INDUSTRIAL
ELECTRONIC CONTROL

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A Guide to the Understanding of Electronic Control Circuits for Industrial Uses

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INDUSTRIAL ELECTRONIC CONTROL

TO THE *electronic service and maintenance engineer, the fighter on the industrial front, who must install and maintain unfamiliar equipment under conditions and handicaps that could never have been anticipated by the designing engineers and the manufacturer*

PREFACE TO THE SECOND EDITION

During the six years since the appearance of the first edition, there has been intensive activity in the field of the electronic circuit, particularly with regard to counting and switching, and circuits for closed-cycle or regulating systems. Some of these circuits have been of a basic nature, and it has been felt worth while to include them in the text. This has required a slight rearrangement of the text in order that the continuity shall be more logical.

The new ASA graphical symbols for inductance and capacity have been adopted, and a list of questions has been placed at the end of each chapter for use in review when the book is used as a classroom text. The reference lists have been revised and enlarged.

New equipment circuits, including some in the instrumentation field, have been added to bring this section more up to date.

Perhaps the most important addition has been a new section on closed-cycle control, or regulating systems. Recent work in the Bell Laboratories, the M.I.T. Servomechanism Laboratory, and elsewhere has brought the understanding of regulating and hunting actions from the realm of the graduate mathematician to that of the practicing electronic engineer.

Electronics are expanding rapidly in this field owing to the ease with which amplification can be obtained over a broad frequency range and to the facility with which correcting networks can be added and adjusted in electron circuits. The industrial electronic worker will often be called upon to service such equipment and, perhaps, to suggest means for improving a system giving unsatisfactory performance. For these reasons, in this new section the author has attempted to present a basic knowledge of regulating-system action in a manner that will make it most easily understood to the student of industrial electronics.

W. D. COCKRELL

SCHENECTADY, N. Y.
January, 1950

PREFACE TO THE FIRST EDITION

The increasing use of electronic devices in industry has made an extra demand on the industrial engineers who must sell, install, and service them. It is especially for these men, electrical engineers with no previous tube experience, that this book is written. Another group who may benefit by this approach to the subject are radio servicemen, recently drawn into industrial electronic service work, who wish to add to their knowledge of industrial-tube applications.

Many excellent books have been written on the theory and construction of electron tubes and the use of tubes in high-frequency communication circuits. There are others on the industrial applications of electronics, but these have stressed application problems rather than electron circuits. In this book no attempt will be made to explain specific applications. Such an explanation would usually include a description of many mechanical and optical devices as well as much material on magnetic control. Also, the same electron circuit might be used repeatedly to illustrate different applications.

The application of electronic control is expanding so rapidly that it is impossible to attempt to cover all devices and circuits. Hence, it has seemed desirable to emphasize basic circuits that may be combined to form an endless variety of complete circuits.

Similarly, this text has been limited to electron circuits. Magnetic control, optics, and mechanical engineering, though a knowledge of these subjects is required for successful application engineering, are of too broad and varied a nature to be included here.

The functions of the various tubes as integral parts of circuits are stressed rather than the phenomena taking place within the tubes themselves. Industrial symbols for electronic and electrical devices are used throughout so that they will be familiar when found on wiring diagrams. Explanations are brief, and mathematical formulas of interest only to designers are avoided. The more common circuit components and elementary circuits are described separately and then combined to assist the reader to analyze a complicated circuit.

Most of the material presented here is not new. The aim has been to arrange the essential material in as compact and logical a form as possible, to avoid excessive duplication of circuit detail, and to omit those items and applications which are of only casual interest to the industrial user. If the reader desires a more detailed account of a given subject, the references provide a wide source of information.

Acknowledgment is made here to those many authors whose writings have formed the background for this text. Many of the circuits described are patented and should not be used without permission, although this is usually the concern of the designer rather than of the service engineer.

Specific and grateful acknowledgment is made to the following men for their generous contribution of time and material, comment and criticism, in the preparation of this work:

E. H. Alexander, Industrial Engineering Division; H. L. Palmer, Industrial Control Division; O. W. Livingston, Industrial Control Division; A. E. Bailey, Jr., Industrial Division; W. C. White and E. D. McArthur, Electronic Department; and I. H. Marshman, Patent Department, all of the General Electric Company at Schenectady, N. Y. Also, E. H. Vedder of the Westinghouse Electric & Manufacturing Co.; F. P. Kent of the United Cinephone Corp.; L. L. Worner of the Worner Products Corp.; S. C. Lawrence of the Electronic Control Corporation; and R. S. Burnap of the Radio Corporation of America.

To these and to the many others who have assisted in the various phases of the work, the author expresses his sincere appreciation.

W. D. COCKRELL

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INTRODUCTION

When anyone not familiar with electronic control first encounters vacuum-tube or thyratron symbols on wiring diagrams or attempts to analyze the strange-looking components on the back of a typical electronic panel, it is small wonder that he becomes somewhat confused and is inclined to feel that electronic control is something far beyond the grasp of the average serviceman, electrical engineer, or electrician.

On better acquaintance, however, this strangeness begins to disappear. Yes, those ceramic tubes are resistors, although somewhat smaller in size than those he has been used to. The varicolored bakelite rods are also resistors, dissipating a watt or so but having a resistance of perhaps a number of megohms. The colors constitute a simple and efficient color code of resistance value and tolerance. The small wax-filled cardboard and metal cans are capacitors (or, as we used to call them, "condensers") similar to those now in common use for spark and radio interference protection, for motor starting and phase splitting, and for power-factor correction. Sometimes the smallest capacitors appear as bakelite blocks coded by colored dots or bands, as are the resistors.

Transformers and reactors appear in their old familiar roles and should cause no confusion. Sometimes a reactor and a capacitor are combined to produce a resonant element to present maximum or minimum impedance, or a reactance and a resistance may be combined to produce a phase shift, but both these phenomena are standard a-c engineering and not peculiar to electronic control.

Electron Tubes. Those essential and so often misunderstood elements, the electron tubes themselves, are fundamentally among the simplest of electrical devices. This statement is worth repeating for emphasis. *The electron tube is one of the simplest of electric devices.* It ranks with the transformer and polyphase squirrel-cage induction motor in simplicity of construction and operation. It is infinitely less complicated than the d-c compound-wound motor or the gasoline engine. This does not mean that, having learned the simple fundamentals of tube operation, one can design efficient and reliable tubes any more than one can design good transformers or motors with only the same degree of basic knowledge. However, this should not prevent anyone from understanding and servicing electronic equipment as effectively as he would transformer or motor equipment. The tubes themselves usually cannot be repaired in the field, but one can be replaced by a spare about as easily as a fuse. Therefore, in this book, little time is spent discussing the details of the internal construction of the tubes. Rather, the effect on the tube output of the change of the input signal will be stressed.

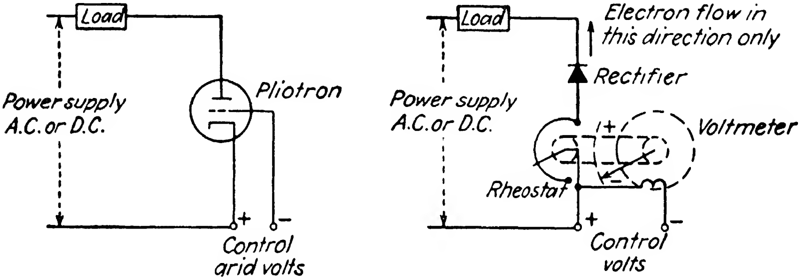


FIG. 0.1. A pliotron tube and an equivalent circuit.

There are two principal reasons for the use of electron tubes. The current is controlled without noise and without moving or wearing parts, and this control is rapid, infinitely more rapid than is possible with any moving mechanical device. Also, the power amplification, or the ratio between the control power and the power controlled, is enormous. It is the effect of this very potent switching and regulating means on the rest of the electrical components that permits the almost limitless possibilities of electronic control and at the same time demands a thorough study and sometimes a new insight into, not the tubes, but the resistance, capacitance, inductance, and motors in the otherwise standard electric circuits used with the tubes.

Electromagnetic Analogies. Better to appreciate the simplicity of tubes, examine Figs. 0.1 and 0.2. Figure 0.1 shows a rheostat and a rectifier in series, with a voltmeter element controlling the rheostat. (The rectifier may be described as a one-way electrical valve.) If we assume that the rheostat slider is frictionless and can be moved at any desired speed, we may use these devices to duplicate the action in *any circuit* of the high-vacuum triode or pliotron. If there is more than one control element, other rheostats may be added in series to copy that high-vacuum-tube's action more exactly.

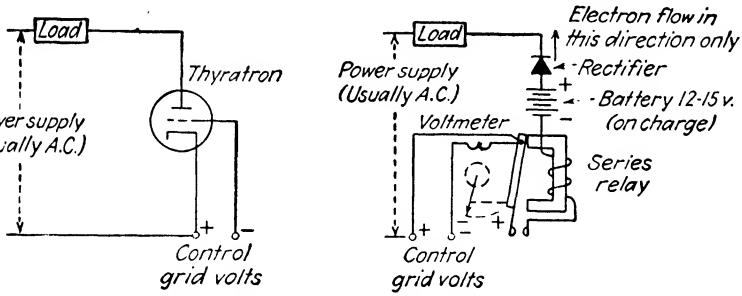


FIG. 0.2. A thyratron and an equivalent circuit.

Figure 0.2 shows a rectifier, in series with a battery of 12 to 20 volts whose potential opposes the current through the rectifier, and a latch-in series relay which, when closed by the voltmeter action, will remain energized until the current ceases to flow through the rectifier. If we assume the relay armature to be frictionless and inertialess and capable of operation at any desired speed, this circuit can duplicate the action of *any thyratron, anywhere.*

If the reader feels that these simple analogies do not give a true picture, let him try these substitutions in any circuit described in this book, or elsewhere, and discover for himself the truth of the above statements.

Section I

ELECTRON TUBES

CHAPTER I

THE VACUUM RECTIFIER

The electron tube as used in the ordinary industrial control circuit is a simple device, and its functions can be simply described. Tubes actually in use will be found to correspond to such a description fairly accurately and consistently. Only in extreme cases do we approach the limit of capabilities of the electron tube itself. The commercial power frequencies of 25 and 60 cycles and even the audio frequencies up to 10,000 cycles are so much lower than the usual radio frequencies for which vacuum tubes were developed that many problems of internal tube capacity and electronic transit time which worry the radio-equipment designer need not concern the industrial electronic engineer.

We will discuss the two principal types of tubes used for control —the high-vacuum tube and the gas-filled tube. The phototube is a special form of tube that may be of either the high-vacuum or the gas-filled type.

The constant-current tubes (ballast tubes) and constant-voltage tubes, which may be simulated by rheostats and batteries, respectively, are mentioned briefly later.

The Electron Tube Is a Rectifier. The first important characteristic of the electron tube as we know it today is that it is a *rectifier.* Electrons are permitted to flow through it in but one direction. There may be only two elements within the tube, the cathode and the anode, by which the electrons enter and leave the tube, or there may be one or more extra elements used to control the electron stream. The English have a name for tubes that is, perhaps, more descriptive than ours. They call them "valves."

Here, at the beginning, must be made clear the difference existing between the direction of conventional current flow and the direction of electron flow. Many years ago, as a matter of convenience, it was stated that current was assumed to flow from a positive to a more negative potential. Now we know that those ultimate particles of matter, the electrons, which compose our current are always attracted to and flow toward the more positively charged potential. In this book it will always be assumed that it is the electron flow from negative to positive within the tube that is being considered.

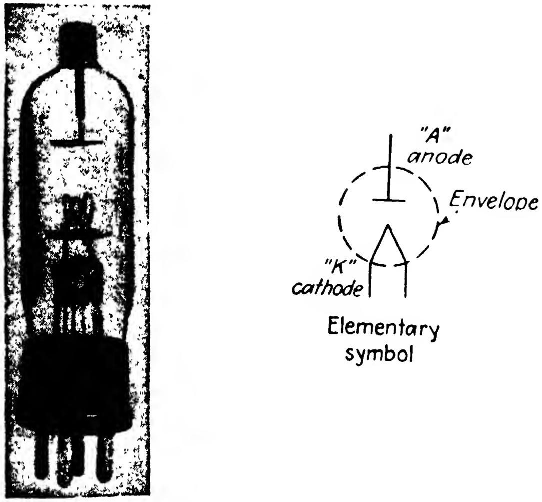


FIG. 1.1. The simple diode rectifier.

Thermionic Tubes. The electron tube as we know it is inherently a rectifier, or a one-way valve for electricity. In its simplest form it consists of two elements: a *cathode*, or electrode from which electrons can be easily removed, usually by making its surface red-hot; and an *anode*, or *plate*, to receive those electrons. The anode, unlike the cathode, is specially constructed so that electrons cannot be easily detached. The electrodes are enclosed in a container which has been evacuated to as high a vacuum as possible or which, in some special types of tube, contains special gases or vapor at a very low pressure. The high vacuum permits the electrons to flow from cathode to anode with the least interference (Fig. 1.1).

If the electron tube is to function as a simple rectifier, only the above two electrodes are needed. However, it is often found useful to control the flow of electrons between cathode and anode; so other electrodes, usually in the form of metal shields with holes or wire "grids," are placed between the cathode and anode to control or throttle the flow.

The fundamental law of electronic attraction may be stated as follows:

An electron, if free to move, will always tend to move toward a point having a more positive potential.

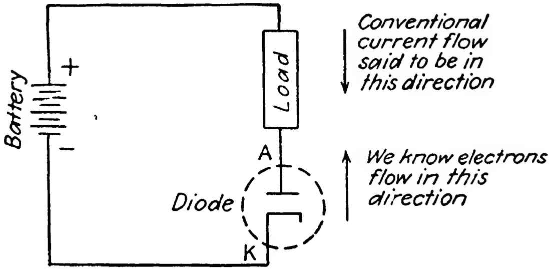


FIG. 1.2. A simple circuit to illustrate conventional current flow compared with electron flow.

In our electron tube this means that if the anode is made more positive than the cathode, for example, by connecting the negative terminal of a battery to the cathode and the positive terminal to the anode, the electrons available at the cathode will be attracted to the anode and a flow of electrons will be set up from cathode to anode to the positive end of the battery, through the battery, and returning at the negative end to the cathode to complete the circuit. This fact should be emphasized: the flow of electrons is from the negative terminal of the battery through the external circuit (the tube) to the positive battery terminal (Fig. 1.2). It will be noted that this is opposite to the unfortunate conventional concept of the electric current flowing from the positive battery potential to the negative in the load circuit. The electron flow in the tube is *always from negative to positive.* If the positive terminal of the battery were connected to one of the control elements, or grids, the electron flow from cathode to grid would take place in the same manner.

If the battery connections are now reversed so that the positive terminal is connected to the cathode and the negative to the anode, the loosely bound electrons of the cathode are no longer attracted to the now negative anode and no electron flow occurs (Fig. 1.3). (It is true there are electrons inside the metal of the anode, but they are bound there and are therefore not free to move across the space to the positive cathode. Hence, no current flows in either direction.) The electrons can flow from the cathode to any other element in the tube that is more positive, but normally no reverse electron flow can take place no matter what the potential of the cathode with respect to the other elements.

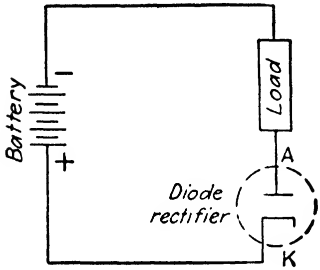


FIG. 1.3. The battery in FIG. 1.2 has been reversed. There can be no current or electron flow in this circuit.

The Cathode. It has been stated that the cathode is specially designed to have the unique property of having electrons so loosely bound that they may be drawn out of the cathode across the space to a positive anode. A more detailed study will indicate how this is accomplished. It is well known that, as most substances are heated, their internal structure becomes less tightly bound. As the temperature increases, solids become liquid and liquids become gases. Somewhat similarly, it may be shown that the free electrons in the cathode material become more active as the temperature is increased, until finally, when the temperature is high enough, they "emit" into the adjacent vacuum space. This makes them available as carriers of negative current to the anode.

Heat may be obtained by making the cathode itself of some high-resistance material such as tungsten and passing an electric current directly through it, or the cathode may be built in the form of an electric stove with an electric-heater coil inside to heat it to the proper temperature. These heaters are energized by either a battery or a low-voltage coil from an a-c transformer. If the cathode is in the form of a lamp filament and is heated by passing current directly through it, it is called a "directly heated cathode" or "filament" (Fig. 1.4*a*). If a separate heater is used, the term employed is "indirectly heated cathode" (Fig. 1.4*b*). In the indirectly heated type the heater may be insulated from the cathode so that it is possible to operate a number of heaters from a single power source even though the cathodes are at different potentials. However, since the insulation is at high temperature,

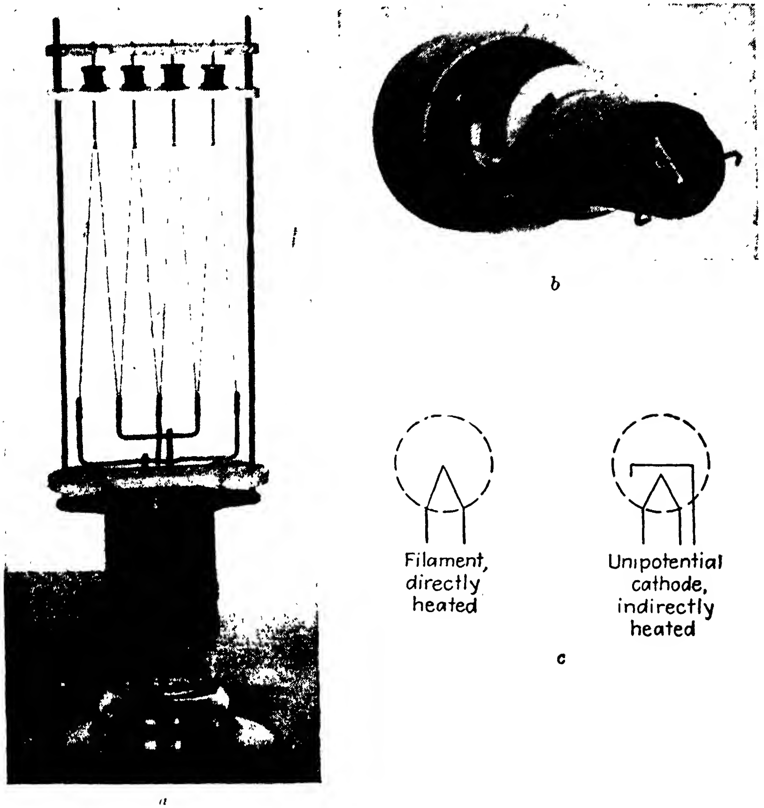


Fig. 1.4. Directly (*a*) and indirectly (*b*) heated cathodes.

its insulating value is considerably less than when cold, and this must be taken into consideration in circuit design. Also, since the heating current does not flow through the indirectly heated cathode, all parts of it are at the same potential. This is very desirable in some applications.

On the other hand, for some uses the directly heated filament type of cathode permits the most efficient use of heating power where this must be conserved, as in battery-operated sets, and where quick heating and maximum emission are desired, as in the case of small rectifiers.

Cathode Materials. Various materials are used for cathodes. The first used was the pure tungsten filament as in the incandescent lamp. This material is still considered the best for high-power high-voltage vacuum transmitting tubes, but the efficiency as expressed in amperes of emission per watt of heater power is low.

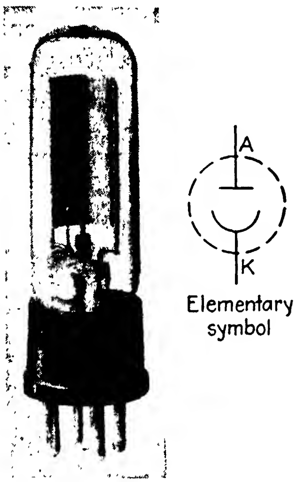
It was next found that by impregnating the tungsten with the rare metal thorium the *thoriated-tungsten* filament became a much more efficient emitter. Whereas for best efficiency the pure tungsten requires heating to an incandescence approaching that of a light bulb, the thoriated filament will produce better emission at a bright red heat. Cathodes using thoriated tungsten are employed for medium-power transmission tubes. The action of the thorium in the tungsten is somewhat complicated and requires that the cathode be always operated at full cathode voltage rating to prevent loss of emission, or "starving," of the cathode. A thoriated-tungsten filament that is low emitting can often be rejuvenated by operation at increased filament voltage for a short time, with anode voltage removed, before using.

By far the greatest number of cathodes, however, in low-voltage tubes such as receiver tubes, thyratrons, and phanotrons, are coated cathodes. These are composed of a base of nickel or similar metal, heated either directly or indirectly to a dull red heat. The base is coated with a paste composed usually of mixtures of barium or strontium salts. The coating is an extremely efficient emitter. Because of its efficiency, its ability to liberate the greatest number of amperes of electrons per watt of heater energy, this type of cathode is found in most of the industrial tubes with which we shall deal. Its greatest defect is the insecure bond between coating and base. Continued operation of the tube or the expansion and contraction due to the heating and cooling of the cathode eventually weaken the bond and permit the active material to flake off until what is left on the cathode is insufficient to furnish the required flow of electrons. If the active material is not lost, the tube will eventually fail owing to the gradual evaporation of the active material. Also, in tubes containing gas molecules, the positively charged molecules (positive ions), which are attracted to the negative cathode just as the electrons are attracted to the positive anode, may under abnormal conditions strike, or bombard, the coating hard enough to blast loose the material. Since the greater the voltage between anode and cathode, the greater the velocity that the ions may attain, it becomes evident why, since all tubes contain slight traces of gas, pure tungsten can be employed for those vacuum transmitting tubes used for the highest voltages, and coated cathodes are used only for those tubes having an anode potential of but a few hundred volts at most. They may be used for gas-filled tubes such as thyratrons and phanotrons because during the conduction period the anode-cathode potential is reduced to only a few volts. (The reason for this is explained later, page 22.)

Phototube Cathodes. It has long been realized that many substances will emit electrons when light strikes them. In most cases this emission can be detected only by the most sensitive laboratory instruments. But in the past few years, materials and methods of processing them have been discovered which produce such efficient emitters in the presence of light that, with the help of other electron tubes to amplify the still very minute output, they have made possible the development of practical light-operated relays.

The usual light-sensitive cathode consists of a silver base, shaped to receive the light, on which is evaporated a very thin layer of the sensitive material. The active material used depends on the particular wave lengths of radiation at which best reception is desired. Cesium oxide is most sensitive to the infrared just beyond the visible spectrum, but its sensitivity continues throughout the visible spectrum. Thus it has proved valuable for use with incandescent light, which is strong in the infrared and red rays. Cesium oxide and antimony with proper processing have great sensitivity to blue and near ultraviolet light. Pure potassium and sodium are sensitive to ultraviolet light but are not nearly so efficient as the cathode materials mentioned above.

In order to take advantage of these light-sensitive cathodes, it is necessary, of course, to enclose them in an evacuated glass envelope and to provide a positive anode to collect the emitted electrons (see Fig. 1.5). For gas in phototubes see page 33.



Elementary symbol

Fig. 1.5. The phototube. There are many sizes and shapes available.

Mercury-pool Cathodes. A unique kind of cathode is the mercury pool used in the ignition type of tube. The mercury pool, as we might expect, is normally not a good emitter. However, once a flow of electrons has been started and the arc is established in the atmosphere of mercury vapor above the pool, the heavy positive ions formed of mercury molecules drift to the mercury surface, drawing out the electrons at the surface, just as if we had an extremely small spark gap, and thus freeing electrons to flow to the anode. Since each ionized mercury atom creates a positive ion for further action, it is clear that the emission possible from the pool is almost limitless. After the flow has ceased, the mercury may recombine and condense to its original liquid form, unaffected by its temporary change of state. This type of cathode is thus quite suitable for the emission of the very large currents required for resistance welding.

The Anode. The anode, or "plate," as it is often called by radiomen, is that electrode which is designed to receive the electrons emitted by the cathode. Since any conducting material will make a fair anode, its construction is much simpler than that of the cathode, but to obtain the greatest over-all efficiency a number of factors must be considered in its design. In the first place, the electrons moving from cathode to anode acquire a velocity depending on the potential difference. When they strike the anode, this kinetic energy is given up in heating it. If the anode retained the heat, its temperature would rise to a point at which it too would become an emitter or at which it might even melt.

Thus two important requirements for the anode are that it shall be a good heat radiator and that it shall be made, or at least have a covering, of a material which is inherently a poor emitter of electrons. It should be composed of a material having a high melting point. Also, it should be made of a material from which absorbed gas may be easily drawn when the tube is exhausted. These conditions are best met by nickel, tantalum, molybdenum, and similar metals, usually coated with graphite or carbon black for better heat radiation. In some cases the whole anode is a molded block of graphite. In some of the largest radio transmitting tubes the anode becomes the actual outside wall of the tube so that it may be cooled by direct immersion in water or may have large radiating fins for forced air cooling.

There is no mystery in calculating the amount of heat to be dissipated. Since all the energy in the electron stream must be changed to heat at the plate (assuming no secondary emission), the heat is simply the product of the electron flow in amperes times the voltage difference between the cathode and the anode, which we express, as usual, in watts. If both voltage and current vary, as they do in any actual circuit, the instantaneous heating must be found and averaged. As the anode effectively encloses the cathode in most vacuum tubes, a large part of the cathode heat will be radiated to the anode, where it must be reradiated.

