angle $\frac{2\pi}{n}$, the output voltage is:

$$V_{dc}=\frac{n}{2\pi}\int_{a}^{a+2\pi/n} V_m \sin\left(wt+\frac{\pi}{n}-\frac{\pi}{n}\right) d\,(wt)-v \quad . \quad . \quad \text{(i)}$$

$$V_{dc}=\frac{nV_m}{\pi}\cos a \sin\frac{\pi}{n}-v$$

(v is the voltage drop across the valve.)

For biphase circuit $\sin\frac{\pi}{n}=1$, and for a three-phase half-wave $\sin\frac{\pi}{n}=\frac{\sqrt{3}}{2}$, giving the relations shown on page 229.

While one valve is conducting, the voltage across the choke is equal to the difference between the instantaneous anode voltage of the tube and the direct output voltage—*i.e.*:

$$v_{ch}=\mathrm{V}_{\max}\left[\sin\left(wt+\frac{\pi}{2}-\frac{\pi}{n}\right)\right]-\left[\mathrm{V}_{\max}\left(\frac{n}{\pi}\cos a\sin\frac{\pi}{n}\right)-v\right]\quad .\quad \text{(ii)}$$

and average current through the choke is the integral of expression (ii) divided by Lw:

$$i=\frac{\mathrm{V}_{\max}}{\mathrm{L}w}\left[\sin\left(wt-\frac{\pi}{n}\right)-\frac{n\,wt}{\pi}\cos\alpha\sin\frac{\pi}{n}+\mathrm{K}\right]\quad .\quad .\quad \text{(iii)}$$

K, the constant of integration, is evaluated by the condition that L has its critical value, say l, when the current is on the point of discontinuity—*i.e.*, drops to zero and immediately starts again—*i.e.*:

$$i=0=\frac{di}{dt}\text{ occurring when, say, }wt=\mathrm{T}$$

Substitution of K in (iii) and integrating over the whole conducting period:

$$\mathrm{I}_{dc}=\frac{n\mathrm{V}_{\max}}{\pi\mathrm{L}_c w}\left[\sin\alpha\sin\frac{\pi}{n}-\left(\alpha-\frac{\pi}{n}\right)\cos\alpha\sin\frac{\pi}{n}+\frac{\pi\mathrm{K}}{n}\right]\quad .\quad \text{(iv)}$$

whence, rearranging and substituting $\mathrm{V}_{\max}$ from (i):

$$\mathrm{L}_c=\frac{\mathrm{V}_{dc}+v}{w\mathrm{I}_{dc}}\left[\tan\alpha-\alpha-\frac{\pi}{n}+\mathrm{T}-\frac{\pi\sin\left(\mathrm{T}-\frac{\pi}{n}\right)}{n\cos\alpha\sin\frac{\pi}{n}}\right]\quad .\quad .\quad \text{(v)}$$

There are two different conditions under which the choke voltage passes through zero.

In Fig. C2 (*a*) the valve discharge starts when the D.C. output voltage exceeds the instantaneous anode voltage of the valve and the choke voltage becomes zero at a later time when these two voltages become equal—*i.e.*, when

$$\frac{n\mathrm{V}_{\max}}{\pi}\cos\alpha\sin\frac{\pi}{n}=\mathrm{V}_{\max}\sin\left(\mathrm{T}-\frac{\pi}{2}-\frac{\pi}{n}\right)$$

or

$$\mathrm{T}=\frac{\pi}{n}-\frac{\pi}{2}+\sin^{-1}\left(\frac{n}{\pi}\cos\alpha\sin\frac{\pi}{n}\right)\quad .\quad .\quad .\quad \text{(vi)}$$

If the valve fires when its anode voltage exceeds the D.C. output (Fig. C2 [*b*]) the choke voltage is zero at this instant or when

$$\mathrm{T}=\alpha\quad .\quad .\quad .\quad .\quad .\quad \text{(vii)}$$

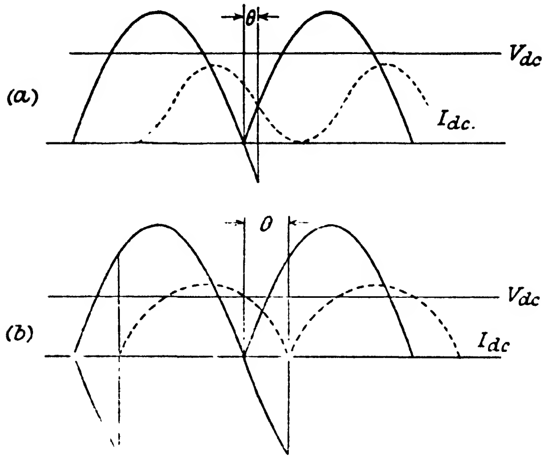


Fig. C.2.

The condition which exists for determining T when the valve fires at the point when its anode voltage equals the D.C. output is:

$$\frac{nV_{\max}}{\pi}\cos\alpha\sin\frac{\pi}{n}=V_{\max}\sin\left(\alpha+\frac{\pi}{2}-\frac{\pi}{n}\right)$$

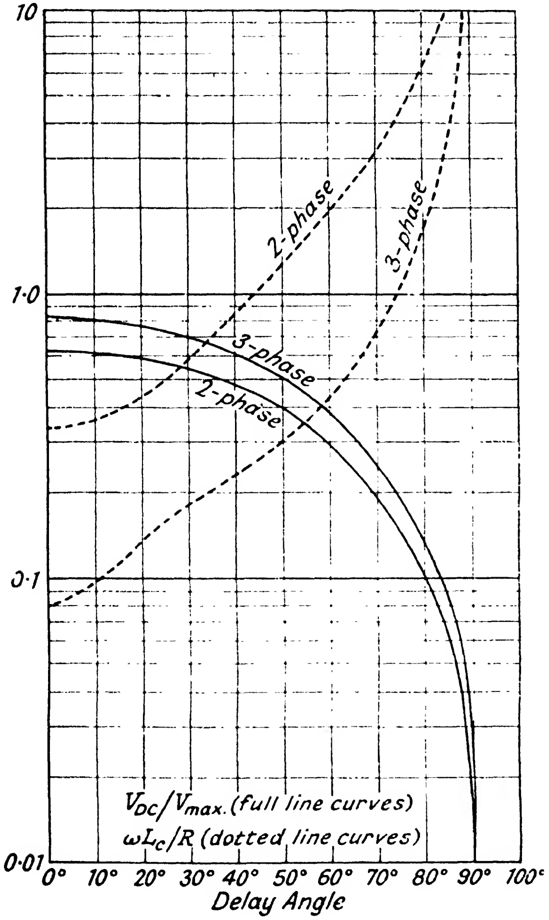
or

$$\alpha=\tan^{-1}\left(\frac{n}{\pi}-\cot\frac{\pi}{n}\right) \quad . \quad . \quad . \quad . \qquad \text{(viii)}$$

For firing angles less than that given by (viii) the value of T is obtained from (vi); for angles greater than that given by (viii) the value of T is obtained from (vii).

APPENDIX D

Fig. D.1, due to Coubeck, shows values of $\frac{V_{DC}}{V_{max}}$ and $\frac{wL_c}{R}$, where L_c is the critical inductance for continuity in conduction and R the load resistance plotted against the firing delay angle for two- and three-phase rectifiers.



These co-ordinate scales neglect the drop v across the valve, so that the values of $\frac{wL_c}{R}$ must be multiplied by $\left(1 + \frac{v}{V_{DC}}\right)$ and the values of $\frac{V_{DC}}{V_{max}}$ divided by the same factor.

Fig. D.1.

Index