Anode Shapes. The shape of the anode is designed to distribute as evenly as possible the flow of the electrons from the whole cathode to the whole anode so that emission from the cathode and heating of the anode will be as uniform as possible. If control grids are to be placed between the anode and cathode, the anode shape may be modified to permit a more desirable distribution of voltage, or *gradient*, between cathode surface and anode. Because of the different characteristics of electron flow in a gaseous atmosphere, the anodes in gas-filled tubes are of a different shape from those in vacuum tubes, usually smaller and spaced away from the cathode rather than enclosing it.

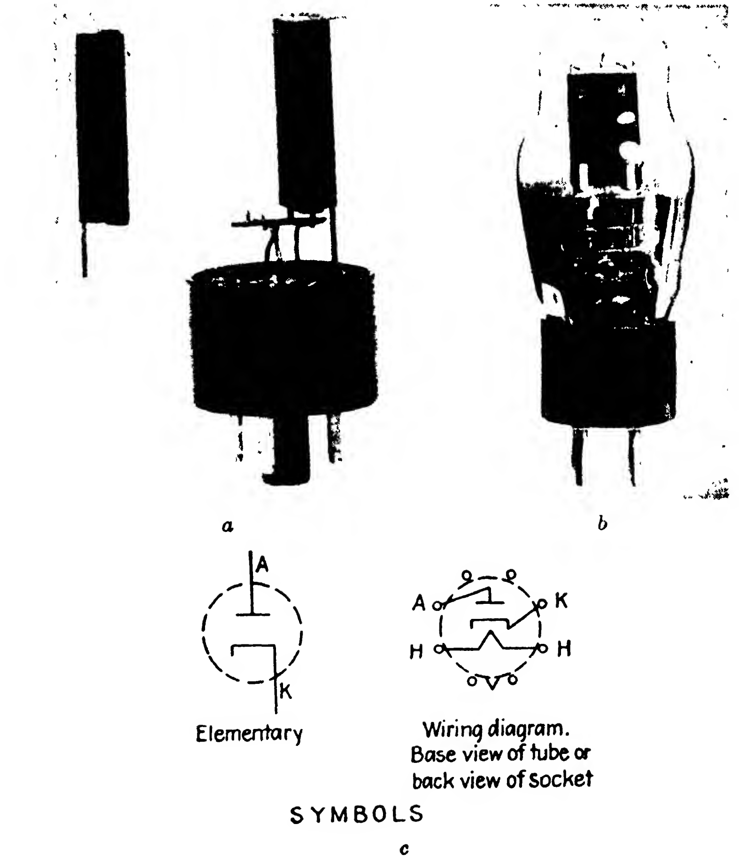


Fig. 1.6. Typical small diode rectifiers. (*a*) A twin-diode type with one anode removed to show the directly heated cathode.

In small tubes, such as phototubes, having electron flows of the order of microamperes, the problem of dissipation becomes unimportant. The anode may consist of a single piece of wire placed where it may collect the electrons most effectively and yet interfere least with the light striking the sensitive cathode.

The anode of an indicator tube may be coated with a fluorescent material that will glow with a visible light when the electrons from the cathode strike it. Sometimes this fluorescent anode is called a "target" or "screen."

Diodes (Fig. 1.6). In the discussion of electronic fundamentals on page 7, the inherent characteristics of the rectifier or diode were stated. Diode means "two electrode," here, of course, cathode and anode. It is a simple one-way electrical valve. At low frequencies it is practically a perfect one-way valve, or rectifier, since, if the anode is designed so that there are no free electrons, there can be no reverse electron flow when the cathode is positive. Therefore, under these conditions the tube becomes an open circuit, the impedance being a combination of the tube insulation and the very small capacity between cathode and anode.

Infinite impedance to reverse current is one of the two requirements of a perfect rectifier. The other is a zero impedance for the forward current. Unfortunately, in practice the tube rectifier does not approach this second requirement nearly so well. The anode must be positive with respect to the cathode to attract the electrons, and in the practical range of potentials the number of electrons attracted increases as the three-halves power of the voltage. As will be seen from the curves in Fig. 1.7, the electron flow between cathode and anode increases according to the three-halves law until a certain current is reached. Then the curve breaks and a limit in current flow is reached so that no appreciable increase is noted as the anode poten-

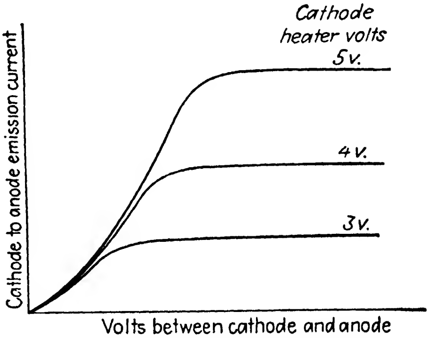


Fig. 1.7. Cathode emission curves, showing emission limit for three values of cathode heat.

tial continues to increase. This is the limit of emission for that particular cathode temperature. However, if the cathode temperature is raised, the emission will be increased and the ultimate limit will, of course, be higher, as shown by the succeeding curves. It should be noted particularly, also, that the curves for each cathode temperature, while similar to each other in the three-halves power range, are not the same but show a slightly increased current at each anode voltage point as the cathode temperature is raised.

Since the emission from a tungsten filament increases rapidly *as the cathode heating voltage is raised, a sensitive voltage or current indication can be had by applying the indicated voltage or current to heat the cathode, using a sufficiently high anode* voltage to ensure obtaining the limit emission, and reading this emission current on a meter in the anode circuit. Except for this application, however, almost all electron tubes are so designed that the maximum current normally drawn will be well below the emission limit for the specified cathode heater voltage and temperature.

Space Charge. Let us go back for a moment and examine more in detail the reason why the diode is not a perfect rectifier, why all the electrons emitted are not immediately drawn to the anode as soon as it becomes positive with respect to the cathode. If the cathode were cold and no current could flow, we could assume that the distribution of voltage between cathode and anode, or the so-called "voltage gradient," would be a straight line with the cathode at zero voltage and the voltage halfway between anode and cathode in space equal to half the anode voltage, as shown in Fig. 1.8. If a single electron were now free to move from the cathode, it would be attracted along toward the anode by a uniform force, gaining speed uniformly as it went until it finally crashed into the anode and gave up its

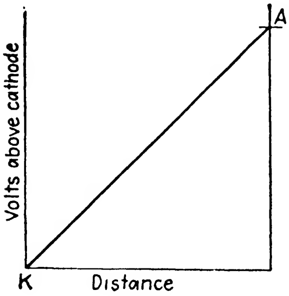


FIG. 1.8. Voltage gradient between cathode and anode when no current is flowing.

kinetic energy in the form of heat (as was discussed previously). This is exactly as a ball under the pull of gravity increases in speed uniformly as it rolls down a uniform grade.

But any usable electron current consists of, not a few, but many millions of electrons, and when all these attempt to leave the cathode simultaneously, a very interesting effect is produced. Since the electrons are at cathode potential, their cumulative effect, as they tend to move out away from the cathode, is as if the cathode itself were expanding. The electrons behind the first layer find themselves on a "plateau of potential," as it were, between the outer layer of electrons and the cathode, both at *the same "height," or potential. Hence, there is no tendency for them to follow the first electrons.*

Actually, nothing so abrupt as this occurs. The electron flow is never great enough to shield completely the cathode from the anode, but the general effect is to slow down the speed of those electrons nearer the cathode because of the presence of other electrons between them and the anode. So for any given anode potential a stable condition is set up in which there are a sufficient number of electrons flowing each second so that the retarding action toward those behind just balances the attraction toward the anode. If the potential-gradient curve is drawn for these conditions, with the height of the curve at any point equal to the velocity imparted to the electron at that point, this gradient is no longer a straight line but a dish-shaped curve becoming steeper as it approaches the anode (Fig. 1.9).

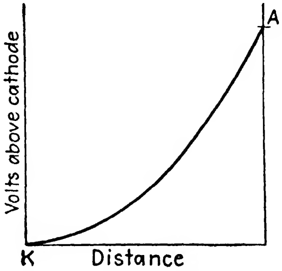


FIG. 1.9. Voltage gradient between cathode and anode when current flows, showing the effect of space charge.

It is this *space charge*, then, or the retarding action by the electrons themselves in the space between cathode and anode toward those behind, which determines that, instead of all the electrons emitted flowing at once from cathode to anode, the flow is limited by the potential on the anode and, as stated before, by the temperature of the cathode.

Initial Velocities and Contact Potentials. The space-charge effect shows itself in another manner when we are attempting to work with anode potentials of a very few volts. Some of the most active electrons at the surface of the hot cathode may actually be "boiled off" into the space surrounding the cathode, even though the anode is absent or is at cathode potential. These electrons naturally tend to return to the cathode, but the boiling action is sufficiently violent in the ordinary cathode materials used in the smaller tubes (barium, strontium oxide, or thoriated tungsten) to maintain a cloud of electrons close to the surface of the cathode, which has a potential of approximately 1 volt *negative* with respect to the cathode surface. Therefore, odd as it may seem, if an electrode which is ½ volt negative with respect to the cathode is placed close to the heated cathode, a small electron current due to this effect will be found flowing to the electrode in apparent contradiction to the law that no current will flow from a cathode to an electrode more negative than itself. As a result of this effect, sometimes called "initial velocity," a disconnected electrode or one connected to the rest of the circuit through a high impedance of several megohms may be found to be charged to a potential, not that of the cathode, but about 1 volt negative with respect to the cathode.

Another effect, sometimes called the "contact-potential" effect, exaggerates the current to an electrode with a slightly negative potential. Just as two dissimilar pieces of metal dipped in a dilute acid indicate a potential difference, two electrodes of different metals in a "bath" of electrons have a potential difference. Thus, if the metal of the anode is in one of the series of metals that is positive to the material of the cathode surface, then the current that flows with zero, or negative, anode voltage is increased.

As might be expected from the very nature of the action, such effects are not stable and constitute one of the most serious limitations in attempting to operate electronic rectifiers and amplifiers on very low anode voltages, especially those of only a small fraction of a volt.

Questions

1. What is meant by a rectifier? How is rectification accomplished in an electron tube?

2. What is meant by a "thermionic" tube?

3. Name two cathode materials and compare them as to (*a*) heating watts per ampere of emission, (*b*) time required to reach operating temperature.

4. How is emission obtained from (*a*) a mercury pool, (*b*) a phototube cathode?

5. How does space charge limit the electron flow?

CHAPTER II

GAS-FILLED RECTIFIERS

The Gas-filled Diode, or "Phanotron." In working with high-vacuum rectifiers and observing the high voltages required to cause useful currents to flow in spite of the space-charge effects, we realize that it would be extremely desirable to try to eliminate or at least to neutralize the space-charge effect. This is done in a fairly satisfactory manner in the modern gas-filled electron tube. The envelope in this type of tube contains a gas at a very low pressure, usually argon or, more recently, xenon. Or a drop of mercury vapor, boiling off in the vacuum at normal room temperatures, provides sufficient gas molecules for proper operation.

Let us now try to visualize what happens when the cathode is heated and a positive potential is applied to the anode. If this potential is below 8 volts, nothing much happens except that the gas atoms get in the way of the electron stream so that the current is even less than without the gas present. However, as the anode voltage is raised to somewhere between 10 and 15 volts (depending on the gas used and other factors), the electrons attain sufficient speed when bouncing from one atom to the next actually to knock free one of the electrons of the second atom, a phenomenon called "ionizing." This leaves two electrons free to move toward the anode, and the atom robbed of an electron has become a positive ion and so is attracted to the (negative) cathode. Normally, the comparatively heavy, slow positive ions drift toward the cathode so slowly that those which do finally reach it contribute less than 1 per cent of the total current flow and do not strike the cathode surface with enough force to cause appreciable damage. Such an ion may combine with one of the electrons to become a neutral atom again, producing the familiar colored glow seen in gas-filled tubes, only to be torn apart again *by a glancing blow from another higher speed electron.*

As a result of the myriads of collisions taking place throughout all the space between anode and cathode, the area quickly becomes filled with flying electrons and positive ions. In the major part of the space, except close to the anode and cathode, there will be an approximately equal number of electrons and positive ions (Fig. 2.1). This is called the "plasma," and in it the presence of the positive ions averages out the space-charge effect of the negative electrons. This is the desired result to be obtained by gas filling. The spaces next to the anode and cathode, or "sheaths," have a great number of electrons entering or leaving the plasma. Because of the electrons in the sheaths, there will be some space-charge effect there. However, the sheaths are but a small part of the total space. Near the anode the concentration of electrons may even permit the anode to be at a slightly lower potential than the plasma, as a continual stream of negative charges drawn from the neutral plasma tends to make the plasma's *average* potential more positive.

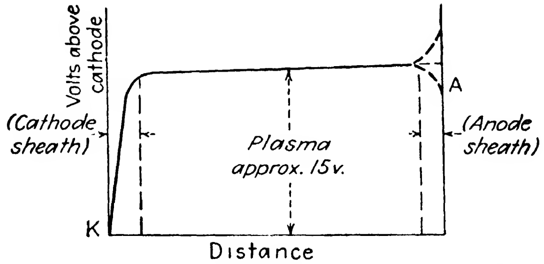


FIG. 2.1. The plasma potential gradient in a gas-filled tube.

The Cathode Sheath. The potential drop in the cathode sheath must be great enough to overcome the space charge and permit the attaining of sufficient speed by the electrons to bombard and ionize the gas atoms of the plasma. Thus the flow of electrons into the plasma from the cathode sheath and the flow out into the anode sheath are balanced by slight changes in the plasma voltage, no matter how great or small the anode current may be. If the plasma voltage tends to rise too high, the added average speed of the electrons from the cathode will increase the ionizing effect greatly, flooding the plasma with a superabundance of free electrons and thus tending to reduce its potential below the ionizing potential. If, on the other hand, the plasma tends to drop below ionizing potential, the slow infiltration of the cathode electrons only cannot replace those lost to the anode so that the positive ions in the plasma will predominate and the plasma potential will quickly rise again to the ionizing potential.

It is beyond the scope of this book to try to give a complete picture of the complex ionizing process. The most important fact to remember is this. Owing to the action of the gas in the tube the space charge is effectively neutralized so that the anode-cathode potential in a gas-filled tube, for *any current* in the cathode emission range, is approximately the ionizing potential of the gas, usually 10 to 15 volts. This means that the gas-filled tube as a current conductor is much more efficient, that is, has a much lower loss for a given anode current, than the high-vacuum tube.

Drawbacks to Gas Filling. By filling the tube with gas a high-efficiency rectifier has been obtained as desired. But what other effects, perhaps not so desirable, has gas filling produced? First, it has slowed down the action of the tube. The ionizing of the gas and the building up of the plasma take time—not much, only about one hundred-thousandth part of a second, or 10 microsec, but still hundreds of times as long as for the unobstructed electron to cover the same distance. Even longer is the time taken for the plasma to deionize, for the positive ions and electrons in the space to reunite to form neutral atoms. This takes $\frac{1}{1000}$ sec, or 1000 microsec, in the usual gas-filled tube, although special tubes are built to deionize faster at the expense of other characteristics. This means that the gas-filled tube, unlike the vacuum tube, is limited to the rectification of a-c frequencies of only a few hundred cycles.

The gas pressure within the tube must be kept within limits for satisfactory results. This is not serious for true gas fillings, for the change in pressure in a true gas like argon or xenon over the normal ambient temperatures is not excessive. These gases do tend to be absorbed by the elements of the tube, though, and this gradual "cleanup" is one of the reasons for tube failure. However, when mercury vapor is used, the temperature range is much more critical. We all know that at sea level water boils at 212°F; that is, at 212°F the air pressure of 14.7 lb per sq in. of the atmosphere is just balanced by the growing vapor tension of the heating water, and steam is produced. On top of a high mountain, on the other hand, where the atmospheric pressure is only half that at sea level, the water will build up sufficient vapor pressure to match this greatly reduced outside pressure at about 172°F, or only 40°F less than that required at double the pressure.

Thus, there is a much greater change in pressure for a vapor than for a gas over a small temperature range. The small drops of mercury in the evacuated bulb of the electron tube boil away at any given temperature until the vapor within the bulb can exert the pressure to balance the vapor tension required for boiling at that temperature. We are lucky that the vapor pressure of mercury vapor in the normal range of ambient temperature is satisfactory for our use. But for outdoor uses in cold climates, unless artificial heat is used, the vapor will not supply sufficient atoms to be ionized into an efficient plasma. On the other hand, if the temperature rises too high, the electrons are unduly obstructed, deionization is slow, and the possibility of disruptive reverse electron current flowing from anode to cathode, an "arc back," becomes much greater.

In favor of the mercury tube, however, it will be remembered that there is always a little liquid mercury left to supply the needed vapor; thus, mercury-vapor-filled tubes do not "clean up." Mercury has the defect that in shipment it may be splashed onto the electrodes and "wet" them; it must then be distilled off by energizing the cathode heater for some period such as a quarter or half hour before the tube can be used again. This is particularly serious in portable equipments.

Hydrogen Gas Filling. For military radar a thyratron was required having an extremely short deionizing time, in the order of 1 microsec. This was made possible by filling the tube with hydrogen gas. Since this is the lightest known gas, the movement of the molecules for a given pressure is the most rapid, permitting much faster deionization. Unfortunately, the chemical activity of the hydrogen is also high, and these thyratrons have a relatively short life. However, research is being carried on to improve their life and so bring to industry the advantage of thyratron control at frequencies much higher than is possible at present.

Cathode Bombardment. A final characteristic of the gas-filled tube arises from its principal feature of a nearly constant potential drop for any value of current. Unless the anode-circuit impedance is sufficient to limit the current that will flow through the tube, the tube may be greatly overloaded and destroy itself. In the discussion of the electron-current flow it was brought out that the maintenance of the plasma in a stable state and the steady flow of current were dependent on a plentiful supply of electrons coming from the cathode. If the demand of the current flow cannot be met by a slight rise in voltage above the ionizing potential, a large number of positive ions will be created, and these may be drawn all the way to the cathode before finding electrons for neutralizing. The positive ions are much heavier than the small electrons and, having been abnormally accelerated by the increased potential drop between plasma and cathode (just as the electrons are in the opposite direction), may strike the cathode with relatively great energy. This energy being turned into heat helps raise the temperature of the cathode, vaporizes its surface, and ionizes its atoms, freeing electrons. The loss of a positive ion from the plasma frees an electron to the anode to preserve the potential balance; and the electrons, blasted from the cathode surface, may be attracted to the plasma just as any other electrons are so that the current required will be maintained until the cathode itself is almost completely destroyed.

Positive-ion bombardment may be indicated in some cases of extreme overload by sparking and sputtering at the surface of the cathode as the active material is destroyed or actually chipped off. This was mentioned briefly in connection with vacuum tubes, in which it may be due to the presence of stray gas molecules, but it is much more pronounced when a gas has been deliberately introduced.

a

b

Fig. 2.2. A mercury-arc rectifier of the pool type with multiple anodes.

It is important to point out that bombardment can occur whenever the cathode cannot supply sufficient electrons for the current demanded. It is easy to see that this may occur on an overload or short circuit of the load. It can also occur if the heater power is lost while the tube is being used, if the heater power is decreased badly by poor connections, etc. In the larger tubes with indirectly heated cathodes, which require several minutes to reach the proper emission temperature, the tube's cathode can be destroyed quickly if power is applied to the anode circuit at the same time that the cathode heater is turned on. Attempts to shorten the heating time specified by the tube manufacturer tend to decrease the cathode's life. In some special cases the heating time is shortened by running the heater at overvoltage during the heating period. Usually the cost of the extra equipment required for this is not justified.

Circuits using some of the smaller gas-filled tubes having directly heated cathodes, which come up to temperature in a few seconds' time, do not employ cathode protective circuits since it is thought that if power is applied to the circuit only once or twice a day, as is usual, the slight loss of tube life due to these few seconds is not serious. Large tubes can be made quick-heating only by means of a prohibitive amount of heater power.

Mercury-arc Rectifiers and Ignitrons. On page 14 reference was made to the mercury-pool type of tube in which the heavy positive ions of mercury drifting close by attract electrons from the surface of a mercury pool, which thus acts as a cathode to supply an almost limitless number of electrons. The two types of tube using a mercury pool as a cathode are similar in their operation of continuing the current flow after the ionization of the mercury vapor is established but differ in their method of starting the cathode emitting spot. In the older type (Fig. 2.2), which uses a common mercury-pool cathode and a number of anodes, one of which is always positive, the current flow, or *arc*, is started mechanically by dipping a rod, or auxiliary anode, into the mercury and drawing it out by a solenoid or other means to start a small arc and create the first ionized atoms. These, in turn, can be drawn into the path between the pool and a main anode to build up the plasma for the regular current flow. In this type the vapor is never permitted to deionize. As one anode becomes less positive, another picks up the current flow. Elaborate baffling is used between the anodes to prevent current flow and short circuits between them. This type is made in large sizes and is often kept evacuated by continuous pumping.

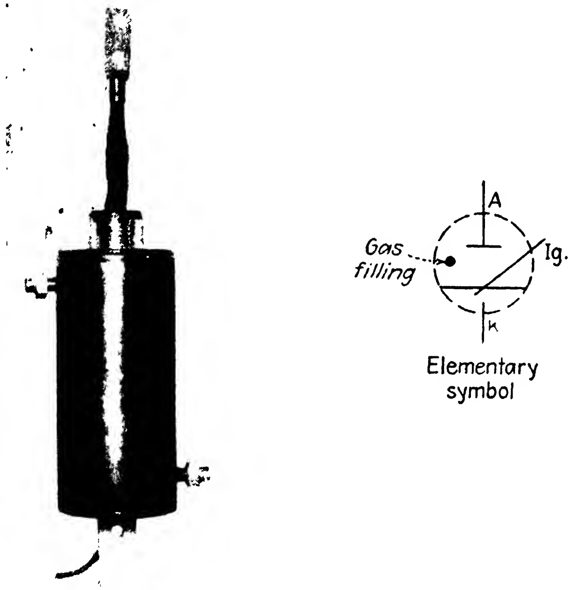


Fig. 2.3. The ignitron.

A more recent development in mercury-pool tubes is the ignitron (Fig. 2.3). Here the arc is started electrically by an *ignitor*, a piece of some crystalline substance such as boron carbide, which projects into the mercury pool but is not wet by it. Comparatively little power is necessary to start an arc on the mercury surface and thus begin the ionizing action. Since this starting action is electrical rather than mechanical and can be performed as often as desired by electronic means, it is no longer necessary to maintain the vapor continuously ionized as in the mercury-arc rectifier. It is possible to have tubes with only one anode and thus do away with the elaborate baffling and the danger of arc backs and cross-anode arcs of the multianode type. Even more important, stopping the ignitor action will prevent the tube from conducting, while operating the ignitor will permit it to conduct at any desired time. This gives a flexibility of control to the ignitron impossible with the older rectifier.

Ignitron tubes, however, have a few drawbacks. The life of ignitors is not unlimited; in fact, they are usually the first part of the tube to fail. Ignitors cannot be permitted to become negative with respect to the pool, for the reverse current may ruin them. They cannot stay more positive than the plasma potential long after the tube has been fired, or they will tend to rob the anode current and burn up. The energy required to fire them, while small compared with the power that can be released, thousands of amperes at many thousand volts, still may be as much as 40 amp at 200 volts and is thus quite large compared with many of the smaller loads to be controlled. Also, if the current in the ignitron is allowed to drop below about 5 amp, the action of the bombardment in the cathode spot may become erratic. Some-

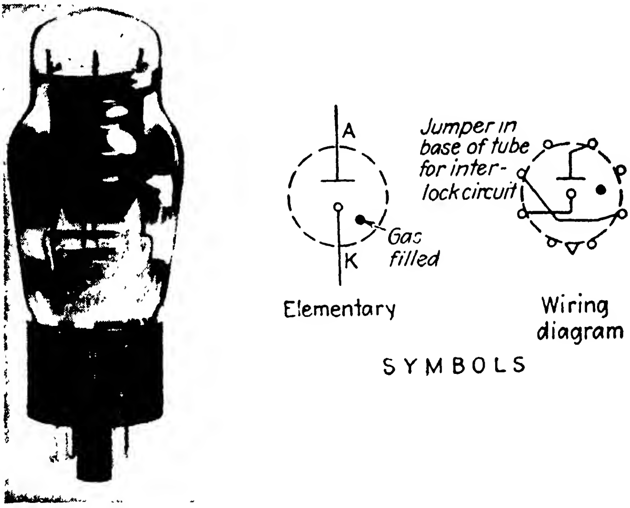


Fig. 2.4. A cold-cathode gas-filled voltage-regulator tube.

times, when it is essential for the ignitron to be stable on small anode currents, an auxiliary anode drawing a parasite current of 5 amp or so is added to ensure the continuation of the electron and ion supply.

Cold-cathode Tubes (Fig. 2.4). Another type of tube, with a cold cathode, is specially designed to take advantage of a characteristic of gas ionization that we have heretofore considered only briefly, the almost constant potential between anode and cathode. For power-conduction purposes it is desirable to keep this *arc drop* as low as possible. For this purpose we use mercury vapor, argon, and xenon. But by using other gases, higher arc-drop potentials may be had. For example, the familiar neon lamp holds a constant potential of between 55 and 60 volts. Other gases hold about 75, 90, 105, or 150 volts (Fig. 2.5). In each case it is necessary to raise the potential between cathode and anode 30 or 40 volts above the arc potential for the creation of the ion bombardment to start the original discharge. A sharply pointed projection is usually welded to one or both of the electrodes to assist in creating a potential gradient great enough for the original breakdown.

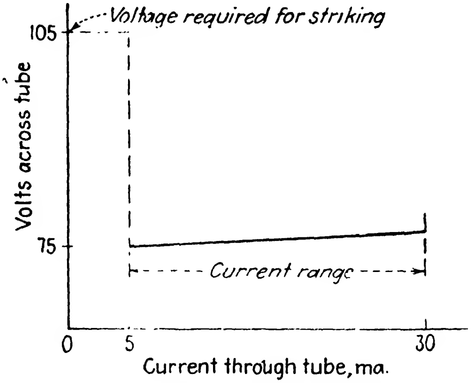


FIG. 2.5. The voltage-current curves for a typical voltage-regulator tube.

A Constant-voltage Reference Source. Cold-cathode tubes make satisfactory constant-voltage sources where the current requirements are not too severe. The commercial models have a current range between 5 and 50 ma. Below 5 ma (10 in some types) the arc becomes erratic and may go out. Overloading the tube may shorten its life considerably. The cathode surface is specially prepared; but since it can be activated only by ion bombardment, *its life is definitely limited by the total number of electrons which flow so that the life may be expressed roughly in ampere-hours for a given type of tube.*

It has been stated that the tube arc drop is almost constant for the complete current range. There will be a slight regulation of 2 or 3 volts, however, over the current range. This is usually satisfactory. If a steadier voltage is needed, a high- or low-voltage regulator tube in cascade will give an extremely constant voltage across the lower voltage tube.

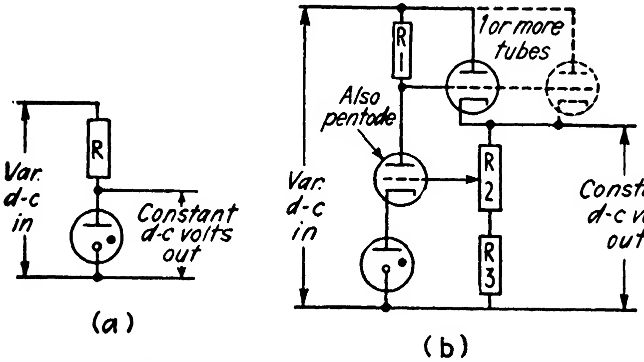


FIG. 2.6. Voltage-regulator tube applications. (*a*) Direct. (*b*) With amplifier, as a reference tube only.

If the greatest possible accuracy is desired, the reference voltage-regulator tube should not be used for other loads. Each time a tube strikes, the voltage held may change slightly.

An Improved Voltage-regulator Tube. In 1947 the Radio Corporation of America announced the Type 5651 voltage reference tube featuring a new emitting surface and improved construction that minimized the voltage change, sometimes as great as 1 volt, which occurred in former tubes when restriking or when the discharge transfers to another spot on the cathode. This tube is intended for use only as a reference with an almost constant current drain of only a milliampere or two, as in the typical regulating circuit (Fig. 2.6*b*), and not as a shunting circuit element, as in Fig. 2.6*a*.

Gas-filled Phototubes. When a phototube is filled with an inert gas, such as argon, the electron current released by the light energy is so small (a few microamperes) that the usual plasma conditions are not established under the normal maximum anode potential of 90 volts. Below 20 volts there is no appreciable ionization; but as the anode potential increases, some ionization occurs, until at 90 volts the original electron current has been multiplied seven or eight times. Higher anode potentials will increase the current, but there is the possibility of excessive cathode bombardment and uncontrolled cold cathode discharge, as discussed above. Naturally, the ionization action is less effective with increased frequency of light change.

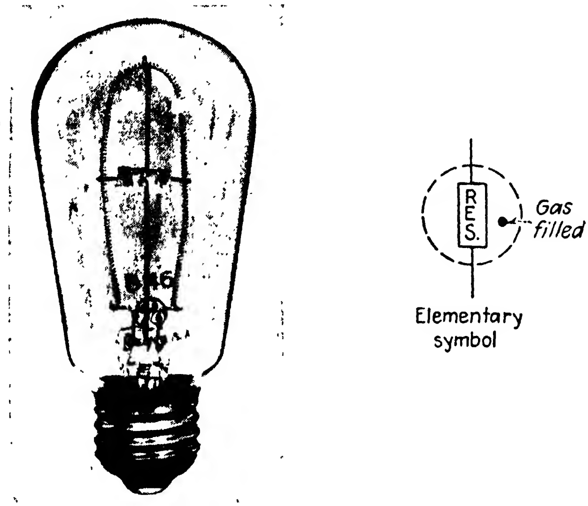


FIG. 2.7. The ballast tube, constant-current tube, or barretter.

The Constant-current Tube, Ballast Tube, or "Barretter." The ballast tube (Fig. 2.7) is described here merely for convenience since it is not a true electron tube. There is no electron flow through space such as is found in the usual electron tube. However, because it is often used in electron circuits for current-regulation purposes, it is included in our discussion.

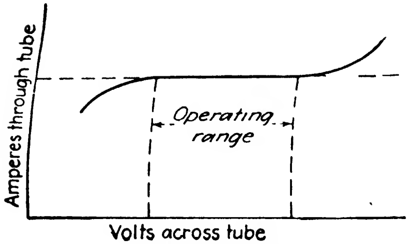


FIG. 2.8. The volt-ampere characteristic of a ballast tube.

The ballast tube consists of a resistor, usually an iron wire, mounted in a gas atmosphere, usually hydrogen, in a bulb of adequate size to permit proper cooling. As current flows through the iron wire, the heat generated tends to raise the wire temperature to a dull red. However, soon after the temperature reaches a dull red, the surrounding gas absorbs the heat so quickly that the temperature remains about constant. Since the resistance of iron increases rapidly with temperature, if the voltage across the ballast tube is a minimum, only a small portion of the wire will be heated red-hot. As the voltage increases, a longer section of the wire is heated, producing a higher total resistance, but the current will have risen hardly at all. Figure 2.8 shows a typical characteristic curve.

Since the regulation depends on the heating and cooling of the wire, it is not extremely rapid; a matter of seconds may be required to reach an equilibrium condition after a voltage change. Iron wire is not very satisfactory for currents below 1 amp. For smaller currents tungsten is used, though the resulting regulation is not so good.

Questions

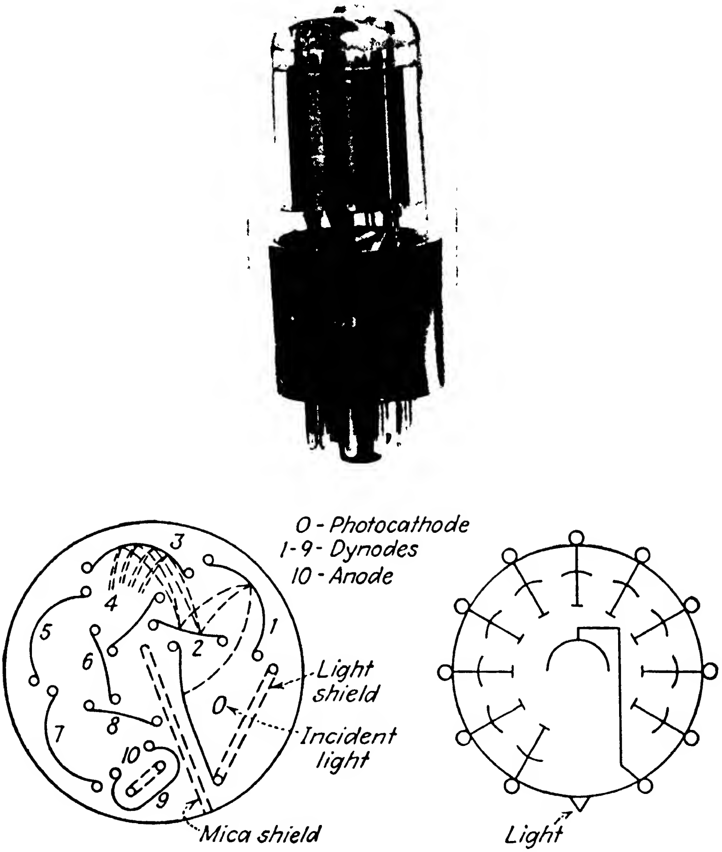
1. What is the principal reason for using gas in electron tubes?
2. Describe ionization within a gas-filled tube.
3. Comment on three drawbacks to gas-filled tubes.
4. Give an advantage for inert gas filling and one for mercury vapor.
5. Describe the starting of an arc in an ignitron.
6. For what current range is the ignitron best suited?
7. What points must be considered when using glow tubes as voltage regulators?

CHAPTER III

SPECIAL TUBE TYPES

Secondary-emission Tubes. These tubes, limited at the present time to low-current devices such as phototubes, use a series of cold anode-cathode electrodes in a cascade effect in which the few electrons emitted by the primary photosensitive surface become multiplied each time the electrons liberated by the bombardment of those from the previous stage strike the emitting surface of the next more positive anode-cathode. The average number of electrons liberated by each arriving electron may be only three or four and depends on the potential across each stage. But a typical tube (Fig. 3.1) contains nine stages, and 4^9 means an amplification of over 250,000. Since this type of tube contains no heated cathode from whose electron boiling surface minute random currents called "thermal agitation" or "Schott effects" may be set up, and requires no high impedances to be affected by stray electrostatic or magnetic fields as do multistage triode or pentode amplifiers (see page 148), these multistage secondary-emission tubes are found to be a stable and interference-free form of amplifier for very small currents. Their biggest disadvantage lies in the high potential necessary for their operation. Since the potentials for each stage must be added, the nine-stage tube mentioned above, with 100 volts on each stage, will require a total voltage of 900 volts compared with the 200 or 300 volts normally used on a small pentode amplifier.

Fluorescent Indicator ("Magic Eye") Tubes (Fig. 3.2). A visual indication of the electrons striking the anode is possible if the anode surface is coated with a fluorescent coating that will glow when energized by the striking electron. If a control electrode is inserted between cathode and anode (usually called a "target" here) and is made negative with respect to the electron stream at this point, the electrons are deflected from the control



Plan of tube, showing dynode arrangement

Elementary symbol

FIG. 3.1. The type 931 multiplier phototube.

electrode, and a shadow appears on the target in the vicinity where no electrons are being received. The more negative the control electrode is made, the farther the electrons are deflected, and the wider becomes the shadow. Hence, the width of the shadow is a visual indication of the potential of the control electrode, which is usually connected to some critical point in the circuit. Note that this shadow-forming electrode is not called a "grid." It is usually only a single vertical blade or wire to deflect the electrons at one point, as compared with the usual grid, which tends to control the average flow to all points on the anode.

In the usual commercial form of indicator tube, 6U6/6G5, a high-mu triode amplifier is also included in the tube envelope to amplify the action of the control electrode, and a form of screen grid is added to the indicator section to ensure a more uniform flow of electrons to the target and hence a more uniform glow outside the shadow area. Another form of indicator, 6AF6-G, has no amplifier but uses two independent control electrodes to form shadows on opposite sides of the cathode.

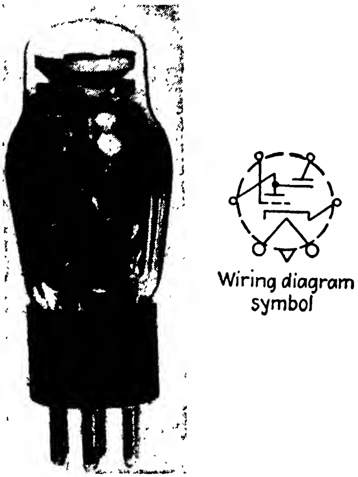


FIG. 3.2. The fluorescent target indicator tube, or "Magic Eye."

Cathode-ray Tubes (Fig. 3.3). There is nothing mysterious about the cathode-ray tube; it is merely a somewhat more versatile form of indicator tube. It consists of a heated cathode, hooded to permit electrons to come out only through a small hole, a control grid to limit the electron flow, and the anode, consisting of fluorescent material coating the slightly curved glass end of a long evacuated tube. Between the cathode and anode (in this tube called a "screen") are two cylinders that might be considered accelerating or screen grids such as will be discussed under Tetrodes (page 52). It might be expected that the electrons would strike the screen surface uniformly, producing a uniform glow of the fluorescent material. But it has been found that by suitably shaping the accelerating electrodes and adjusting their potentials with respect to the cathode and each other, an electrostatic "lens" is formed which can bend the electron flow back to a small spot at the screen just as a glass lens retracts light rays onto a camera film or as the sun's rays are concentrated to start a fire. (Incidentally, in some of the larger cathode-ray tubes, where high screen potentials produce extremely high electron velocities, if the focused spot is permitted to remain too long at one place on the screen it may burn up the fluorescent material there and even melt a hole in the glass.)

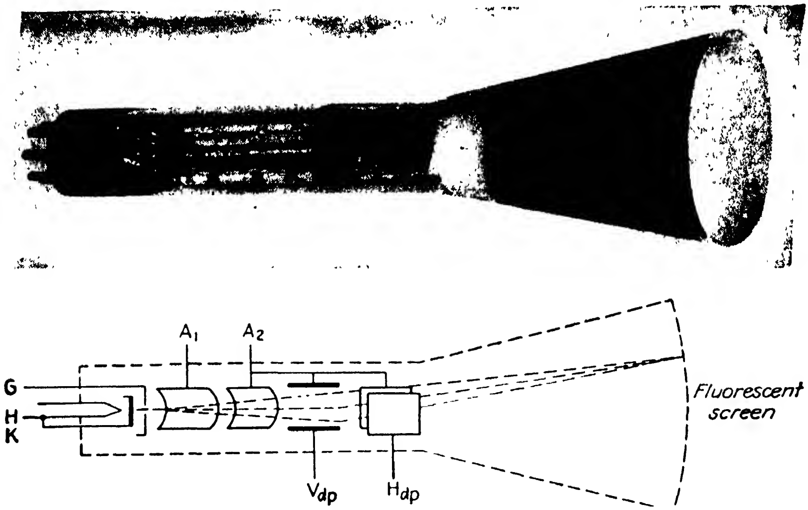


FIG. 3.3. The cathode-ray tube with electrostatic deflection.

Deflecting Plates. So far we have an electron "gun," which shoots a focused stream of electrons out to produce a small bright spot on the fluorescent screen. Next are added two small insulated plates, one on each side of the electron stream, just beyond the accelerating electrodes. Following the fundamental law of the repulsion of like electric charges discussed previously (page 9), if one of these deflecting plates is made negative to the electron stream, the stream will be deflected away from it; conversely, if the opposite plate is made positive, the stream will be attracted, doubling the deflection effect. By varying and reversing the potentials on the two deflecting plates the luminous spot can be swept in a line completely across the screen. This line will be perpendicular to the deflecting plates.

In order to move the spot in two dimensions on the screen, a second pair of deflecting plates at right angles to the first is added just beyond the first pair. Then, by juggling the potentials and polarities of both sets of plates, the spot may be made to move to any point on the screen. Since the deflecting plates draw no current but merely deflect the beam, they consume no power.

Many of the older cathode-ray tubes used in industrial electronic servicing are so designed that one plate of each pair is connected directly within the tube to the adjacent accelerating electrode. Newer tubes, to attain better balance and a sharper trace, change the potential of both plates equally above and below an average value.

Practical Oscillographs. In the usual cathode-ray oscillographs there is not only the power supply for the cathode-ray tube itself but also a timing circuit, which may be applied to sweep the spot horizontally at any desired constant speed across the screen and to cause it to fly back and repeat almost instantaneously. If the voltage to be observed is connected to the other set of plates, both its instantaneous magnitude and variation with time may be observed. If the observed phenomenon repeats more often than about ten times per second and the horizontal time sweep is set to synchronize, a continuous picture of the voltage trace will appear on the target screen, to be studied at leisure. Many oscillographs have amplifiers to amplify the input signal before it is applied to the deflecting plate.

To sum up, in the cathode-ray oscillograph we have a very useful voltmeter combined with a time axis so that instantaneous voltages and wave shapes may be observed easily with almost no loading on the circuit under observation. It has a more rapid response than is possible with any mechanical oscillograph and is not readily damaged by any overvoltage that does not actually break down the circuit insulation. In servicing cathode-ray circuits it must be remembered that, while the smaller tubes with 3-in. and smaller screens normally have no more than 600 volts between cathode and target, the larger tubes may use many thousand volts. For these the proper precautions must be taken.

Television "Picture Tubes." The cathode-ray tube in modified form is the television "picture tube." Here a rapid timing circuit sweeps the spot across the target screen while a slower timing wave moves it vertically to produce a rectangle of light. The electron beam itself is then modulated by the control grid to produce the light and dark areas of the picture. The details of television transmission and reception are far beyond the scope of this book since the subject involves the amplification of extremely high frequencies and a thorough understanding of radio theory.

There are two main differences between the cathode-ray tubes used in television and in oscillographs. In an oscillograph it is desirable to observe a slow trace. To assist this there is mixed in the fluorescent material of the target screen a small amount of phosphorescent material that will continue to glow for a short time (about $\frac{1}{25}$ sec) after the electrons cease striking the spot. In the television tube, on the other hand, this "persistence" must be kept as short as practical to prevent objectionable lag when rapid motion is shown on the screen.

For special work a wide variety of screen materials, or "phosphors," are available. Another development is the depositing of a fine layer of aluminum behind the phosphor to reflect more of the light forward.

Also, the larger television tubes, to decrease the cost of the tube itself and to isolate the deflection circuits from the high-voltage electron gun, use magnetic rather than electrostatic deflection. Since the electron stream is an electric current that may be acted on by a magnetic field just as if it were in the armature of a d-c motor, by placing properly shaped coils close around the tube about where the deflecting plates would have been, the proper deflection action may be obtained when the coils are energized.

Magnetically Controlled Kenotrons and Phanotrons. This type of tube, in which a magnetic field is set up by a coil placed around the tube to replace the electrostatic grid control of the electron stream, has definite possibilities but has not yet been exploited to any great extent in the industrial field. Since there are inherent RI^2 losses in the magnetic coil compared with the negligible power required to control a negative grid, this form of control will never supplant the grid control for general use, although improved forms of tubes will probably find applications in current control and other specialized uses.

Multicavity Magnetrons and Klystrons. As noted above, the simple magnetron has not been widely used. However, the rise of radar saw the development of two special types of tubes for the generation of extremely short radio waves of correspondingly high frequencies. Typical radar wave lengths are only a few centimeters, with a frequency of thousands of megacycles per second. Although the use of such frequencies industrially is limited, a knowledge of their method of generation is worthwhile.

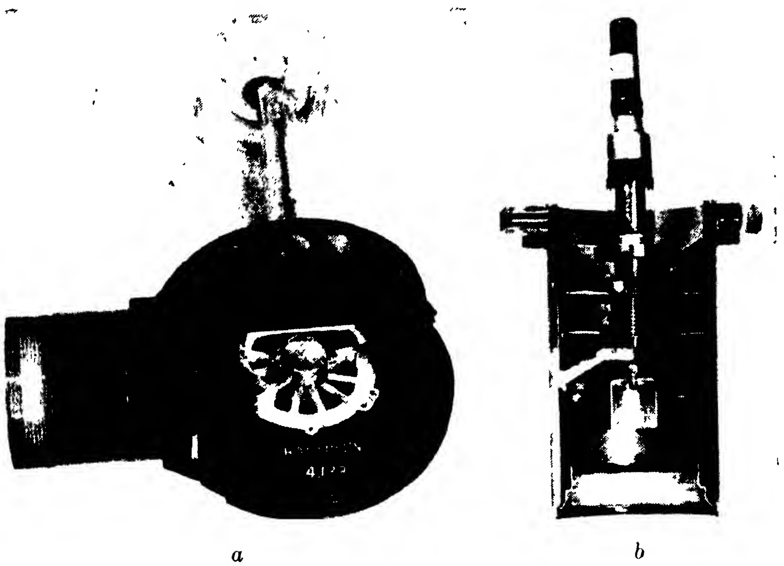


FIG. 3.4. Magnetrons. (*a*) The multicavity magnetron for generation of high-power pulses at super-high frequencies. (*Courtesy of Raytheon Manufacturing Company*) (*b*) The water-cooled magnetron. The resonance cavities surround the filament cathode. (*Courtesy of General Electric Company*)

As the cutaway view of the multicavity magnetron shows

(Fig. 3.4), the cathode consists of an axial cylinder and the anode of a cylindrical chamber with slits leading to a number of cavities. The electron flow outward from the cathode is acted upon by an intense axial magnetic field that deflects it almost at a tangent to the anode cylinder wall. As the grazing flow of electrons hops from point to point around the cylinder, the current flow in the cavity walls is affected by and reacts on the minute inductive and capacitive effects in a cavity to create oscillations of extremely high frequencies. The resonance-current surge further reacts on the grazing electron beam to strengthen the effect. Alternate poles may be connected together by the conductor rings, as shown, better to parallel the effect.

The high-frequency power is usually drawn off by means of a simple loop, or "hook," of wire inserted in one of the cavities or fed directly to a wave guide. At these wave lengths the energy will travel along the inside of a metallic pipe, or wave guide, quite freely and may be concentrated by reflectors of practical size such as might be used for light or sound waves.

The klystron acts upon a somewhat different principle. As the flow of electrons follows a fairly narrow beam from cathode to anode (the "collector"), resonance chambers surrounding the beam have excited in them oscillating currents which, in turn, react on the electron flow, slowing down some groups of electrons and accelerating others periodically, thus "bunching" them so that the effect of their flow past a point is that of a periodically varying current of extremely high frequency. These are shown in Fig. 3.5 as the input cavity, the "buncher," and the output cavity, the "catcher."

Small reflex klystrons, used as local oscillators in receivers for these short waves, employ a negative electrode at the end of the electron path to reflect the bunched electrons and reinforce the oscillations.

In practice the multicavity magnetron has been used mostly for short pulses of power of high intensity while the klystron has been used for more moderate but continuous generation of superhigh frequencies. A newly developed water-cooled magnetron for continuous service in high-frequency heating is shown in Fig. 3.4*b*.

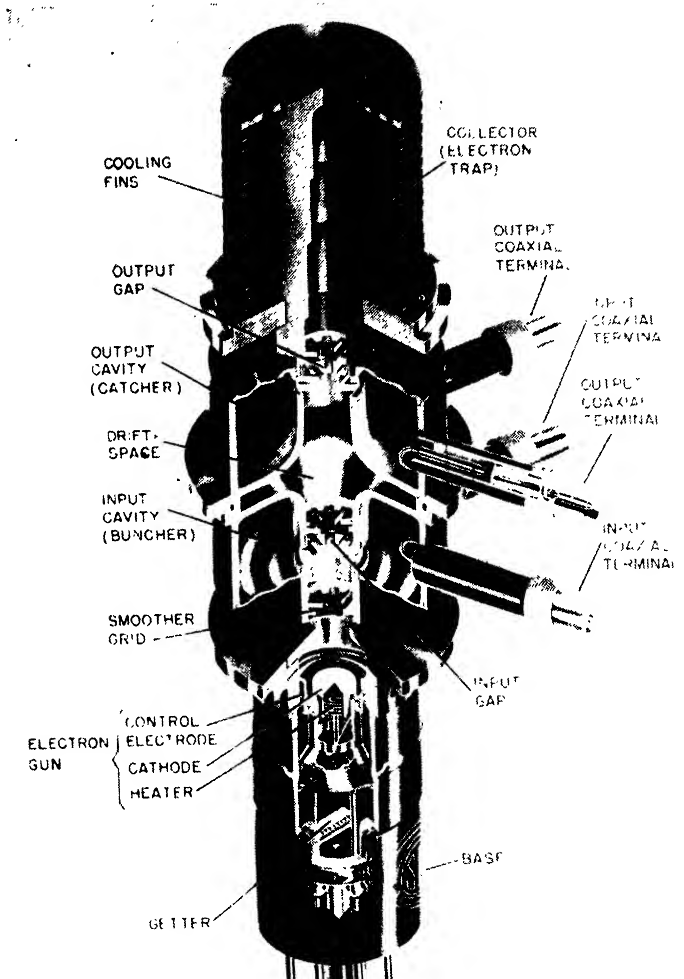


Fig. 3.5. The Klystron. Cutaway view with parts named. (*Courtesy of Sperry Gyroscope Company*)

Magnetically Deflected Beams for Control. Mention was made above of the magnetic deflection of the cathode-ray beam for television use. If, instead of a screen, we use one or more pick-up electrode plates, the deflection of the beam can be used for control. This principle was proved successful many years ago, but the cost of the special tubes in the small quantities then needed was prohibitive. It is hoped that the greatly increased industrial electronic activity will so alter the economic picture that this form of control tube can be more widely used.

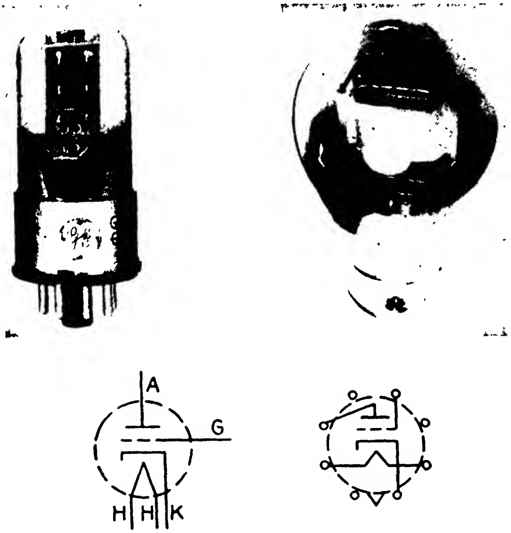
Questions

1. Name an advantage and a disadvantage of the multiplier phototube as compared with a conventional phototube and amplifier.
2. Sketch a cross section of a cathode-ray oscillograph tube, showing the path of the ray and naming the essential parts.
3. What are the two methods used to deflect the cathode ray? Give an advantage for each.
4. What is the difference between the action of a multicavity magnetron and a klystron?
5. How is a cathode-ray tube used in a television receiver?

CHAPTER IV

GRID-CONTROLLED VACUUM TUBES

It may seem that an undue amount of space has been devoted to a discussion of the simple two-element tube and too much emphasis laid on the different types of cathode and their use and abuse. This extensive treatment, however, is necessary; for after a good working knowledge of electron emission and flow is obtained, the relatively simple action of the various control grids that may be added will present no difficulties.



Elementary

Wiring diagram
(one form)

SYMBOLS

Fig. 4.1. The triode vacuum-tube amplifier.

The triode is the simplest type of grid-controlled vacuum tube.

High-vacuum Triodes (Fig. 4.1). Let us first take up the addition of a control electrode, or *grid*, placed between the cathode and anode in a vacuum tube. The grid, as its name implies, is composed of a mesh of fine wire supported by uprights. Although the mechanical construction is in the form of a coil of wire with accurate spacing between turns, each coil is short-circuited by the uprights so that the inductive effect is neglected and only its ability to create an electrostatic field potential in its immediate vicinity is considered.

In the discussion of space-charge effects (page 18) it was shown that even the negative-potential field of about a volt set up by the stray electrons near the cathode was effective in limiting the emission which could be obtained with a given potential between cathode and anode. If a grid is added and maintained at a potential negative to the cathode, it will have a much more pronounced effect in diminishing the electron flow and, if negative enough, may cut off the flow entirely. Perhaps the simplest way to visualize the action of the grid is as follows: The electrons are drawn toward the anode because there is a positive potential (a positive electrical "slope") near the cathode. If this slope, or gradient, can be made negative, the electrons in that area will tend to return to the cathode. The metal structure of the grid is definitely negative; so the electrons are deflected from it. But if the grid wires are widely spaced and the grid is not too negative, there will be spaces between the wires where the strong positive field from the anode will predominate, causing this point to be positive with respect to the cathode and permitting an electron flow to take place (Fig. 4.2). Since the grid is negative, no electrons are attracted to it; and since the electron flow is what we call an "electric current," we have in the grid a remarkable element that can control the cathode-anode current by its potential alone. As our definition of power consumed in a d-c circuit is the product of voltage and current, the grid power required is thus a theoretical zero, and the power-amplification ratio, or the ratio of control power to the power controlled, is infinite. While in practice this is not completely true because of insulation leakage in the grid circuit and other minor effects, the possible amplification of power in a high-vacuum tube is extremely great.

Grid Construction. Naturally, the degree of control exercised by the grid will depend on how closely the grid wires are spaced and the spacing between grid and cathode. In modern tubes in which it is desired that the cathode-anode current shall be controlled with the minimum change of negative grid potential, the grid wires are spaced as close together and as close to the cathode as mechanical considerations will permit. As usual, along with the characteristic high-amplification factor we have some drawbacks. Even when the tube structure is made on accurate jigs and assembled on accurately punched mica spacers, there are slight mechanical differences between tubes; and when the grid is only a few thousandths of an inch from the cathode, even a thousandth of an inch variation will greatly affect the potential-

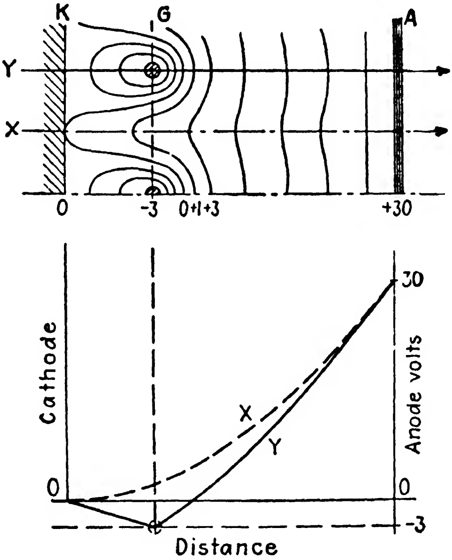


Fig. 4.2. The potential distribution near the grid of a triode, showing positive gradient to assist electron flow between the grid wires and negative gradient behind them to hinder the flow.

gradient pattern and the control characteristic. Also, there is a definite limit to the close spacing of the grid wires. The electrons must flow between the wires; so if the wires themselves take up too much of the room, the electron streams will be unduly constricted and the presence of the concentrated mass of electrons will tend to lower the potential at that point, thus presenting a serious space-charge problem. Therefore, while in any tube having a control grid the current between cathode and anode will be less than if the grid were removed, if the grid mesh is made finer for greater control the current will be even further decreased so that tubes having the highest voltage amplification factor are inherently low-current tubes.

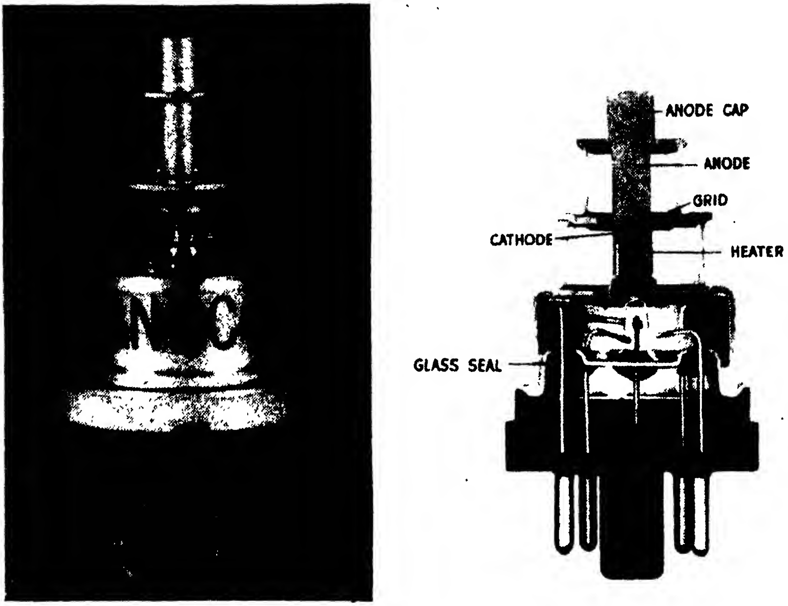


Fig. 4.3. The "lighthouse" tube, designed to fit directly into the cylindrical sections which form the tuned circuit. In the cutaway view note the extremely close spacing of cathode, grid, and anode. (*Courtesy of General Electric Company*)

In the ultra-high frequency triode nicknamed "the lighthouse tube" cathode, grid and anode are all plane surfaces and spaced as close together as mechanically practicable. Such tubes can oscillate efficiently as high as 3 billion cycles a second. Figure 4.3 shows this tube.

Definitions of Tube Characteristics. In describing any tube there are certain items that obviously must be included, such as the voltage and current required to heat the cathode, whether the cathode is of the directly heated filament or indirectly heated unipotential type, whether it is of tungsten, thoriated or coated, and also the permissible range of anode potentials (plate voltages) or at least the maximum allowable anode potential and the maximum average anode current that may be used without overheating the anode. Two unfamiliar terms are now introduced to give an indication of the possible grid control. These are *mutual conductance*, or *transconductance*, and *amplification factor*.

The anode current is dependent on both the anode potential and the grid potential. If we hold the *anode potential constant* and determine how the current changes as we vary the grid potential over a small range, we may express our answer as follows:

$$\frac{\text{Change of anode current}}{\text{Change of grid potential}} = \text{transconductance}$$

As any ratio of current divided by voltage gives an answer in reciprocal ohms or mhos, transconductance is expressed in this unit or, more usually, in micromhos (a millionth of a mho) to avoid fractions. This might be thought of as the measure of power amplification in a tube. Typical modern tubes have a transconductance of between 1000 and 5000 micromhos. Tubes having up to 10,000 micromhos transconductance are used, but this increase in power amplification in small tubes is made possible only at the loss of some consistency between tubes because of the very close and accurate grid spacing required. For this reason, replacing a tube often requires circuit adjustments.

Amplification Factor or Mu. Amplification factor is obtained from our three variables by holding the *anode current constant* and determining how the anode potential must be changed to hold this constant current as the grid potential is varied. That is, for constant anode current,

$$\frac{\text{Anode-voltage change}}{\text{Grid-voltage change}} = \text{amplification factor}$$

As the amplification factor is found by dividing one voltage by another, the result is a simple ratio, expressed as a pure number. The amplification factor is most important in voltage amplifiers where it is desirable to increase a small input voltage to a larger value, which may be applied to the grid of a second tube. Some triodes have amplification factors as high as 100. Others may have a mu as small as 3 but a high transconductance, which makes them more desirable where power amplification is desired. Some special tubes have an amplification factor of even less than 1.

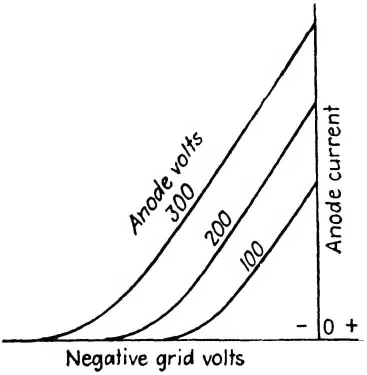


FIG. 4.4. Typical transfer characteristic curves for a triode.

Since the characteristics of no one tube are exactly the same over a wide range of anode voltage or current, the conditions for which the amplification factor and transconductance are stated must be given. The points chosen are usually in the mid-range of operation; but if similar information is desired for other points, it may be better to plot the tube characteristics as a group of curves.

Tube Characteristic Curves and Their Uses. These curves usually take one of two forms. The *transfer characteristic* curves are a family of curves plotted for grid potential as the abscissa (x axis) and anode current as the ordinate (y axis). The curves are taken for various values of anode potential (see Fig. 4.4). The second form, called the *plate* or *anode characteristic curve*, is more useful for most amplifiers. It uses the anode potential as abscissa and the anode current as ordinate. The curves are drawn for various values of grid voltage (see Fig. 4.5). A line drawn horizontally (constant current) provides a simple solution

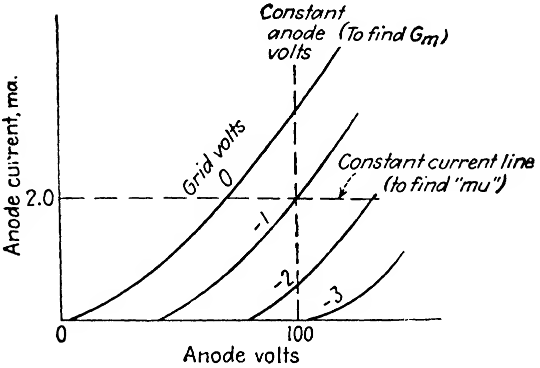


FIG. 4.5. Plate, or anode, characteristic curves for a triode.

for the amplification factor at any value of grid or anode potential. A vertical line gives the solution for transconductance for any grid potential or anode current at the anode potential selected. A point anywhere on the chart represents a current flowing in the tube at a certain anode potential and may be thought of as the apparent resistance within the tube. The term *anode* or *plate resistance* found in a table of tube characteristics refers to the slope of the characteristic curve at that point, that is,

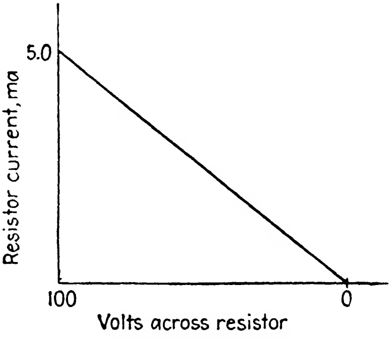


FIG. 4.6. Ohm's law for a 20,000-ohm resistor.

$$\frac{\text{Anode volts change}}{\text{Anode current change}} \text{ rather than } \frac{Ea}{Ia}$$

The same type of chart may be used to express Ohm's law for any resistor as shown in Fig. 4.6. (The abscissa is scaled from the right.) If now the tube and the resistor are connected in series across a battery or other d-c supply, the potential will be divided between the two, as shown on the superimposed charts, at the point where the resistor line crosses the line of the grid potential applied to the tube at the moment. The use of *load lines* drawn in this manner over the tube characteristic curves is of great importance to the circuit designer. It gives him a graphic solution to many problems in circuit design that would otherwise involve higher mathematics; and since characteristics of replacement tubes may vary 10 per cent or so, the graphical solution is usually accurate enough.

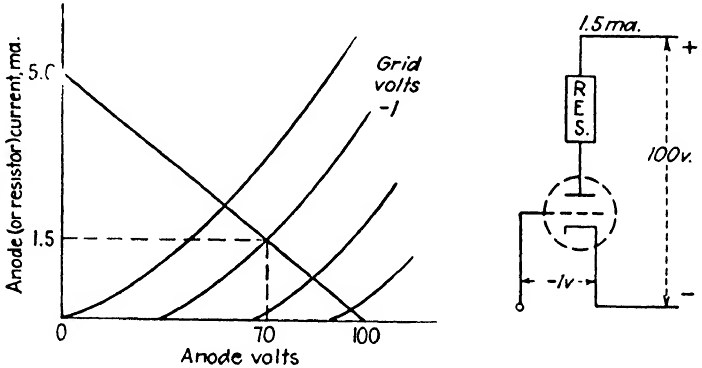


FIG. 4.7. Combination of FIGS. 4.5 and 4.6 to show current flow and voltage division between tube and resistor load.

The load line as drawn will be a straight line for resistance loads and resonant impedances. For inductive loads the potential drops in the load and in the tube (which acts as a pure resistance for low frequencies) will be out of phase, as they are in any other series circuit, so that the load line takes the form of an ellipse. However, best efficiency is obtained by using a load with a high power factor, and so the resistance load line is the most usual case.

Tetrodes, or Screen-grid Tubes. In studying the anode current-anode potential curves, two things should be noted about the voltage amplification to be expected in using any tube and any load resistance. For higher mu tubes the characteristic curves are seen to lie more horizontal, and the load line for a higher value of load resistance also lies more horizontal. Either or both of these factors permit the load line to cross the characteristic line at a smaller angle. This is another way of saying that the difference in anode potentials for the successive values of grid potential has become greater or that the voltage amplification obtained in this particular tube circuit, or *stage*, has become greater (Fig. 4.8).

Naturally, the highest practicable values of anode resistance are used. The practical limit is somewhere around ½ to 1 megohm.

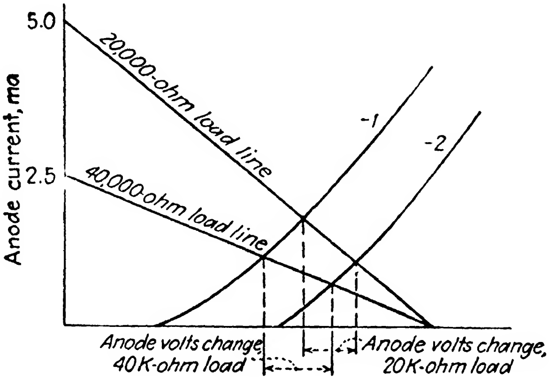


FIG. 4.8. Comparison in stage gain (anode-volts change) with increase in value of anode resistor.

The Screen Grid. The amplification factor of a triode can be increased by winding the grid in closer mesh and placing it closer to the cathode. The practical limit here is a mu of about 100. But always, in the case of a triode, we find that as the anode current rises and the *IR* drop in the load consumes more of the available supply potential, the ability of the anode to attract electrons from the cathode through the retarding action of the negative grid decreases as the three-halves power of the anode potential.

This fact has led to the search for some means to accelerate the electrons that is independent of the decreasing anode potential. The most practical solution has been the placing of a second grid between the first grid, which we may now call the "control grid" or "No. 1 grid," and the anode. This second grid, appropriately called the "screen" grid (Fig. 4.9), is usually connected directly to some potential positive with respect to the cathode but lower than the anode-potential supply. It is maintained at an essentially constant potential with respect to the cathode, and this exerts an accelerating force on the electrons coming from the cathode that is fairly independent of the varying anode potential. Although a number of the electrons are collected by this grid, from 20 to 30 per cent in some designs, the larger portion of the electrons are moving so rapidly that their inertia carries them past the screen grid toward the anode. If the anode is more positive than the screen grid, whether by much or little, it will collect these extra electrons, whose rate of flow is determined almost entirely by the control- and screen-grid potentials. If the characteristics for a tetrode are plotted, it will be found that for potentials above the screen potential the characteristic curves lie almost horizontal (Fig. 4.10). This indicates an extremely high mu, or possible voltage amplification within the tube, amounting to more than 1000 in some types.

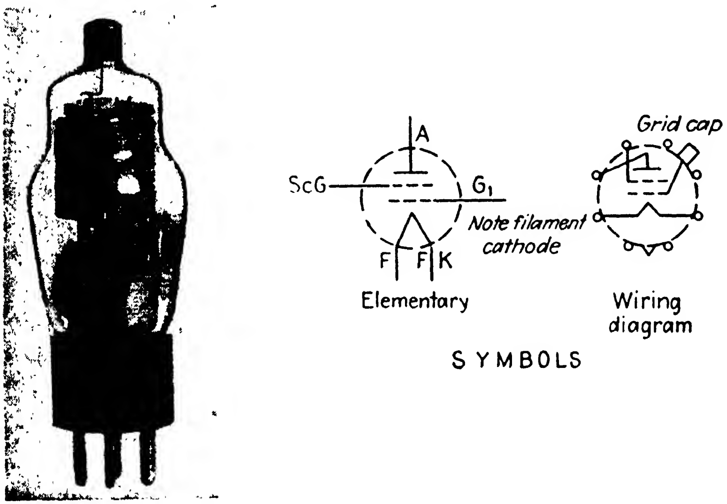


FIG. 4.9. A tetrode, or screen-grid tube.

In high-frequency circuits, such as those used in radio, where inter-electrode capacities become serious, the screen grid serves another useful purpose in shielding the input circuit (control grid) from the output circuit (anode).

Pentodes, or Tubes with Three Grids. In discussing tetrodes particular stress was placed on the fact that the desirable characteristics are obtained only when the anode potential is above the screen potential. When the anode potential drops lower than that of the screen, a retarding rather than an accelerating action takes place between screen and anode. If the potential difference is small, many electrons will still have sufficient velocity to reach the anode. As the anode potential becomes lower, however, a larger percentage of the electron flow returns to the screen grid at the expense of the anode current. Actually, under some conditions when the anode is much below the screen potential, the electrostatic field between these two elements will be so strong that electrons striking the anode will release other electrons in a manner discussed previously under Cathode Bombardment so that more electrons will leave the anode than arrive. This *secondary-emission effect* may thus cause an actual reversal of the anode current. Needless to say, it is not usually desirable to operate a tetrode in this range.

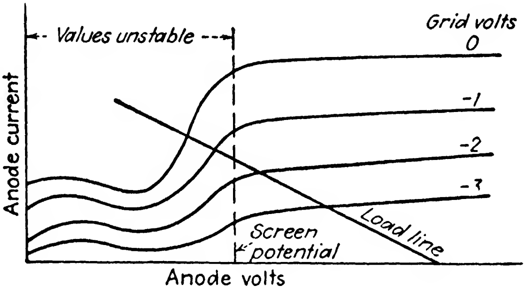


FIG. 4.10. Characteristic curves for a screen-grid tube, showing smooth, almost horizontal lines above the screen potential and erratic curves below it.

The Suppressor Grid. To prohibit operation in the range of potential below the screen potential is to lose an appreciable percentage of the supply voltage for useful work in the anode load. It thus becomes desirable to eliminate the secondary-emission effect. An effective way is to introduce a field between screen and anode which can be held always negative with respect to the anode and of such construction that the secondary effects from it are negligible. In the pentode tube this takes the form of a third grid between the screen grid and anode, called a "suppressor grid" (Fig. 4.11). It is made of fine wire widely spaced and is usually held at cathode potential. A characteristic curve for this type of tube (Fig. 4.12) shows that most of the previously restricted potential range is now available. The electrons acquire sufficient speed owing to the accelerating potential of the screen grid to coast past the retarding field of the suppressor grid until they again reach the accelerating field between suppressor grid and anode.

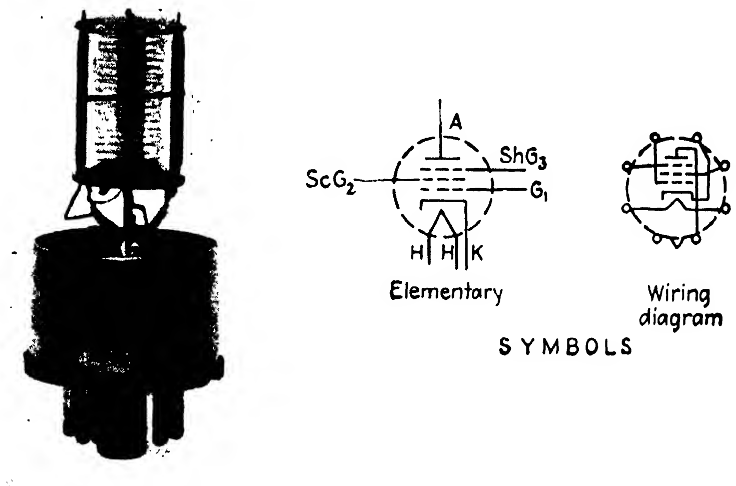


FIG. 4.11. A typical pentode tube (glass envelope removed). Some pentodes have the suppressor grid connected to the cathode within the tube.

This type of tube has replaced the tetrode almost entirely in voltage amplifiers.

Beam Tubes, Tetrodes with Pentode Characteristics. A better knowledge of the physical action within the tube, acquired in attempts to improve the tetrode and pentode, has made possible yet another type of tube that, while having only four elements, like a tetrode, simulates the action of the pentode and has a better efficiency than either. In designing this tube it was found that by placing the screen-grid wires accurately behind the control-grid wires advantage can be taken of the "beaming" of the electrons away from the control-grid wires toward the less negative field between them (Fig. 4.13). Since the electrons tend to follow fairly straight paths on past the grid toward the anode, most of them travel past the screen-grid wires rather than striking them so that the ratio of anode current to screen current is better than doubled. It was also found that the uprights supporting the two grids cause a bad distortion of the potential fields in their vicinity and lower the efficiency. Therefore, two solid plates were placed between the screen grid and the anode at these points. These plates are held at cathode potential and, by preventing electron flow in their vicinity, help concentrate the electron beam through the grids. Also, it was found that, by the proper shaping and spacing of the beam-forming plates with respect to screen grid and anode, a retarding field for the suppression of secondary emission from the anode can be formed without using a suppressor grid (Fig. 4.14).

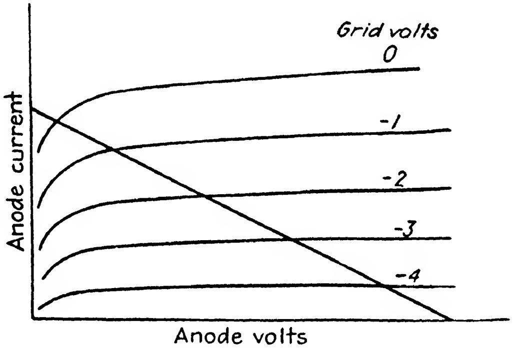


FIG. 4.12. The characteristic curves for a pentode. The curves are smooth almost to the cathode potential.

This type of tube has characteristics very similar to those of the pentode, and, because of its higher efficiency due to the smaller screen-current requirement, it finds a place as the output tube for receivers and for low-power amplifiers and transmitters. However, for the largest power sizes of vacuum tubes, requiring the highest anode voltages and currents, the simple, sturdy triode is still preferred.

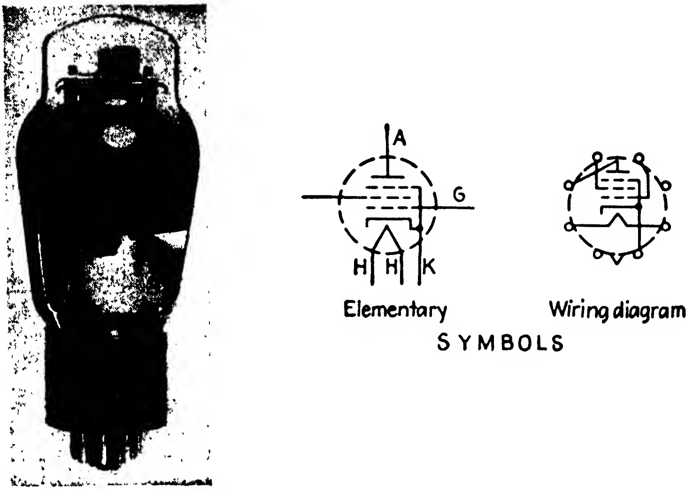


FIG. 4.13. The beam tube. This is generally shown, for the sake of simplicity, as a pentode.

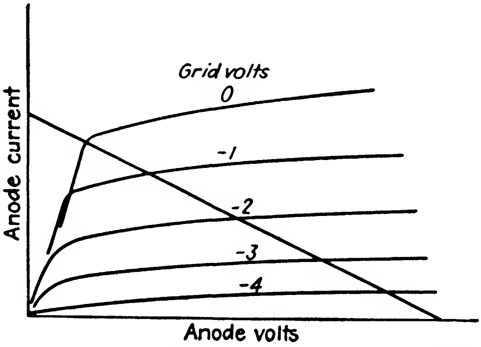


FIG. 4.14. Beam-tube characteristic curves. Note similarity to those of the pentode, FIG. 4.12.

Questions

1. Which of the following conditions tend to *increase* the electron flow through the pliotron: (*a*) closer spacing of control-grid wires, (*b*) higher anode voltage, (*c*) more negative grid voltage, (*d*) higher screen voltage in a pentode?

2. Define pliotron transconductance and amplification factor.

3. What is the difference between a triode, screen-grid tube, pentode, and beam tube?

4. Why is a pentode preferred to a screen-grid tube?

5. What is the advantage of a beam tube over a pentode?

CHAPTER V

GRID-CONTROLLED GAS-FILLED TUBES

Thyratrons, Gas-filled Electron Tubes with Grids (Fig. 5.1). In the discussion of the gas- or mercury-vapor-filled diode rectifier, or phanotron, emphasis was placed on its low, almost constant arc drop at any current, as compared with the high space-charge drop of the vacuum tube, and on the resulting higher efficiency. It would seem, then, a simple matter to put a grid into such a tube and duplicate the triode action with much better results.

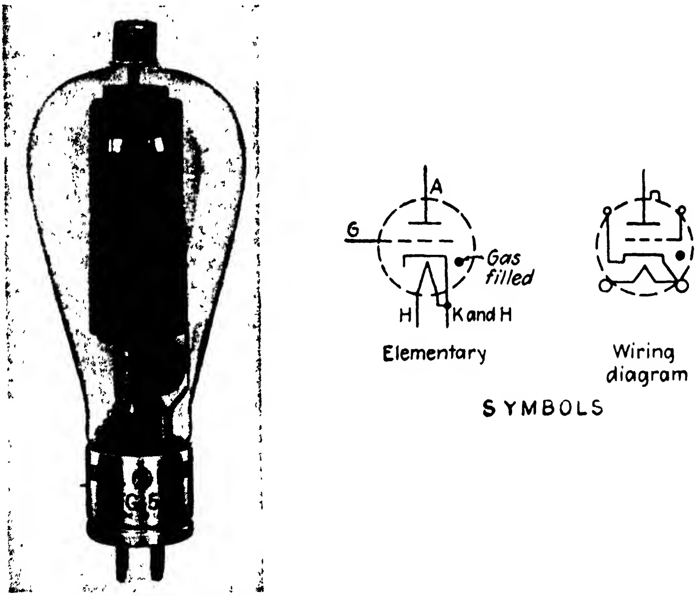


FIG. 5.1. A triode thyratron with indirectly heated cathode.

But let us recall again the picture of the plasma, consisting of atoms, electrons, and positive ions all swarming in a highly agitated state. The flow of current is maintained by adding electrons to the plasma at the cathode side and withdrawing electrons at the anode side as the plasma strives to keep its potential balance. This is far different from the vacuum-tube action in which the individual electrons follow fairly direct paths from the cathode to the anode.

Before an appreciable number of electrons are permitted to flow, before the plasma can be established, the restraining action of the negative grid can hold off the flow of electrons and render the gas-filled tube nonconducting in the same manner as the similar grid action in the vacuum tube. But once the plasma has become established, as might be expected, the result is different. If the grid has a positive potential, it simply becomes another anode and attracts electrons in the usual manner. However, if the grid is negative, it attracts the positive ions from the plasma, building up a neutralizing shield, or sheath, of positive ions in a coating around it. The sheath is normally thin compared with the other dimensions of the tube so that the effect of the negative grid on the general flow of current between cathode and anode is negligible. The negative grid is usually powerless to cut off conduction. If the current flowing is small and the grid is forced far negative, it is possible to stop the ionization and regain control; but this condition is rarely met in practice. Generally, if an appreciable anode current is flowing, any attempt to force the grid more than a few volts positive or negative after ionization is started will result in a large enough electron or positive-ion flow to the grid to cause damage.

To prevent this damage a protective resistor is connected in series with the grid so that excess applied grid voltage will be absorbed in the resistor *IR* drop. The maximum value of the resistor is limited by grid emission due to contamination with active material from the near-by cathode and the capacity effects between the grid and the other tube elements and other parts of the circuit.

Thyratron Construction. *As the path of any electron from the cathode to the plasma and toward the plate is composed of a series of ionizing collisions rather than a direct line, it is not* necessary for the anode to "see" the cathode for best efficiency, as is the case in the vacuum tube, in which each electron travels a direct route. This permits designing cathode, anode, and grid for best results according to other considerations. For example, the cathode may be of folded or wrinkled construction, with heat baffles and heat shields to prevent undue loss of heat, so that the maximum cathode heating and emission may be obtained with the minimum number of watts. The anode no longer need completely surround the cathode and so may be of smaller and simpler construction. The grid no longer controls the average electron flow but has only a "trigger" action to permit ionization to start so that the only control portion is that in the area where the anode and cathode are closest together and the space-charge potential gradient is greatest before ionization. Therefore the thyratron grid is usually of solid construction (rather than a wire mesh), almost completely surrounding the cathode and with a single hole in the area between cathode and anode to control the ionization. The solid grid wall serves both to reflect back some of the cathode radiation and conserve heat and to shield the cathode from stray charges on the walls of the tube (if of glass) that might alter the control characteristic.

By properly proportioning and spacing the grid it is possible to prevent ionization from taking place until the grid is actually driven positive with respect to the cathode for the usual range of anode potentials. These so-called "positive tubes" are useful for higher frequencies than the thyratrons controlled at a negative grid potential since the factors that give the positive grid control action also assist rapid deionization after the anode potential becomes lower than the arc-drop value.

The effect of using a light gas such as hydrogen to speed deionization has already been discussed (page 25).

Temperature Effects. The grid potential required for ionization varies with the gas pressure present, being more negative for greater pressures (Fig. 5.2). Thus, for tubes containing mercury vapor, where the vapor pressure increases rapidly as the temperature rises, we find an appreciable change in characteristic with the vapor-temperature change. In tubes using an inert gas, where the gas pressure changes little with temperature, the change in breakdown, or ionization characteristic, is not appreciable. Therefore, for precise control over a wide temperature range the gas-filled tube is usually preferred. However, as mentioned previously (page 25), the gas-filled thyratrons have a shorter life owing to the tendency of the gas to clean up, or be absorbed by the metal and glass of the tube structure. They also are limited in permissible plate voltage.

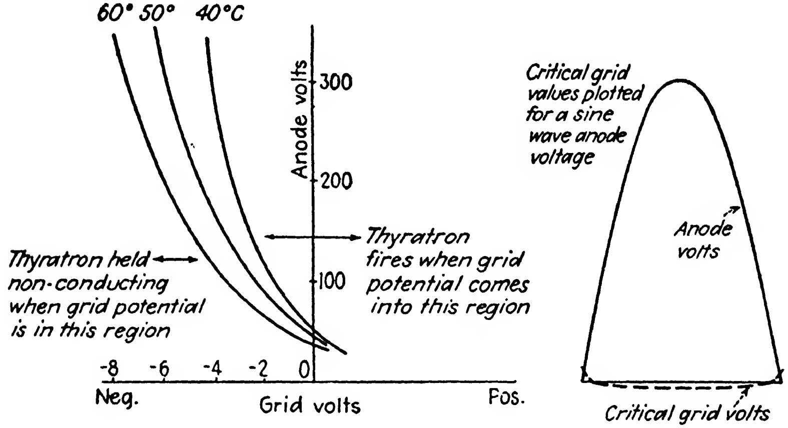


FIG. 5.2. The grid characteristic curves for a typical mercury-vapor-filled thyratron. An inert-gas-filled thyratron does not show any change with varying temperatures.

Shield-grid Thyratrons (Fig. 5.3). In the discussion of the thyratron grid it was brought out that only a small part of the grid actually performs the control function. The larger part merely shields the cathode from undesirable effects. In the shield-grid thyratron these functions are separated. The shield-grid envelope now surrounds the cathode and is usually held at cathode potential. The control grid becomes only a small ring *guarding the exit hole at the top of the shield grid. The shield grid usually has a second partition between the control grid and the anode to shield the control grid from capacity coupling to the anode, whereby a sudden rise in anode voltage might draw the grid positive, thus firing the tube.*

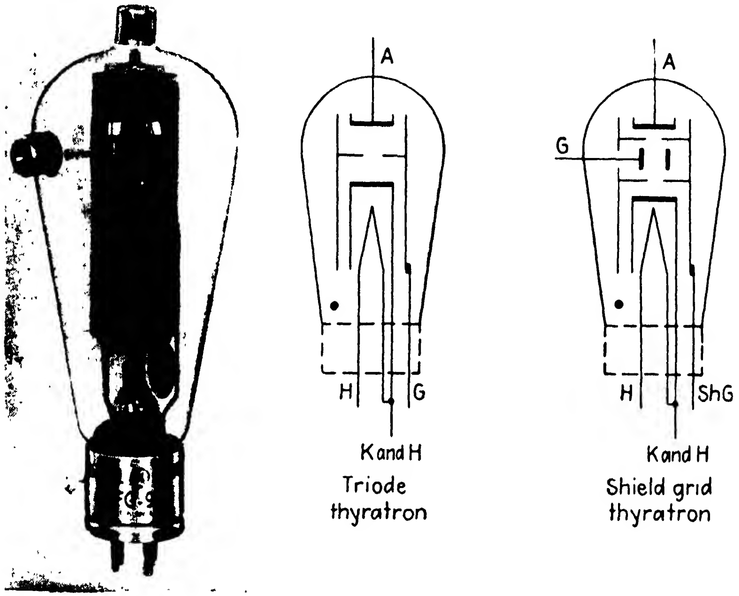


FIG. 5.3. The shield-grid thyratron compared with the triode. Note the excellent shielding of the control grid in the shield-grid type.

The advantages of the shield-grid thyratron are threefold. The control grid is protected from contamination due to active material being evaporated or bombarded from the cathode. It is also protected from the radiant heat of the cathode, which might raise its temperature sufficiently to cause it to emit. The control-grid circuit is protected from *constriction*, or *surging*, of the tube current. This destructive action may be explained thus: At times, when the cathode emission or the gas pressure is low, there may be a starving of electrons in the cathode sheath, suddenly decreasing the current. If there is appreciable inductance in the anode circuit, a high potential is generated, forcing the current to continue to flow by bombardment of the grid with positive ions to obtain a source of electrons. The circuit continues through the grid circuit back to the cathode. Since the grid circuit is usually not designed for the heavy anode currents and may contain high resistances and inductances, such as reactors or transformer windings, these parts may be damaged or destroyed by the high current surge. In the shield-grid tube this surge current is more likely to be drawn from the large shield grid than from the small, protected control grid. As the shield is connected directly to the cathode, a momentary transfer of the current from the cathode to the shield grid should not cause appreciable damage.

As an indication of the effectiveness of the shielding of the control grid in a shield-grid tube, it should be noted that the practical limit of impedance in the control-grid circuit of a typical three-element thyratron is about ¼ or ½ megohm; in the equivalent shield-grid tube this may be raised to 10 megohms for the same anode-current rating. This greatly decreased current drawn by the control grid is the chief practical advantage of this type of tube.

Questions

1. Describe the action of the grid in a thyratron.
2. What happens in a conducting thyratron when the grid potential is forced far negative?
3. Sketch the cross section of a shield-grid thyratron and tell why it is better than a triode thyratron.
4. Why is the shape of a thyratron grid different from that of a pliotron grid?
5. Give the approximate grid impedance permissible in a triode thyratron and in a shield-grid thyratron.

CHAPTER VI

THE MECHANICAL CONSTRUCTION OF TUBES[1]

Electron tubes vary in size, from the appropriately named Acorn tubes to ignitrons too large and heavy for a man to lift. However, the general construction and the principle of operation are the same; in fact, usually the larger tubes are simplest, being triodes or ignitrons. The smallest special-purpose tubes are generally glass; the next larger size, such as those used in the typical radio receiver, may have either a glass or a metal envelope. A number of the more popular tubes are available in either form, their electrical characteristics being almost identical. In a radio set the metal tube has the advantage of being shielded without the use of a separate shield and is slightly smaller and less liable to be broken. However, in most industrial circuits the shielding is not necessary, and so glass tubes of the equivalent type may be substituted freely, particularly the GT types.

Receiver-type glass tubes often have designations ending in -GT or -G. The older -G form uses a larger bulb than the newer -GT, which are not much larger than the metal tube of similar type. Since the larger bulb is no longer made except for rectifiers and output tubes requiring a large envelope for heat dissipation, many of the -GT tubes are branded -GT/G to indicate that they replace the older type.

The "Red" Line of Industrial Small Tubes. In 1947 the Radio Corporation of America took a very progressive step in bringing out a line of tubes similar in characteristic to some of the more popular receiver-type tubes but built specifically for industrial requirements. Refinements included heavier heater conductors and more heater watts for greater reliability and longer life, special

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[1] See Fig. 6.1.

materials and coatings, and closer tolerances and more inspection for higher quality. They are also given a greatly increased "preburning," or aging time, to weed out initial defects.

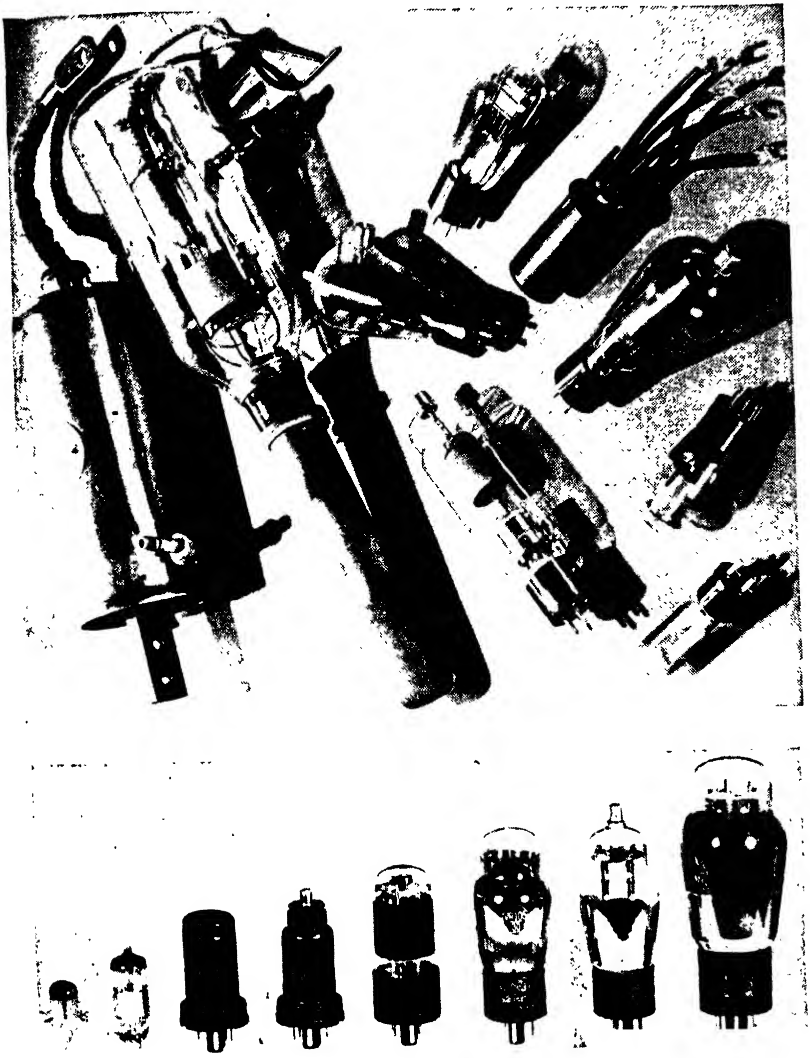

FIG. 6.1. There is wide variety in the size and shape of electron tubes.

Although the extra steps in manufacture mean a more expensive tube, the greater reliability more than justifies the cost. For most industrial applications failure due to a faulty or short-lived tube may cost many times the tube price in shutdown time and spoiled material in process.

Preferred-series Tubes (Manufacturers and JAN). If a red tube of the desired function is not available, it is suggested that the designer try to use one on the preferred list of the manufacturer or JAN (Joint Army-Navy). This tube will usually be more widely available and its characteristics better maintained than other tubes not listed.

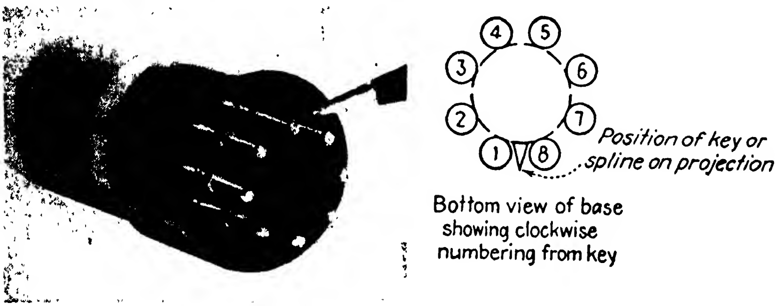

FIG. 6.2. The octal tube base. The locktal, button, magnal, and other types use the same method of pin numbering.

The Octal Base. Many of the present-day receiver-type tubes use the *octal* base for mounting and connections (Fig. 6.2). This provides for eight connecting pins in a circle, at the center of which is a projection having a key spline molded on one side by which the tube may be lined up accurately in its socket to position the connections correctly. Variations of the octal base are the *locktal,* having a groove in the center projection to hold the tube more securely against vibration, and the various *bantam* types for the very small tubes used in portable receivers. Some of the older type high-mu amplifiers had the grid lead brought out through a cap connection at the top for better shielding from the rest of the circuit. By advanced construction and better shielding within the tube it has now become the practice to bring all leads out of the bottom and dispense with the top lead. However, this puts a greater responsibility on the circuit designer to shield the grid lead from other leads as it runs near them when leaving the tube socket.

The first small tubes with bases had only four pin connections (the UX type); then came five pins (the UY type), six pins, and two sizes of seven-pin types. Finally, with the advent of the metal tube the Radio Manufacturers' Association adopted as standard the convenient octal socket and also a standard form of tube designation. A uniform method of numbering the pins was set up. Starting with the pin to the left of the projection spline as the observer faces the tube base (spline down), the pins are numbered clockwise, ending at 8 on the right-hand side of the spline. Pin 1 was to be connected to the metal envelope or other tube shielding (although on some glass tubes it has been used for other purposes). Pins 2 and 7 were cathode-heater leads. Pin 3 was the plate or anode. Grids were connected to pins 4, 5, and 6 and to the cap. Pin 8 was the cathode. The arrangement proved quite satisfactory until it was decided to do away with the top cap connection and bring the control grid through the base also. Then it was found that the widely separated a-c leads for the cathode heater caused trouble; so 2 (heater lead) was changed to 8. On other types it was found desirable to change the plate-lead number to 8 and sandwich the control-grid lead on pin 4 between the cathode at pin 3 and the suppressor at pin 5. In other words, at the present time the well-ordered system, for practical reasons, has become somewhat disorganized.

As the number and complexity of tubes grow, many base styles appear to accommodate the larger number of necessary pins for connections. As many as 14 pins are sometimes used.

The miniature all-glass tube is also finding increased use in industrial equipments in spite of its extremely small leakage path between pins.

Tube Designations. With the coming of the metal tube, tube designations also were reorganized. Each tube number was to be composed of three parts; the first number indicated the nominal cathode-heater voltage, a letter following indicated the sequence in a series, and another number at the end indicated the number of active elements in the tube. This system, though sometimes abused, has been pretty well maintained. Later -G and -GT or -LM (locktal metal) or even -LT (GT tube with locktal base) were added.

The heater-voltage number is especially useful to the serviceman or control engineer. The most familiar is the 6- series, having a heater with a nominal rating of 6.3 volts, to be used with an auto battery of 6 volts or a similar voltage from an a-c transformer. 12- tubes are designed for heating from 12-volt batteries (12.6 volts nominal) or an equivalent transformer winding. Also, 25-, 35-, 50-, 70-, and 117- tubes have heaters operating at the indicated voltage, the 117- tubes, for example, operating directly from the 117-volt lighting circuit without requiring a transformer. Exceptions to the general rule are the 1- type, which is operated from a 2-volt battery, and the 7- tubes, which are 6.3-volt heaters but with locktal bases. In a similar manner, 14- tubes have 12.6-volt heaters with locktal bases.

The letter designations are of less help since they are assigned in sequence as the tubes are developed. Amplifier tubes usually are designated by letters from the beginning of the alphabet and rectifiers by letters from the end, but this practice is not consistently followed. The final digit is likewise not always informative. Hence, it is usually necessary to memorize the whole group and associate it with the tube characteristic. For example, type 6H6 is a twin-diode (two diodes in one envelope) but a 6L6 is a pentode amplifier. But they both have 6.3-volt heaters. The 6H6, 6H6-G, and 6H6-GT or 6H6-GT/G are all interchangeable electrically.

Industrial-tube Designations. Only recently has an attempt been made to coordinate the designations of thyratrons or ignitrons. Only a few of the smallest thyratrons can use the receiver-tube bases and sockets because of the much greater current requirements of the larger sizes. The intermediate sizes use flexible leads and screw terminals whereas the largest sizes of ignitrons, which may pass thousands of amperes momentarily, require typically heavy bus structure. The smaller thyratrons have glass envelopes; the medium sizes may be glass or metal; the largest thyratrons, ignitrons, and phanotrons are now almost always of metal with a double wall through which water flows to permit cooling. The largest high-voltage kenotrons (diodes) have glass envelopes with the anode brought out the top because of insulation requirements. The largest sizes of high-vacuum amplifier tubes are constructed so that the anode itself forms part of the wall of the tube and may be cooled by direct immersion in a water well, or the anode is provided with large radiating fins past which a blast of air may be forced for cooling.

For many years tube manufacturers made industrial tubes to fit a specific application with little attempt to standardize designs. However, as the industrial use of tubes increased, it became evident that some standardization both in characteristics and designation was necessary. The newer designs of industrial tubes now have four-digit numbers assigned in order above 5500. Because of the wide variety possible, no attempt has been made to code them as in the case of the RMA receiving tubes. A few of the older tube types in limited use still retain the manufacturer's distinctive numbering.

On page 339 there is a cross-reference chart for some popular industrial-tube designations.

Questions

1. What are the advantages of the industrial "red" tubes?

2. Why should tubes be selected from the "preferred list" for new equipment design?

3. What is meant by an octal base?

4. How are the larger industrial-type tubes designated?

5. What is the greatest objection to miniature all-glass tubes in industrial equipments?

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Vol. 17. Components Handbook.
Vol. 18. Vacuum Tube Amplifiers.
Vol. 19. Waveforms.
Vol. 20. Electronic Time Measurements.
Vol. 21. Electronic Instruments.
Vol. 22. Cathode Ray Tube Displays.
Vol. 25. Theory of Servo Mechanisms.
Vol. 27. Computing Mechanisms and Linkages.

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Section II

CIRCUIT COMPONENTS

CHAPTER VII

INSTRUMENTS AND METERS

It has been some time since most of us studied the fundamentals of electricity and of the basic circuit components with which we deal every day. We are prone to think loosely of a resistor as something to dissipate heat, an inductance as something producing a lagging power factor, which may be corrected by the use of a capacitor, which, in some mysterious way, produces a leading power factor. Too often we think of a-c flowing through a capacitor as d-c flows through a resistor, without analyzing the detail of the action taking place. In dealing with electron-tube circuits many wave forms of both current and voltage are found which differ widely from the sine-wave a-c or the constant-voltage d-c with which we are most familiar. Hence, it is well to pause here to review briefly the fundamental nature of familiar items such as resistance, capacity, and inductance, when subjected to voltages and currents of an unfamiliar nature.

Before discussing the voltages that may be impressed on circuit elements and the resulting currents, it is desirable to decide just how these voltages and currents are to be measured.

In most electrical work we have used only two simple voltage and current forms: direct current, in which both voltages and currents are constant in direction and magnitude or, at least, change so slowly that the pointer of the instrument can follow the change; and alternating current, usually a relatively pure sine wave, reversing its direction completely twenty-five, fifty, or sixty times a second.

The d'Arsonval, or Permanent-magnet, Instrument. In order to read a direct current we use a permanent-magnet, or d'Arsonval, type of instrument in which the current to be read flows through a coil to react with a fixed magnetic field, producing a torque that turns the coil a definite amount against the torque of a calibrated spring. The d-c voltmeter is simply an ammeter that measures the current flowing through a calibrated resistor and hence the voltage drop across it.

Some of the better-grade d'Arsonval-type combination voltmeter-milliammeters, are now made with moving elements requiring only 50 microamperes or less for full-scale reading. This extends greatly their range of usefulness.

If the instantaneous value of the current varies too rapidly for the pointer to follow, the instrument will read the *average* current. For example, on a pure sine wave the d-c instrument will read zero since the positive and negative current loops are equal.

The RMS Instrument. For alternating current we must use a different type of meter, one in which the torque on the moving coil is in the same direction even though the current to be read reverses its polarity. To do this we replace the above-mentioned permanent magnet by a fixed coil in series with the first, and the magnetic field set up by this coil reacts with the moving coil to give the requisite torque.

This change accomplishes three things. First, it produces the desired result. As the current in the moving coil reverses, so do the current and the magnetic field set up by the series fixed coil, and the resulting torque drives the pointer upscale as before. Second, whereas the magnetic field was constant before, it is now proportional to the current that creates it. The torque from this field and from the current in the moving coil, both of which are proportional to the current being read, is thus proportional to the current times itself, or the square of the current. And since the current is usually changing its value and direction fairly rapidly, the pointer position is an indication of the average of the current squared. Third, since we should prefer the instrument to read amperes rather than amperes squared, we usually mark that position of the pointer as the square root of that average, or mean, square; hence the classification *root-mean-square*, or *rms*, *instrument*.

In the d-c instrument, reading average current, the smoothly increasing torque acting against a spring permits the use of a linear scale, which may be read with equal ease along its whole length. The rms instrument, however, having a torque proportional to the current squared, would have a linear scale only if the scale were calibrated in current squared. Since the preferred scale is current, the divisions are no longer of equal size and the scale becomes crowded for the lower values. In some forms of meter the fixed and moving coils are placed in such a manner that the torque action is less effective for higher currents; they thus tend to minimize the spread at the high end, but the resulting scale is only a compromise. Another defect of the rms meter consists in the amount of power required for operation. In the d-c instrument, the magnetic field of the permanent magnet is made as strong as practical and the circuit under observation has to supply only the losses of the small moving coil. In the rms instrument the circuit must also supply the power to create this magnetic field. For example, standard rms instruments may require 10 ma for a reliable full-scale reading, whereas d-c permanent magnets used by electronic servicemen operate reliably on 50 microamp, or one two-hundredth of the former value. Small d-c meters with multiple scales requiring only 1 ma for full-scale readings (so-called "1000 ohm per volt") are quite small and inexpensive.

Hot-wire and Thermocouple Instruments. Other types of a-c instruments depend on the heating effect of the current flowing in a known resistor. These types, such as the old *hot-wire* and the newer *thermocouple* instruments, are necessary at high radio frequencies but are rarely used for low industrial frequencies. Since the heating is proportional to the square of the current, these instruments also have nonlinear scales.

Another form of rms meter uses a small inclined disk in place of the moving coil. Eddy currents in the disk produce the torque, but the reading is still that of current squared with the resulting nonlinear scale.

Rectifier Instruments. A different way of obtaining an a-c instrument requiring little power for operation is through the use of a d-c permanent-magnet element and a rectifier bridge to force the current through the meter in the same direction at all times. This type of instrument tends to read the average value of current away from zero and thus should have a linear scale. However, there may be distortion in the rectifiers since the dry-plate type is not efficient at very low voltages. Hence, it is not practical as an ammeter and is not reliable for voltages below 3 or 4 volts. But such instruments are more sensitive than the rms type, reading full scale with a current of 1 ma. Their reliability is limited by the drift and aging of the rectifiers used. However, small size and sensitivity make them convenient for "trouble shooting" in the field.

One peculiarity about rectifier a-c meters must be noted carefully. Since they read average rather than rms and since the average and rms values of one-half of a sine wave are not equal (a ratio of 9 to 10 approximately), these meters are usually calibrated in terms of the rms value of the equivalent sine wave rather than in the actual average value read. This means that on d-c the instruments will read about 10 per cent high.

Electronic-type Instruments. Of the electronic-type instruments, the peak voltmeter, as its name implies, reads the highest instantaneous voltage that occurs during the cycle. It may be calibrated directly in peak volts, or it may be calibrated to the rms value of a sine wave that has the peak value read. This type is often used to read radio-frequency voltages. It is easy to check the scale calibration if this is unknown. If the meter reads the same as a d-c meter when applied to the same d-c voltage, its reading is peak volts; if it reads about seven-tenths of the d-c value (the ratio of peak to rms on a sine wave), it is calibrated in equivalent sine-wave rms volts. It should then read the same as another a-c meter or a sine-wave a-c voltage.

Electronic d-c instruments of the slide-back and *VoltOhmyst* type may be considered regular d-c permanent-magnet instruments, reading the average d-c voltage but requiring an operating current of only a fraction of a microampere. Some types include a probe containing a rectifier so that a peak reading a-c voltmeter is obtained capable of reliable readings at frequencies of many megacycles.

Cathode-ray Oscillographs. The cathode-ray oscillograph is a versatile instrument. Not only does it equal any of the other instruments in sensitivity, requiring no more power than the electronic voltmeters, but the moving pen of the electron beam on its fluorescent screen shows all the details of the actual voltage wave shape without leaving so much to the imagination as in the case of any meter with a mechanical pointer.

Wave form	Usual reading	Cathode-ray curve	Calibrated for equivalent rms on sine wave, per cent			
			D'Arsonval (permanent magnet) per cent	Rectifier type, a-c	Rms, moving coil	Peak voltmeter
Sine wave. .	Rms		0	100	100	100
Half sine wave	Rms of equivalent sine		45	50	70.7	100
Rectified sine wave	Rms of equivalent sine		90	100	100	100
	Average		100	111	111	111
D-c.	Average		100	111	100	70.7
D-c half time.	Average of d-c		50	55.5	70.7	70.7

FIG. 7.1. Readings of different types of meters for some representative wave forms.

Comparative Instrument Readings. Let us pause to sum up briefly the reactions of the meters on standard wave forms (see Fig. 7.1). First take a fairly constant d-c voltage. The cathode-ray oscillograph, if built to read d-c (and all industrial cathode-ray instruments should be so constructed), will show this voltage as a horizontal line displaced from the neutral axis. The d-c meter will read correctly, as will the rms meter if there are no strong d-c fields near. (If necessary, reverse the meter, and take the average of two readings.) The rectifier meter will read 10 per cent high, and the peak meter may read only 70 per cent of the correct value.

On an a-c sine wave, as shown by the cathode ray, the rms and rectifier meters will read correctly, the d-c meter will read zero, and the peak meter may read correctly or may read about 40 per cent high.

Therefore, it is especially important in using a meter on unfamiliar wave shapes to realize just what is being read. The pointer on the scale may not point to the same value as that of another type of meter reading the same voltage. Yet both meters may be reading correctly, each in its own way.

Questions

1. If an oscilloscope indicates 60 volts peak for a voltage wave consisting of the positive half of a sine curve, what will a voltmeter calibrated for rms read when connected across this same voltage?

2. Under the conditions of question 1, what will a d'Arsonval (d-c) voltmeter read?

3. What will a d-c voltmeter read when connected across a totally displaced sine wave having a peak value of 200 volts ($e = 100 \sin \omega t - 100$)?

4. What will a rms voltmeter read when connected across the voltage specified in question 3?

CHAPTER VIII

RESISTANCE AND CAPACITANCE

RESISTANCE

A pure resistance is the simplest component with which we deal since under all conditions it follows Ohm's law that the potential drop across the resistor (volts) is the product of the current flowing (amperes) and the resistance (ohms). This is because the electrical energy entering the resistor is immediately turned into heat and dissipated. It is important to note that no energy is stored in a form from which it can be returned again as electrical energy. Therefore, in *pure* resistance the form of the current wave follows that of the voltage instantly and exactly, and as soon as the circuit is broken, the voltage across the resistor and the electrical energy within it drop immediately to zero. Since a resistor must have a physical size and shape, it must also show some slight inductive and capacity effects, but in a properly made resistor these are negligible at the frequencies normally found in industrial use.

Resistor Sizes. The size and shape of the resistor depend on the heat to be dissipated and the number of ohms (see Fig. 8.1). Resistors vary from the large cast-iron or alloy grids capable of dissipating kilowatts, to coils of nichrome or other resistance wire wound on ceramic spools and covered with an enamel or plaster binder, and down to the smallest sizes, which may be rods of a carbon mixture or thin glass rods coated with a carbon solution and encased in plastic. The last types may be only ½ in. in length and ⅛ in. in diameter and may dissipate only ⅓ watt or so, but they may have a resistance of several megohms. These small resistors are usually connected into the circuit by soldering the tinned copper wire leads molded into the resistor ends.

Modern mass-production methods have made it possible to produce them very cheaply so that they are used extensively in electron circuits. The numerical color code used for small resistors is included in Appendix I.

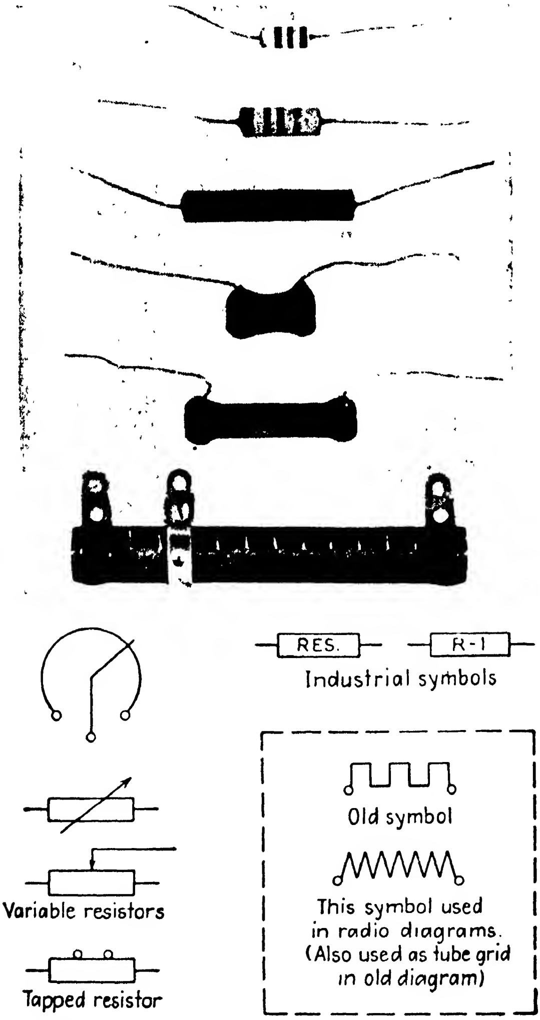


FIG. 8.1. Some resistor types used in industrial electronic control.

CAPACITANCE

Capacitors (Fig. 8.2) are sometimes called "condensers." They consist essentially of two sheets, or plates, of a conducting material separated by a layer of an insulator, or *dielectric.* If a battery

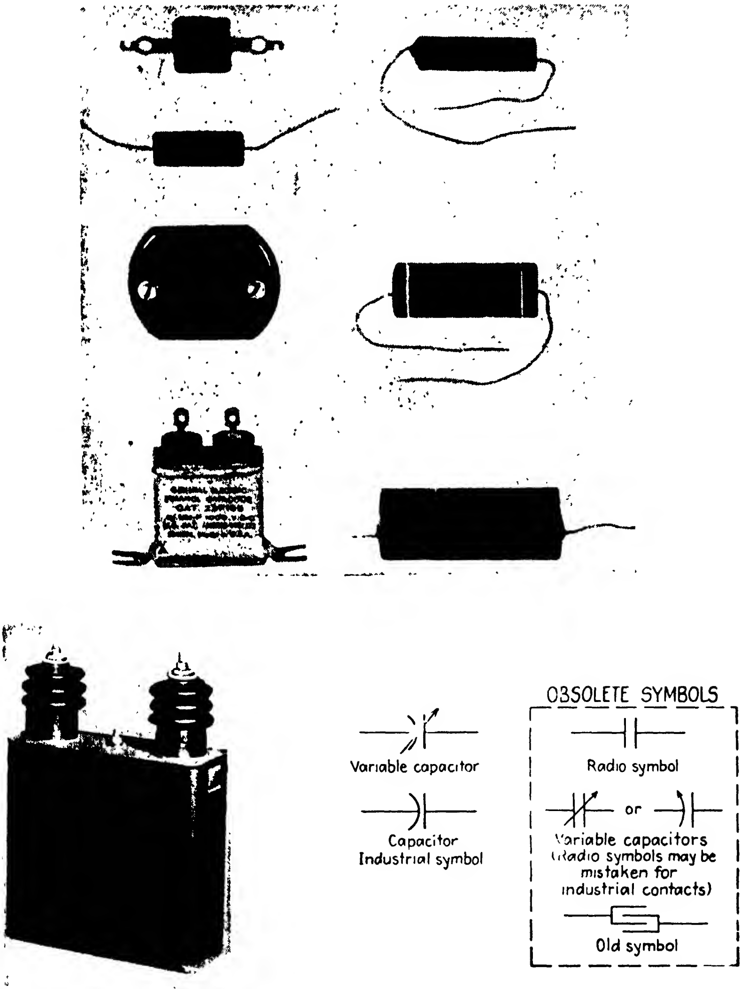


FIG. 8.2. Some capacitor types used in industrial electronic control.

is connected to apply a potential between the two plates, the electrostatic field set up by the attraction between the positive and the negative plate will tend to create a strain in the dielectric material. (If the strain is too great, the dielectric will be ruptured, an arc will jump between the plates, and the capacitor may be ruined.) In order to produce the electrostatic field the battery potential draws electrons from the positive plate and adds an equal amount to the negative plate in a so-called "charging current." If the battery is then removed, the electrons will remain trapped as they are, and the dielectric will remain stressed. The potential between the plates will remain at battery potential.

Energy Storage. Energy is stored in the capacitor equal to the product of the battery voltage and the ampere-seconds of charging current that flowed. If the insulation of the dielectric were perfect, the energy might be kept stored in this state as long as desired. It may be released at any time by joining the opposite plates by any continuous electrical circuit. At the instant that the circuit is completed, a voltage equal to the original battery voltage will appear across the circuit. However, as the capacitor gives up its energy, or becomes discharged, neutralizing the electron charges of the positive and negative plates, the voltage between the plates dies down to zero. If the discharge circuit is opened before the capacitor has become completely discharged, the remaining charge may again be retained indefinitely. A good mechanical analogy is the flexing of a spring, as in the action of winding a watch.

It is obvious that if the battery potential were reversed the charging and discharging currents of the capacitor would be the reverse of the above. Also, the time required to discharge the energy in the capacitor is proportional to the impedance of the discharge circuit, since if the impedance of any circuit is decreased the current rises proportionately and, for a given voltage, the energy consumed per unit time increases.

Let us stop a moment and review the simple capacitor action described above. The capacitor is a device for storing electric energy. This energy is applied as a voltage between the plates and is stored as a stress in the dielectric. There should be no electron (current) flow through the dielectric between the plates.

Capacitor Currents. If the application of voltage or the discharge is made suddenly through a circuit of low impedance, very high currents may flow. If the potential source is such that the voltage applied to the capacitor is changed slowly and smoothly (as from a sine-wave a-c voltage), it will be found that the charging and discharging currents are proportional to the *rate of change* of voltage. If, indeed, we take the sine wave as an example, it will be noted that the value is increasing or decreasing fastest at the instant that the numerical value is zero and that the rate of change is least (zero) when the numerical value is most positive or negative. Hence, if the current flow to and from the capacitor plate is plotted as a function of rate of change and compared with the sine voltage curve, it will be seen that it seems to form a similar sine wave displaced 90 deg ahead of the voltage (Fig. 8.3). But it must be remembered that the similarity of the voltage and current waves is a coincidence which occurs only in the case of a sinusoidal wave form of voltage. If the voltage wave form had been different, for example, a square wave, the current, obeying the rate-of-change law, would have been of an entirely different shape from the voltage wave (Fig. 8.4). When circuits are completed quickly, as when a switch is thrown or, of more interest to us, when a thyratron or ignitron is "fired," a large current may flow owing to the rapid rise in voltage. The irregular voltage wave produced by amplifying the results of the variation of light striking a phototube produces an interesting wave form of current when used to charge a capacitor.

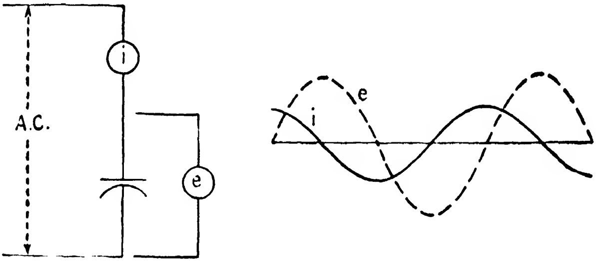


FIG. 8.3. Capacitor current on sine-wave a-c.

The energy stored in the capacitor is proportional to the product of the square of the voltage between the plates and a term called the *capacity*, determined for any capacitor from the area of the plates, the distance between them, and the material of the dielectric. In order to express the energy in work units, or joules, corresponding to the usual units of volts, amperes, and seconds, the capacity must be expressed in farads. However, the farad is such a large quantity that we ordinarily use the millionth part of it, the *microfarad*, in most of our work. Also, since it is extremely difficult and expensive to build a capacitor of a capacity of even a small fraction of a farad, it becomes necessary to resort to high voltages to store an appreciable amount of energy in a capacitor such as might be compared with the chemical energy in a battery or the kinetic energy in a rotating wheel. On the other hand, the high efficiency of the capacitor is shown in its ability to return, whenever needed, a high per cent of the energy stored in it. The energy is instantly available. Sometimes the availability of the energy as a high electric voltage is quite useful. A final advantage is the capacitor's apparent ability to permit the transmission of a surging and receding alternating current while holding back the flow of a unidirectional, or direct, current. This important phenomenon will be taken up later under Amplifiers (page 150).

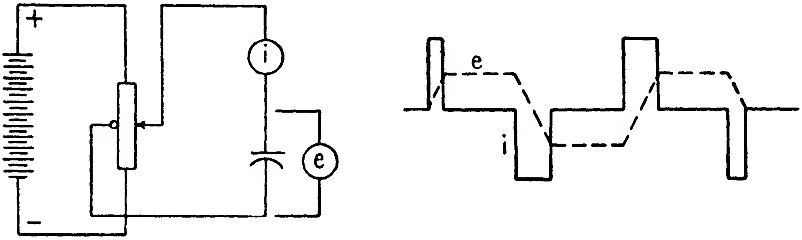


FIG. 8.4. Capacitor current on trapezoid voltage wave.

Electrolytic Capacitors. The physical size and shape of the capacitor vary even more than those of the resistor. Different forms are the small bakelite encased blocks the size of a postage stamp, having mica for the dielectric; the familiar tubular, or "firecracker," type, having a waxed-paper dielectric; and the large high-voltage types filled with oil or a special fireproof liquid, such as askarel (Pyranol, Dykanol, Inerteen, etc.), that impregnates the paper between the plates of metal foil, usually aluminum. A very interesting form is the electrolytic capacitor in which a large capacity is assembled into a small volume (Fig. 8.5). It is usually of the *polarized* type; one plate is always negative and the other always positive. The positive plate is the usual aluminum foil, often etched mechanically or chemically to present the maximum possible surface. The negative plate is a cloth saturated with a special solution composed of a hydroxide that under the action of a polarizing d-c voltage gives up hydrogen atoms to form a very thin hydrogen-gas layer between the conducting solution (the negative plate) and the foil positive plate. Although the construction sounds simple, it has taken years of research and development to produce the reliable and long-lived electrolytic capacitors of the present day.

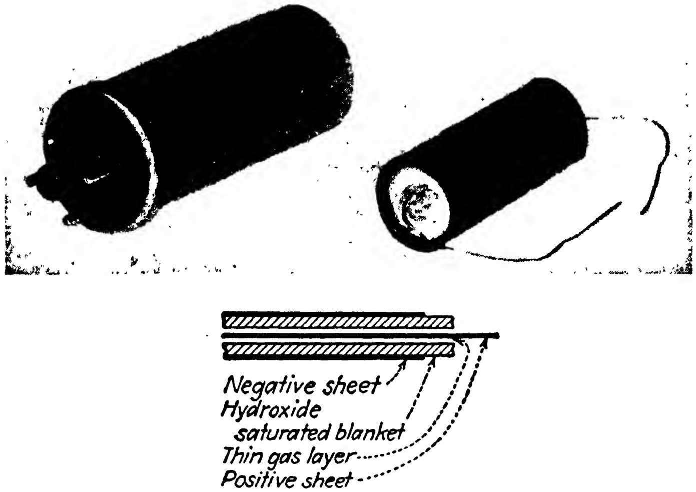


FIG. 8.5. Electrolytic capacitors and greatly enlarged cross section. (Note plug-in type for easy replacement.)

The electrolytic capacitor is used principally in d-c potential supply filters, where its large storage capacity assists in maintaining a practically constant potential in spite of moderate a-c requirements. In some cases two electrolytic-capacitor structures have been assembled effectively in a series to form a *non-polarized* capacitor for use where a large capacity is needed for short-duty cycles, as in starting split-phase motors, etc.

Other Dielectrics. Spurred on by the wartime demands for smaller and more efficient high-voltage, low-capacity units, the industry developed two new forms of dielectric material which show considerable promise. The first is a film of synthetic plastic, one trade name of which is Electrofilm. Since it is extruded in a continuous sheet, it is fairly free from the holes and variations in thickness inherent in a paper dielectric. The second development is that of ceramic dielectrics such as barium titanate ($BaTiO_3$), which has a dielectric constant 1500 times that of air. Thus, while the ceramic dielectric cannot be made as thin as the film of paper types, the high dielectric constant largely compensates for the increased thickness, and the high insulation and breakdown characteristics are valuable.

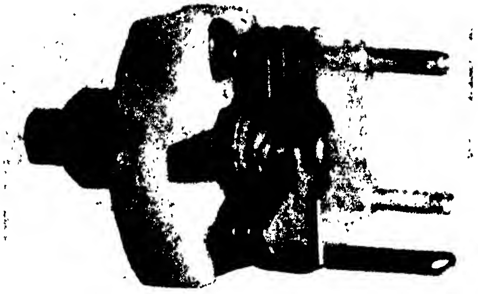


FIG. 8.6. A small variable capacitor with air dielectric.

Capacitor Sizes. As the capacity depends on the nearness of the two plates, most capacity values are made in a reasonable physical size only by using a very thin dielectric and sandwiching a number of plates in parallel. An attempt to vary the capacity of a capacitor by moving the plates toward and away from each other is feasible only in the smallest values. The most common form of capacitor for frequent adjustment consists of semicircular plates mounted on a shaft that may be rotated to interleave the plates with similar fixed plates (Fig. 8.6). For capacitors that are adjusted infrequently a form has come into use in which one of the plates is closed down on the other (protected by a sheet of mica) just as the cover is closed on a book. Another development in the smaller sized capacitors is the use of special ceramic dielectrics that change their dielectric constant, some positive and some negative, with a change in temperature and that thus may be used to compensate for changes due to heating in other parts of the circuit.

Questions

1. Draw three graphical symbols for a resistor. Which is preferred in industrial electronic circuits?
2. What is the resistance of a small resistor having the following color bands: (*a*) red, yellow, yellow; (*b*) green, brown, orange, gold; (*c*) black, blue, brown, silver; (*d*) brown, black, blue?
3. Draw three graphical symbols for a capacitor. What is the preferred symbol for both industrial and radio work?
4. What are capacitors often called by radio technicians?
5. Name three commonly used dielectrics and give an advantage for each.
6. Describe the action of an electrolytic capacitor. Where is it most commonly used?
7. Name a dielectric material especially suitable for high-voltage, small-capacity use and explain its advantage.

CHAPTER IX

INDUCTANCE

The capacitor is a device that stores energy given in the form of electric voltage or potential. The inductance is a device that stores energy given in the form of an electric current. The capacitor stores the energy in the form of stress in the dielectric. The inductance stores the energy in its magnetic field. In the case of the capacitor it is necessary to add or subtract energy in order to change the *voltage* across the capacitor. In the case of the inductance, energy must be added or subtracted to change the *current* flowing in the magnetic circuit. The capacitor once charged can retain its charge for long periods of time without loss of energy. The inductance, unfortunately, is not so efficient a device, for while it will attempt to retain its current flow for a short time, a few seconds at most, the heat generated by the flow of the current through the resistance of the conductor quickly saps the energy in the circuit. A mechanical analogy of the inductance is the inertia of a flywheel or a sliding block, where friction represents resistance.

If a potential is applied suddenly to an inductive circuit in which current is flowing, the potential across the inductive circuit will immediately become the same as that of the applied potential. However, there will be no sudden change in the current flow. The change will be comparatively slow and, as might be expected, will at first be proportional to the applied potential. As the current changes, the drop of potential due to the resistance will gradually increase to absorb the potential difference. In the intermediate stage, part of the potential difference will be balanced by the *IR* drop, and the remaining potential will be available to produce a further current change (Fig. 9.1).

Inductances on D-C. If an inert inductive circuit is connected to a battery or other source of potential, the current will build up slowly from its zero value, as the energy is absorbed in the magnetic field. But once the current has started to flow, any attempt to stop the flow by interrupting the circuit must take into account the energy stored in this field, which must be dissipated before the current will cease. If there is little resistance in the circuit, most of the energy must be lost in the arc formed at the point of circuit interruption. This recovered energy appears as heat. Since the current cannot be stopped suddenly any more than it can be started suddenly, the current that was flowing just before the circuit was broken will continue to flow immediately thereafter *no matter how high* the inductance of the circuit must force the potential across the break to ensure the flow of current. Since there is a definite amount of energy available, if a high potential is required the energy will be more quickly expended.

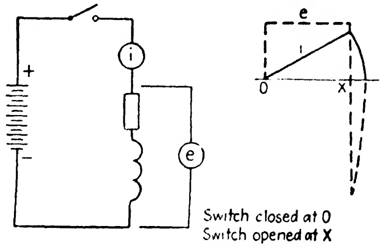


FIG. 9.1. Inductance current produced by a square-wave voltage pulse.

It is sometimes not appreciated what extreme values of potential can be produced in disconnecting highly inductive circuits supplied from comparatively low-voltage d-c sources. Many of us are familiar with the tremendous energy available when a circuit including a strong magnetic field, such as a shunt field on a large d-c motor or a large d-c magnet, is opened. If an attempt is made to open such a circuit quickly when a heavy current is flowing, the potential across the coil may build up to such a value that the insulation between the opposite ends, or even between some sections of the coils, may be broken down to form an alternate path for the current.

To prevent this destructive action, highly inductive circuits are usually protected by a parallel resistance through which the current may flow until the energy is dissipated. Since if this resistance were left in the circuit at all times it would tend to waste power from the supply source, a special switch is often used to connect the resistance into the circuit just before the power circuit is broken.

A special form of resistor called *Thyrite* is also used. This material has the unique property of having a resistance that decreases as the potential across it increases. In one form, as the applied voltage is doubled, the current increases about sixteen times. So, if across the coil a discharge resistor of this material that normally passed one-sixteenth the normal coil current were connected, when the circuit is broken the voltage across the coil due to the inductive surge will be limited to only twice the normal applied voltage. On the other hand, if the coil insulation will permit a voltage of four times normal to be produced, it is clear that the stand-by loss in the protective Thyrite resistor will be small, only $1/256$ the normal coil current.

Energy Exchange between Inductance and Capacitor. Another and very interesting method of handling the released energy of the inductance is to connect a capacitor in parallel. When this is done, the inductance current is diverted to charge the capacitor. Here we have an effect quite different from that occurring when a resistor is used. The resistor changes the energy to heat and radiates it. The capacitor has only received the energy and stored it in electrostatic form to be returned again to the circuit. This interchange of electromagnetic energy and electrostatic energy is an important action and will be discussed in much greater detail later (page 120); for the present it will suffice to state that the capacitor, once charged, will discharge again through the inductive circuit, starting a current flowing which will create a magnetic field, thus again storing energy in the electromagnetic form. Since the current flow at the capacitor terminals on discharge is naturally in the reverse direction from the charging current, the current flowing in the inductance is now reversed to its previous flow and as the capacitor becomes discharged the magnetic field will be built up with opposite polarity to that previously found. Then, as the current continues to flow and the capacitor is again charged, it also will be charged in the opposite direction. Once more the capacitor discharges, sending current through the inductance in the same direction as that of the current which first flowed through it, and the whole cycle is repeated. Each time current flows in the circuit, the resistance losses take their proportional toll of the energy until eventually it is all absorbed. If the resistance of the circuit is small compared with the energy in the circuit to be absorbed, a large number of these oscillations will occur and the circuit is said to have a *low decrement* or to be poorly damped. If, on the other hand, the resistance is high, the oscillation is quickly damped out and the circuit has a high decrement (Fig. 9.2).

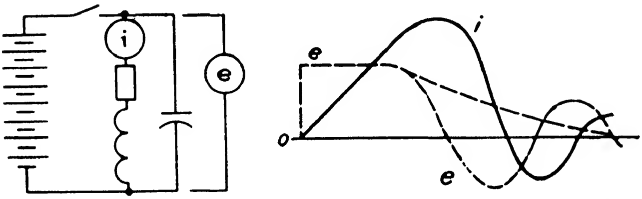


FIG. 9.2. Effect of a parallel capacitor on the circuit of Fig. 9.1.

There are two important points to remember in using a capacitor in this manner. (1) The capacitor must be large enough to store the energy transferred to it by the inductance. (2) There must be sufficient resistance in the circuit between the power source and the capacitor to limit the charging current to the capacitor when the power is applied to the circuit. Often a small resistor is placed in series with the capacitor to limit the charging current to a safe value. It also permits a higher decrement in the discharging oscillations although, of course, at the cost of a higher generated potential across the inductance, which must now, at the instant of circuit interruption, force the normal inductance current across the resistance and capacity in series.

The Current in an Inductance. If the resistance of the circuit could be neglected, the current flowing in a closed inductive circuit would continue to flow indefinitely at the same value without the application of any potential. If a potential is applied, the current will *increase at a rate proportional to the added potential.*

Note that nothing is said about the maximum value that the current might reach because, theoretically, with no resistance the current would continue increasing without limit, the energy from the power source being converted into a stronger and stronger magnetic field. If, say, the potential applied were 2 volts instead of 1 volt, the current would simply increase twice as fast. (Needless to say, in any practical circuit the *IR* drop soon rises to a value that balances the applied potential.) This gives us a unit in which to measure an inductance. Accordingly, we say that in a circuit containing inductance only, if the application of 1 volt of potential causes the current to rise at the rate of 1 amp a second, that circuit has an inductance of 1 *henry.* Although some inductive elements, often called "reactors" or "chokes," are made having a value of many hundred henrys, others are also made of such a low value of inductance that we find it convenient to express their inductance in millihenrys, the thousandth part of a henry, and microhenrys, the millionth part of a henry. Every electrical circuit has some inductance.

Inductance Sizes. As in the case of the capacitor, where the size and energy-storage value were expressed not only in the microfarads capacity but also in the voltage that might be safely applied without breakdown, the size and energy storage of an inductance is measured by both the henrys inductance and the current that it may safely carry. The current is not entirely limited by the inductive storage of energy (which is in the magnetic field and not in the conductors); it may be limited principally by the heating of the conductors due to their resistance. Hence, it is possible for an inductance to have a short-time current rating much higher than its continuous rating.

Iron Cores—Saturation. We know that if we provide an iron path for the magnetic field created by the inductive circuit the magnetic flux is increased many times. The henry inductance of a well-designed iron magnetic-path inductance may be hundreds of times that of a similar coil with the iron removed. However, if the current and flux are increased too much, the iron path begins to "saturate" and the gain in inductance due to the presence of the iron begins to decrease until at extremely high values the *additional* current produces *no appreciably greater* flux than if the magnetic circuit were air. Needless to say, for most uses where efficiency is important the inductance is designed so that the flux does not reach the saturation point, although operating at or beyond the saturation point creates some interesting control possibilities that will be mentioned later (pages 105 to 109).

Inductance of Sine-wave A-C. We have discussed what happens when a potential is suddenly applied to an inductance. Let us consider now a slowly changing potential and its effect on the current flowing. Suppose we take a simple sine wave of voltage, starting from zero to a maximum in one direction and then reversing through zero to the maximum in the opposite direction. Let us assume that the circuit is entirely inductive and that no current is flowing. As the voltage starts from zero, the current will increase slowly at first; but as the potential increases to its maximum, the current will tend to increase faster until as the potential reaches its peak at the 90-deg point of the cycle the current will be increasing at its most rapid rate. As the voltage recedes toward zero, but is still positive, the current will continue to increase though at a slower and slower rate until as the voltage has reached zero, 180 deg in the cycle, the current value has reached a peak value.

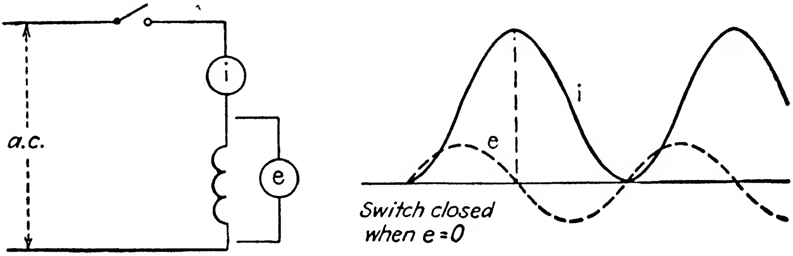


FIG. 9.3. Inductance current on a-c initial transient.

Next, as the voltage reverses and begins to increase in the negative direction, its effect is to cause the current to increase in the negative direction at a rate proportional to the applied voltage; but since we already have current flowing in the positive direction, the actual effect is to reduce that current at a rate proportional to the applied voltage. As the voltage reaches its maximum negative value, 270 deg in the cycle, the current will be decreasing at its most rapid rate. Finally, as the cycle is completed and the voltage returns to zero, the rate of change of current will again drop to zero (Fig. 9.3). Since the positive and negative voltage loops were symmetrical and equal, equal forces have been acting during the first half cycle to increase the current and during the second half to decrease the current. At the end of the cycle the current should have the same value it had at the beginning, or in this case, zero.

Current Wave Shapes. It is true that the above description of the current wave produced by a sine voltage impressed on an inductance does not correspond closely to our usual conception of a 90-deg lagging current. But suppose, instead of starting with zero current at the instant at which the voltage passes through zero, going positive, we start with a current at its maximum negative value. The current wave will have the *same shape* as before but now will be placed symmetrically with respect to the zero-current axis and will pass through zero halfway up in its positive rise, which is at the instant at which the voltage has reached its maximum peak (Fig. 9.4). This is the lagging power-factor inductive current wave with which we are familiar. It must be remembered, however, that this is only one of the family of possible curves of the inductive current, all of the same shape but displaced vertically depending on the current flowing at the beginning of the impressed sine wave.

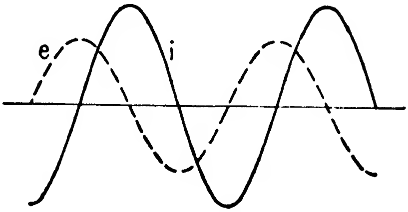


FIG. 9.4. Inductance current on a-c steady state.

The vertical position (d-c component) of the inductive current wave may be determined in another way. Suppose that no current is flowing in the inductance and a sine voltage is suddenly applied by closing a switch or permitting a thyratron or ignitron to conduct, not at the beginning of the cycle, but sometime later on when the voltage has already reached a finite value. The answer is still the same. The current will, of course, start from zero at the instant at which the switch is closed but from then on will take the *same shape* as under the other conditions (Fig. 9.5).

If the circuit is completed through a thyratron or other rectifier, the current will cease flowing when the zero axis is again reached; but it is apparent that the current wave will always be symmetrical about the point on the time axis where the voltage changes from positive to negative. Previous to this time the voltage acts to increase the current; afterward it acts to decrease it.

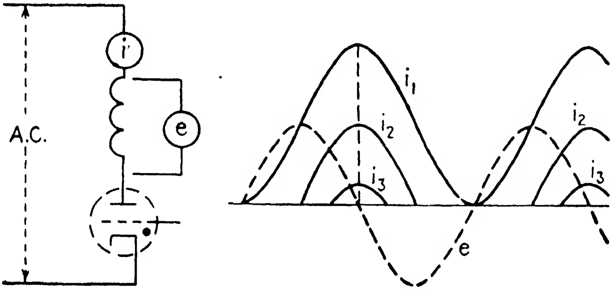


FIG. 9.5. Current in an inductance in series with a rectifier on a-c.

Steady-state Conditions. In order not to confuse the reader who knows from experience that in normal a-c circuits, where the current in the inductance has been flowing for a sufficiently long time to ensure stable conditions, the current wave form is a sine wave symmetrical about the zero axis and displaced 90 deg behind the voltage, the above discussion has dealt only with the theoretical pure inductance. In any practical inductance there will be some resistance, and if there is an iron magnetic path, there will be eddy-current losses in the iron. These losses naturally will always act to decrease the current so that, no matter how far displaced from the axis the average of the initial cycle is found, the losses will soon absorb the excess energy on the predominant side until the curve is pulled down symmetrical to the axis and the losses are supplied equally by the positive and negative voltage loops. How quickly symmetry is reached depends on the ratio of the energy that may be stored in the inductance to the losses in the circuit. If the losses are small, it will take a much longer time to absorb the unbalanced energy.

A Rectifier Is Added. If a rectifier is inserted in the circuit, it will prevent the reversed current from flowing and hence open the circuit during that part of the cycle after the negative loop of the sine voltage has reduced the positive current to zero, thus tending to maintain the unsymmetrical wave form (Fig. 9.5). Various aspects of this action will be taken up later (page 118).

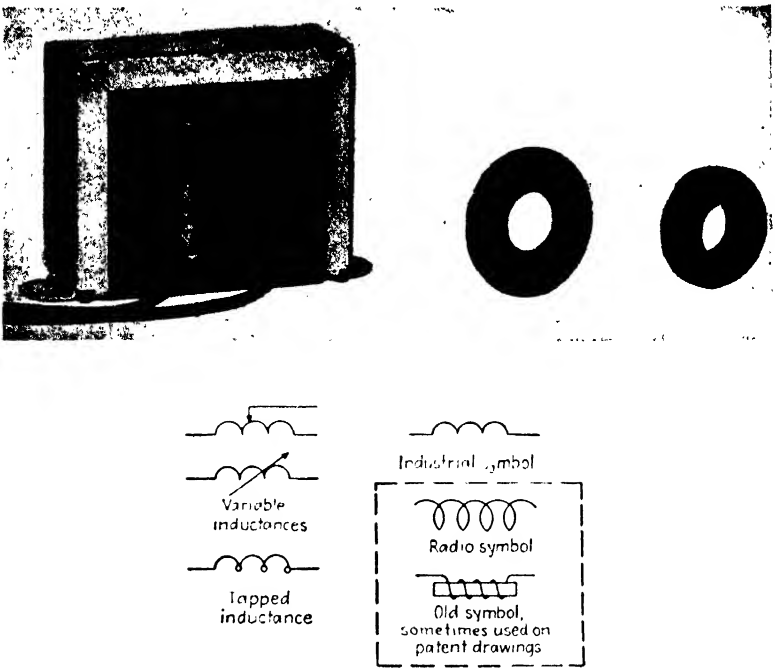


FIG. 9.6. Inductances used in industrial electronic control.

Forms of Reactors or Inductances (Fig. 9.6). The size and shape of inductances (reactors or chokes) vary almost as much as those of capacitors. The important factors are the required henrys inductance and the current to be carried. Inductances for the lower frequencies, which include frequencies up to the radio intermediate value of 500,000 cycles, use iron cores to provide a more efficient magnetic path. The smaller sizes are air-cooled, though generally varnish-impregnated or sealed in a can full of pitch for protection against moisture. The larger sizes are usually mounted in a tank of oil for cooling and for insulation. Because of the high voltages that may appear across the inductances when an attempt is made to interrupt the circuit suddenly, the coils should be properly insulated. Thyrite or spark gaps are placed in parallel with large inductances for protection.

Questions

1. Draw three graphical symbols for an inductance, indicating which are preferred for industrial use and which for radio.

2. What is the difference in energy storage in an inductance at the instant that the current rises to one ampere when the power supply is a-c and when it is d-c?

3. Two amperes flow through an inductance in parallel with which is a resistor of 10 ohms. The external circuit is suddenly interrupted. (*a*) What is the initial voltage across the resistor? Indicate polarity. (*b*) Assuming that the resistor is 100 ohms, what will the initial voltage be? (*c*) If the resistor is Thyrite with 100 ohms resistance for 1 ampere flow, what is the initial voltage?

4. What is meant by a damped oscillatory circuit having a "low decrement"?

5. Is more total energy stored in an iron-core inductance which is saturated or in the same inductance unsaturated? Why?

6. If a sine-wave a-c voltage is applied to a pure inductance at the instant the voltage wave crosses zero, how will the peak value of current compare with that under steady-state conditions?

CHAPTER X

TRANSFORMERS AND MISCELLANEOUS COMPONENTS

Transformers (Fig. 10.1). The transformer is fundamentally a device for transferring electrical energy from one circuit to another through the medium of a magnetic circuit. If the circuit that normally receives the energy, usually called the *secondary*, is open, the energy-supplying circuit, the *primary*, transfers energy to the magnetic circuit and then receives it back at a later part of the cycle, thus acting exactly as an inductance, and may be so considered in circuit analysis. However, there is the one difference that a voltage appears across the secondary terminals. Theoretically this is of little importance since no current flows and no work is done. If the turn ratio is high, however, this voltage may be so high that the insulation will be broken down and damage will result.

Secondary Volts and Current. If the secondary of the transformer is loaded with a resistive, capacitive, or inductive load or a combination of these, the load will respond to the induced voltage of the secondary in its characteristic manner, permitting a current to flow. This current tends to reverse the magnetizing effect of the primary current; so additional primary current must flow to maintain equilibrium. Thus, the total primary current will be a combination of the magnetizing current and the load current reflected from the secondary. Since the transfer of energy between primary and secondary takes place through the magnetic circuit and since the magnetomotive effect is a product of ampere turns (amperes × turns), if the turns of primary and secondary differ, the load currents must vary inversely, that is, a winding with twice the turns will require half the current. Likewise, since each turn of wire, whether primary or secondary, links the same amount of changing magnetic flux, the ratio of primary to secondary volts will be directly proportional to the number of turns on each winding.

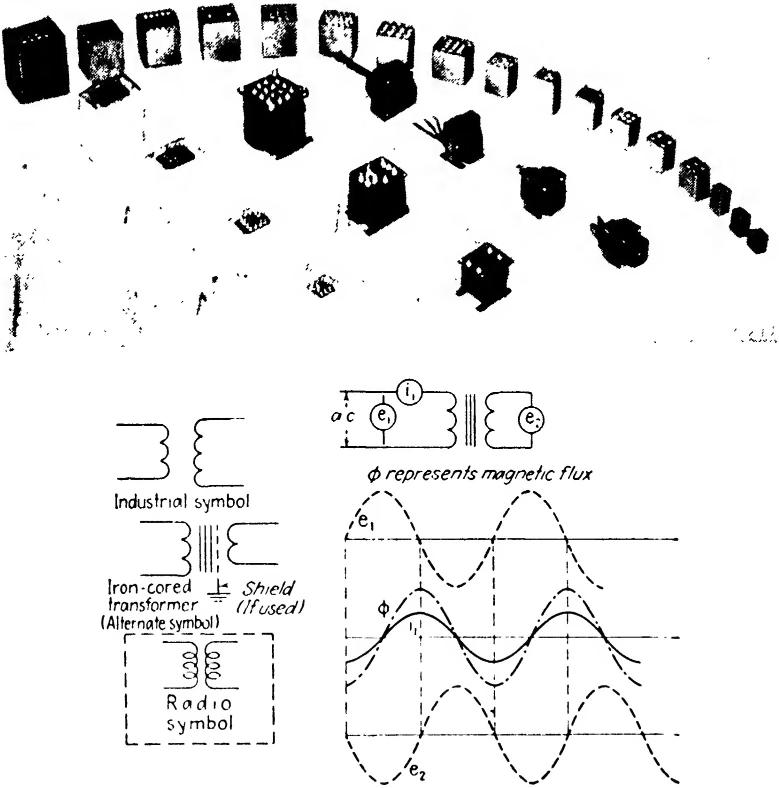


FIG. 10.1. Transformers used in industrial electronic devices.

So far we have assumed that the magnetic circuit was capable of responding effectively to the magnetizing action of the primary. But suppose the magnetic circuit is inadequate and tends to saturate above a partial value of primary magnetizing current. This means that not only does the primary current rise rapidly owing to the drop in the inductive effect but also that the energy which can be transferred to the secondary is definitely limited. To express this in another way, the magnetic flux is proportional to the ampere turns in the primary until saturation occurs, when the ratio of flux to current decreases rapidly. And since the induced voltage in the secondary winding is proportional to the rate of change of the magnetic flux cutting it, as saturation slows down the growth of flux the secondary voltage must suffer accordingly. When the magnetic circuit has become completely saturated, the primary current can change greatly and produce little voltage in the secondary (Fig. 10.2).

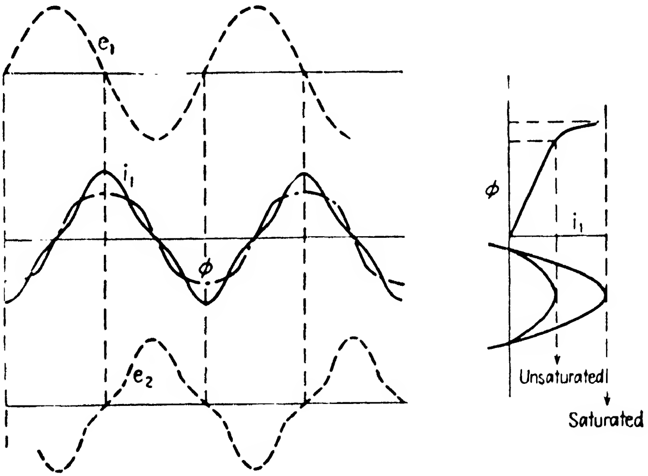


FIG. 10.2. A saturated transformer.

Effect of Saturation. Let us see what this means in practical cases. Suppose a transformer, designed so that the magnetic circuit will not quite saturate when normal rated a-c voltage is applied to the primary, is connected to that same voltage in series with a rectifier. If current first flows in the circuit at the beginning of the positive half cycle, it will be remembered from our discussion on inductances that the primary current will tend to rise to twice the normal steady-state value found on a-c circuits—that is, it would if the inductance remained constant. But as the magnetic circuit saturates, the inductive effect drops rapidly and the primary current rises very high, often damaging the transformer. One solution for this trouble is, of course, to delay the current's starting until later on in the cycle by the use of a controlled rectifier such as a thyratron or ignitron. If we so fire the thyratron that the current starts at the point in the cycle at which it would normally reverse if no rectifier were used, there will be no unusual saturation and the transformer will act, for that half cycle at least, in its normal manner. If a second thyratron is now placed reversed in parallel with the first to conduct the other half cycle and is also phased back to the proper phase angle, the two thyratrons together will form a switch that will permit energizing the transformer without any undesirable transient effects (Fig. 10.3). This is better than can be done with a mechanical switch, or circuit breaker, which is too cumbersome to be closed at such a precise point in the cycle.

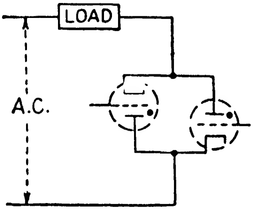


FIG. 10.3. Inverse-parallel thyratrons.

Residual Magnetism. Again it must be remembered that while in designing transformers we strive to use iron for the magnetic circuit which will retain as little as possible of its magnetism after the magnetizing current is removed, this *residual-magnetism effect* is present to a certain extent in all iron. Hence the energy transferred to the secondary for the first half cycle after the circuit is completed will differ somewhat, depending on whether the last previous half cycle before the circuit was interrupted has been in the same direction and has left a residual magnetism that permits the magnetic circuit to saturate more easily or whether it has been in the opposite direction. The latter would make it possible for the flux to be reversed and then built up in the opposite direction, allowing a greater transfer of energy.

Peaking Transformers. We sometimes use the saturating effect to good advantage. We may wish to drive the grid of a thyratron positive for only a small part of the a-c cycle instead of for half the time, as would be normal on a sine-wave circuit. If we force through the transformer many times more primary current than is needed for saturation, we find that a voltage can be induced in the secondary only during the very short time in which the flux is swung from the saturated condition in one direction to the saturated condition in the other direction. During the saturated periods almost no voltage will be induced (Fig. 10.4).

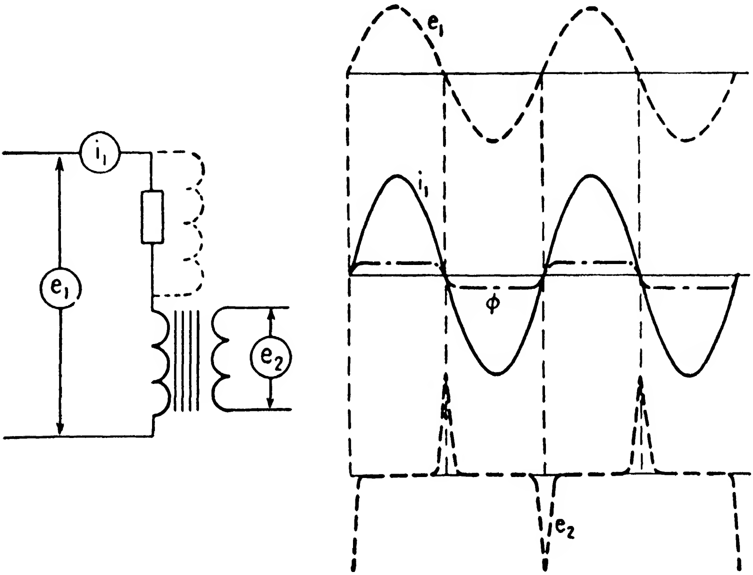
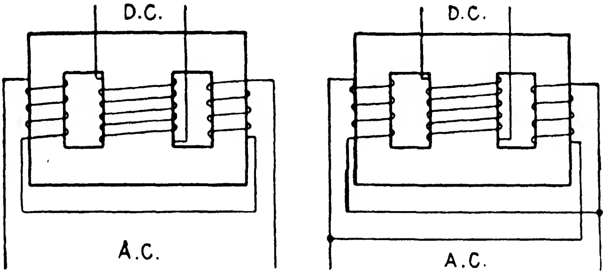


Fig. 10.4. The principle of the saturated peaking transformer (the series impedance may be inductance or resistance).

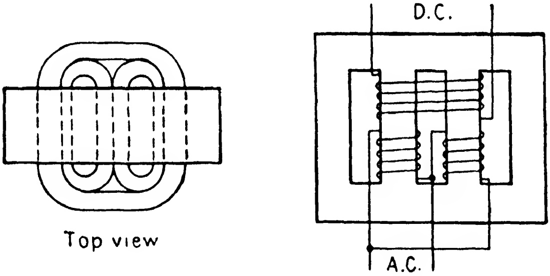
It is usually practical to limit the primary current to a value not too much greater than the saturating value by means of a series resistor or unsaturated reactor to prevent waste of power and undue heating of the peaking transformer. Sometimes the series reactance effect is built into the transformer by permitting only that portion of the magnetic circuit on which the secondary is wound to become saturated. Needless to say, a peaking transformer is not particularly efficient; but the output required of it for grid excitation is never very large.

Saturable Reactors. Another device by means of which we make deliberate use of the saturating effect for loads both large and small is the saturable reactor. Here we take an inductance, or reactor, with an iron core that would normally permit only a small current to follow for a given impressed a-c voltage and deliberately saturate the core by winding on it a coil through which d-c is passed. This decreases the inductive effect for the a-c also and permits a much greater current to flow (Fig. 10.5). Since, once the d-c has built up to its full value, the losses in this circuit are only slightly more than the resistance heat losses, it is possible for a small amount of d-c energy to control many hundreds of times as much a-c energy in the other winding.



Series a c windings   Parallel a.c.windings

THREE-LEGGED SATURABLE REACTORS



FOUR-LEGGED SATURABLE REACTOR

FIG. 10.5. Saturable reactors.

The construction of the saturable reactor is not so simple as it at first appears. If the d-c winding were added as a transformer secondary might be, the voltage induced in its many turns might be extremely high. Therefore, the a-c winding is split into two parts arranged so that their effect on the d-c winding will be neutralized.

Saturable reactors have been built that obtain control from a few microwatts d-c. Others can control as high as 32 kva a-c from a d-c input of only 20 or 30 watts. They have also the desirable feature of permitting the a-c and d-c circuits to be insulated from each other. Either winding may be wound with a large or small number of turns as best suits the voltage and current available. The four-legged type shown, although more expensive to build than the three-legged type, is more efficient because of the better coupling between a-c and d-c magnetic paths.

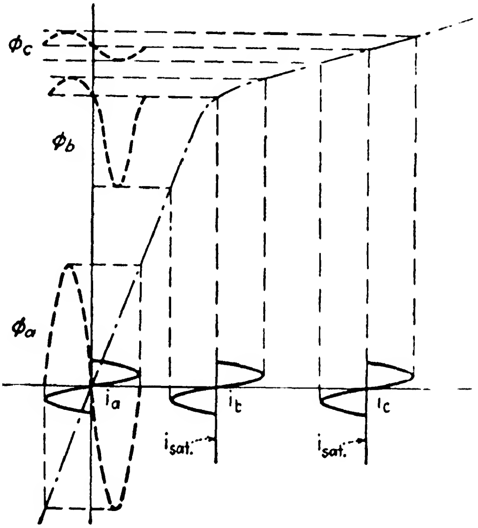


FIG. 10.6. Effect of saturation on change of flux and inductance in a saturable reactor (note maximum distortion at *b*).

The disadvantages of saturable reactors are as follows: First, since they depend for their control action on a d-c inductive circuit, they are inherently slow. Speed of response can be obtained only at the expense of efficiency. Second, since the magnetic saturation is more effective for the maximum currents at the peak of the cycle than for the smaller currents near the reversal point, the control is not truly linear and the harmonics introduced into the load circuit may be objectionable for some types of load. As might be expected, the harmonics are most troublesome at about the middle of the control range, where the effect of saturation is not apparent too early in the cycle (Figs. 10.6 and 10.7). If the series load impedance is low enough, the rush of a-c current at saturation will maintain the saturation until the end of the current cycle, even though the d-c current ceases.

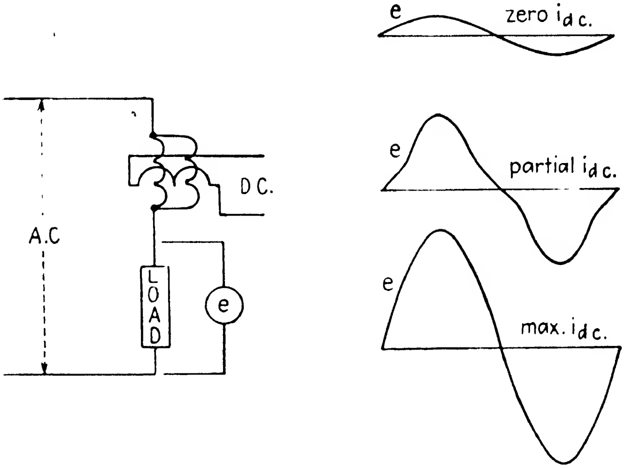


Fig. 10.7. Harmonics of the current in a load in series with a saturable reactor.

The chief use for the saturable reactor has been in the control of incandescent lighting and electric furnaces where the current wave shape has not been a factor and the saving in the kilowatts lost in the reactive control over the usual rheostat control has been considerable. The fact that the d-c for the saturable reactor may be produced and controlled by electronic means is the principal reason for our interest in its use.

Magnetic Amplifiers. When a-c power was adapted for the largest airplanes, the frequency of 400 cycles was chosen because of the smaller size and weight of the transformers and reactors required. (For a given amount of iron and copper only a definite amount of energy may be transferred at each cycle. Hence the higher frequency means a smaller physical unit for each power rating.) However, the availability of high frequency for use with saturable reactors opened many new possibilities for control applications for which the 60-cycle reactor was much too slow. By using the rectifier output of one reactor to saturate the next and by feeding back some rectified output current to reinforce the control circuit, considerable amplification may be obtained with a speed of response adequate for many servo and regulating applications. But the speed of response cannot compare with that of electron tubes; so it is expected that magnetic amplifiers will supplement rather than replace electronic amplifiers.

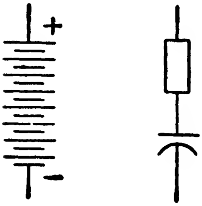


Fig. 10.8. The battery and equivalent electrical circuit.

MISCELLANEOUS COMPONENTS

Batteries (Fig. 10.8). A battery may, for transient loads, be considered as a constant-potential source of direct current. In this respect it acts like a capacitor of almost infinite capacity. But a battery also has a certain amount of internal resistance. It is thus necessary to add to the theoretical capacitor a little series resistance in order to duplicate more nearly the reaction of a battery to the varied application of current and voltage.

Direct-current Motors and Generators (Fig. 10.9). The d-c motor or generator of the shunt, or separately excited, type also has a generated emf due to the rotation of its armature, which tends to hold a constant potential at its terminals in spite of the demands of the external circuit. This is a typical capacitor response. The armature circuit also has some resistance and inductance, which require the addition of a small resistor and inductance in series with the generated emf when its output is viewed from an external circuit. The amplidyne is

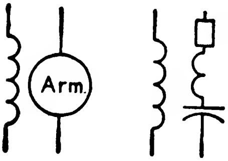


Fig. 10.9. The d-c generator or motor and equivalent electrical circuit.

simply another form of d-c generator with multiple-field coils. Because the control fields have a relatively small inductance and require little power, it is possible to obtain rapid response for control.

Hence we have three components of widely differing appearance that react similarly to any given outside circuit. All are inherently constant-potential devices and must give or receive energy to produce a change in potential. The *capacitor* can store relatively little energy in the electrostatic form but, because its internal losses are low, can give it up extremely rapidly. The energy in the *battery* is stored in chemical form, and thus for a given amount of material the battery can store many times the energy in the capacitor. However, the battery's internal losses and stand-by losses are much greater than those of the capacitor. A given battery can store energy at but one potential, whereas the potential charge on a capacitor may be set at any value within its voltage rating. The *d-c motor or generator* is without doubt the least efficient of the three since its energy is stored as mechanical energy in the rotation of the armature, where it is subject to the losses of bearing, brush, and air friction. Its electrical losses appear as heat in both the copper conductors and the iron magnetic circuit. But because it is one of our most useful and flexible means of conversion between mechanical and electrical energy, its reactions in the circuit deserve careful study.

Alternating-current Motors. As the electron tube is a rectifier, it was logical that it should first be used to control d-c motors. However, electronic control of a-c motors is increasing for special applications. Since the early 1930's experiments have been made toward the use of thyratrons and ignitrons to supply an adjustable frequency a-c to the rotor of an induction-type motor to obtain good regulation over a wide speed range.

For miniature devices such as recording pens, valves, etc., a two-phase motor has been developed in which one phase is excited continuously and the second phase excited and reversed in phase by electronic means to reverse motor direction.

Many machines utilizing a web of material, such as a printing press, require a small threading motor, operating through an over-running clutch to permit the low speed needed for threading the web. An alternate electronic threading drive eliminates the threading motor by taking advantage of the difference in torque of single- and three-phase operation of the main motor. A pair of inverse-parallel thyratrons or ignitrons placed in one input lead may close the circuit to permit three-phase operation or open it for single-phase operation or, by conducting part time, provide the exact torque needed to maintain the desired low, constant threading speed.

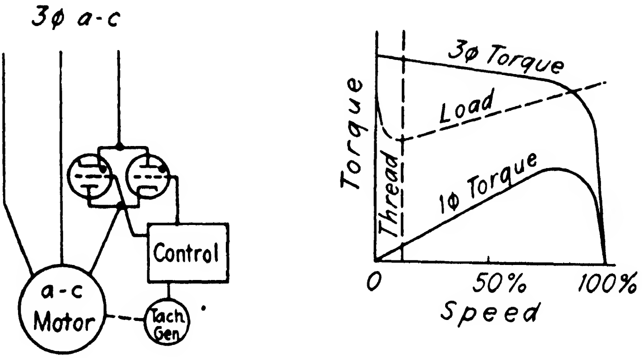


FIG. 10.10. Alternating-current motor control for threading speed. By permitting regulated partial conduction through the third line the torque is held between the single- and three-phase values to hold the desired speed.

Figure 10.10 shows the basic circuit and the motor torque-speed curves for single- and three-phase power. A typical load curve is indicated by the dashed line. If the tachometer generator indicates a variation from the desired speed, the power tubes are phased on or off to correct the speed by changing the line current and torque.

Thyrite and Metallic Rectifiers and Other Nonlinear Elements (Fig. 10.11). Luckily for us the nonlinear elements at power frequencies act as almost pure resistances, the only difference being that, instead of following Ohm's law that the current flowing is proportional to the impressed potentials, the relation between current and voltage follows a curve which is something other than a straight line. For example, as the voltage across Thyrite is doubled, the current increases sixteen times. As the voltage across a metallic rectifier disk approaches zero, the decrease in current is much more rapid than might be expected. Perhaps the simplest way to analyze circuits using elements of this type is to consider them resistances, the value of which must be obtained by a step-by-step process as the current or voltage is varied over the expected range.

Crystal Rectifiers, or "Detectors." In the early days of radio the rectifier, or "detector," of the radio-frequency wave was often composed of a sharp point in contact with a natural crystal such as galena, iron pyrites, or carborundum. This eventually gave way to the more consistent and reliable electronic rectifier. The ultrahigh frequencies of radar demanded a detector-rectifier with minimum capacity effects, and the crystal rectifier was redeveloped using a germanium crystal to create a sturdy and reliable device. This rectifier is capable of withstanding higher reverse voltages than the metallic oxide rectifiers, although its current rating is usually lower.

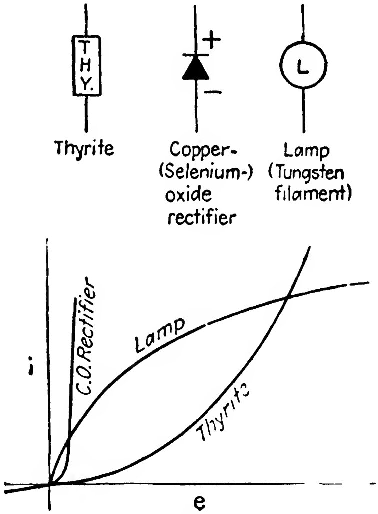


Fig. 10.11. Nonlinear resistance elements.

The metallic oxide rectifiers cover a wide range of materials of roughly similar characteristics. They include copper-oxide, selenium oxide, selenium sulfide, and magnesium sulfide, to name a few. Stacks of disks, sometimes with cooling fins, are made up to cover many current and voltage combinations. The metallic oxide rectifier is most widely used for voltages below 100 volts. Installations for hundreds of amperes have been built for applications such as electroplating.

Crystal or metallic rectifiers may be used in any of the circuits described in the chapter on Rectifiers later in this book.

Questions

1. If the transformer open-circuit secondary voltage is three times that of the primary and there are 300 turns on the primary winding, how many turns are there on the secondary?

2. A current transformer has a primary consisting of a single conductor passing through the iron core. If 40 amperes flow in this conductor and there are eight turns in the secondary winding, what secondary current will flow?

3. In an unloaded peaking transformer does the secondary voltage peak occur at the primary-voltage zero or at current zero?

4. At what part of the saturation range does the maximum harmonic current appear in a saturable reactor circuit?

5. Sketch the equivalent circuit for a d-c separately excited motor.

6. Explain the basic action of an electronic threading drive for a three-phase a-c motor.

CHAPTER XI

COMBINATIONS OF COMPONENT ELEMENTS

After almost any complicated circuit has been analyzed and the correct values applied to the elements, it will be found that the circuit divides into a number of subcircuits in which only one or, at the most, two of the fundamental elements, resistance, capacity, and inductance, predominate. We have discussed the reactions of the single elements. Let us see what happens if we combine two of them, especially with a-c power applied and a series rectifier in the circuit.

Resistance and Capacitance. As might be expected, a resistance in series with a capacitor slows up the flow of current into the capacitor as the voltage changes so that the charging action is always a little later than for a capacitor alone. Hence, the current in the combined circuit is always a little closer in phase with the applied voltage. If the resistance is high or the capacity large, the capacitor can never become very highly charged on an a-c potential before the voltage has reversed. Most of the potential drop will be in the resistor, with a current almost in phase with the applied a-c voltage. On the other hand, if the resistance is small or the capacitor is small and can be charged quickly, the charging current will be small and the IR drop in the resistor will have little effect in delaying the phase of the current (Fig. 11.1).

Suppose now that a rectifier, such as a thyratron or kenotron, is added in series. As the charging current flows into the capacitor while the a-c voltage is building up to its positive peak on the first cycle, a charge of a part of this peak potential will be trapped in the capacitor as the a-c voltage again recedes past this point. But on the next cycle, as the a-c voltage again rises past the capacitor potential, a further charge is added until, in a very few cycles, the capacitor has received the peak a-c potential charge and no further action can take place. If the resistance is high and the capacitor is large, this might be used as a timing circuit.

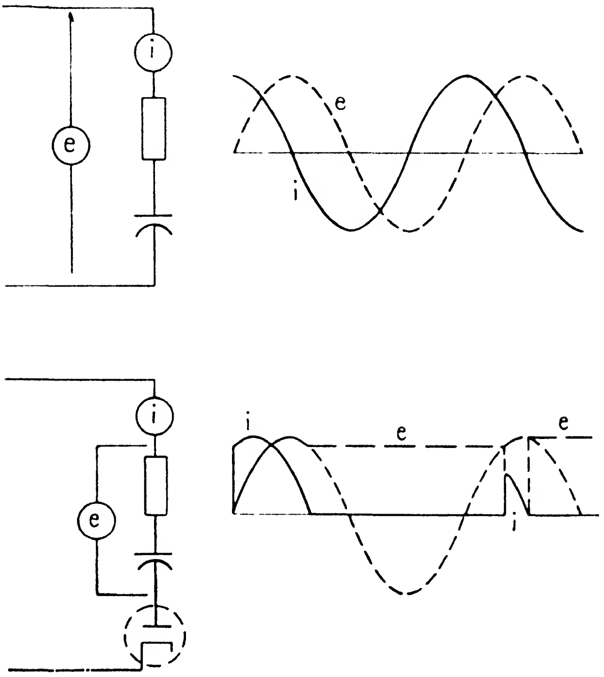


FIG. 11.1. Resistance, capacitance, and a rectifier in series on a-c.

Next let us try a resistor in parallel with a capacitor. Now between the positive peaks of the a-c voltage a part of the capacitor charge will be lost as leakage current through this resistance. If the resistance is low, most of the charge may be lost; but if it is relatively high, if, as we say, the resistor-capacitor circuit has a long *time constant*, a little capacitor potential will be lost between cycle positive peaks with their renewing charge and a comparatively constant d-c potential useful for low current drains results (Fig. 11.2).

Resistance and Inductance (Fig. 11.3). A resistance in series with an inductance diminishes the change in current that may be produced by the changing a-c voltage. Furthermore, shortly after the peak positive voltage has been reached, the *IR* drop in the resistance, gradually increasing because the positive voltage is tending to cause the current in the inductance to increase, may become equal to or even greater than the value of the diminishing positive voltage; and the net negative voltage applied to the inductance to cause its current to decrease will appear much sooner than if the resistance were not there. Since this action occurs on both half cycles, it is clear that the peak currents in the inductance are now closer in phase with the applied voltage; the larger the relative resistance, the more nearly the current will be in phase.

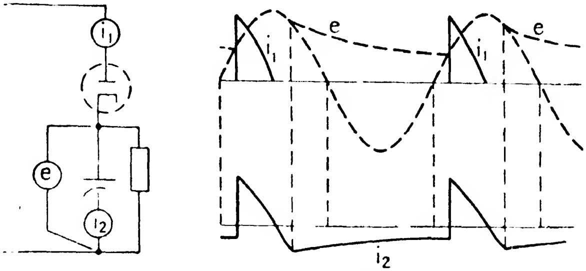


FIG. 11.2. Resistance and capacitance in parallel and in series with a rectifier on a-c.

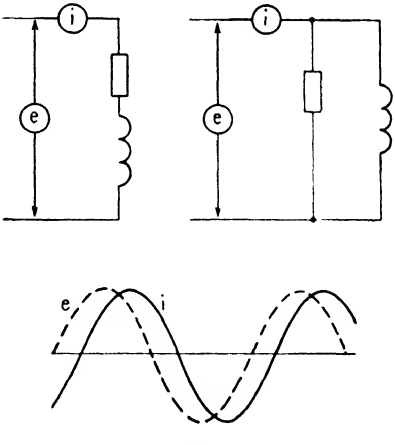


FIG. 11.3. Resistance and inductance in series on a-c.

Resistance, Inductance, and Rectifier (Fig. 11.4). Next let us add a rectifier to the circuit. The series resistor will diminish the build-up of current in the positive half cycle as before; and as the negative half cycle begins, the inductance must not only consume its stored energy to feed current through the rectifier against the increasingly negative voltage but must also force it through the resistance, supplying the resistor losses also. This means that the current stops in the negative half cycle at a much earlier point than in the case of inductance alone.

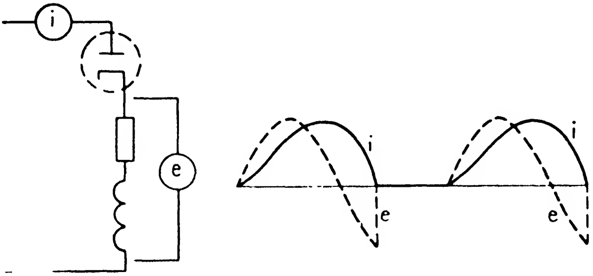


FIG. 11.4. Resistance, inductance, and a rectifier in series on a-c.

Finally, consider the case of a resistor and inductance in parallel and both in series with a rectifier and an a-c supply (Fig. 11.5). So long as the rectifier conducts, the inductance and resistor act as individual elements. However, as the voltage goes negative, the inductance must feed out its energy both into the rectifier

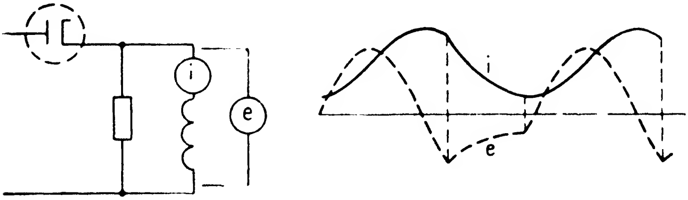


FIG. 11.5. Resistance and inductance in parallel and in series with a rectifier on a-c.

and source and into the parallel resistor. Soon a point is reached at which, even if the whole inductance current flows through the resistor, the required *IR* drop will not be so great as the negative voltage at that instant, so that the rectifier ceases to conduct and the remaining energy in the inductance is consumed in the resistance. But if the resistance is low, the current in it may not have decreased to zero before the next positive half cycle begins. In this case, the current in the inductance starts increasing *from this residual value* rather than from zero. Naturally, by the end of the next cycle the residual current is even higher; therefore, the average current in the inductance builds up until after a few cycles the losses during the negative half cycle exactly balance the current gain during the positive half cycle.

An interesting feature of this circuit should be noted. Since the current in the inductance always tends to flow in the same direction, when the resistor completes the circuit after the rectifier ceases to conduct, the current must flow in the reverse direction through it and the IR drop thus added to the source voltage will cause the potential across the rectifier to become positive somewhat earlier than the normal voltage reversal point of the a-c supply.

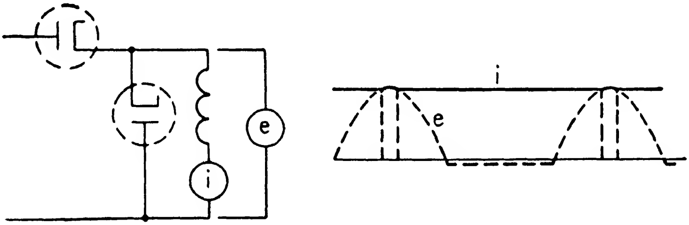


FIG. 11.6. Inductance and inverse rectifier in parallel and in series with a rectifier on a-c ("freewheeling" circuit).

The "Freewheeling" Circuit.[1] It has been stated that the energy fed back into the line through the rectifier is less if the resistor is low; and, of course, for a given current the heat losses in the resistor are less on the *negative* half cycle when this is the case. (On the positive half cycle the energy taken by the resistor from the line will be greater.) But suppose we replace the resistor by a rectifier connected so that the forward current from the line and line rectifier will be stopped but the reverse current can flow to permit the current to continue in the inductance (Fig. 11.6). Here, then, is an ideal element for this function, an infinite impedance to the parasite loss from the line on the positive cycle

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[1] Also called "Half-wave Shunting-tube" circuit.

and a negligible resistance to the continued inductance current on the reverse cycle. Under this arrangement after a few cycles of operation the current in the inductance builds up to a value almost equal to the current that could be obtained with an equivalent applied average d-c potential.

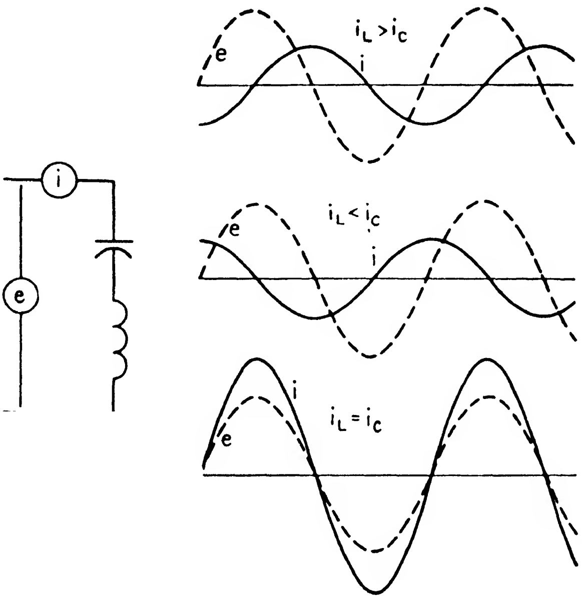

FIG. 11.7 Capacitance and inductance in series on a-c.

Capacitor and Inductance in Series (Fig. 11.7). If a capacitor and inductance in series are connected across a source of a-c potential, the results cannot be foretold until we know the relative value of the two. If either offers predominant impedance to the current flow at the specified frequency, the resulting current will be inherently leading or lagging the applied voltage, as the case may be. The most interesting case occurs when the impedances of the two are equal; that is, if either alone were connected across the source, an equal amount of current would flow, leading by a quarter phase in one case and lagging by that amount in the other case. When two such elements are connected in series across the a-c source, which attempts to charge and discharge the capacitor and to increase and decrease the current in the inductance, it is found that the natural period for the transfer of energy between the magnetic and electrostatic fields is in tune, or *resonance*, with the timing of the a-c positive and negative pulses (see page 94 for a description of this energy transfer). Since there is little loss in the circuit except the small resistance and iron losses in the inductance, the energy transferred within the circuit may become tremendous, with the source supplying only the losses.

However, since this is a series circuit, any currents circulating between the capacitor and the inductance must also circulate through the source circuit, so that this combination looks to the source as an extremely low impedance or almost a short circuit. Also, because the current supplied by the source is used only to supply losses (or, ultimately, heat), it is a resistive current and so in phase with the voltage. But should the impedances of the two elements not be equal, the currents demanded by the one will not be supplied by the other and the difference must be made up from the source, so that its total current now becomes leading or lagging. Further, since there is no longer so complete an interchange of energy, the impedance of the whole circuit has increased so that the total circulating current will be less than at resonance. Thus, as we go out of resonance by changing any one of three factors, capacity, inductance, or source frequency, two effects occur: the current decreases, and the current goes out of phase with the voltage.

Effect of Frequency. Since an inductance resists attempts to change the current flowing in it, its impedance naturally increases as the frequency of the source increases. Because a capacitor can store up only a limited amount of energy for a given applied voltage but can absorb it rapidly by permitting a large current to flow into it for a brief time, it is also natural that the total current flow into and out of a capacitor will increase as the frequency of the a-c voltage reversals increases; in other words, the impedance to the current flow decreases with increased frequency. Thus, as the impedance for zero cycles change per second (d-c) is zero for an inductance and infinite for a capacitance, and for an infinite frequency is infinite for an inductance and zero for a capacitor, it follows that for any inductance and capacitor in series there will be some frequency at which they will be resonant.

What happens when we place a rectifier in series with the above circuit (Fig. 11.8)? What happens when we put a rectifier in any circuit containing a series capacitor? The capacitor charges up to or beyond the peak a-c voltage, and then the rectifier can no longer conduct. The potential to which the capacitor is charged depends on the relative sizes of the inductance and capacitor since any energy due to the current flowing in the inductance at the peak supply voltage must be transferred to the capacitor or back to the supply before the current stops.

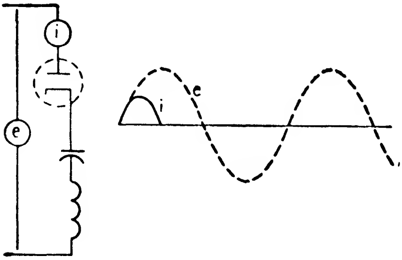

Fig. 11.8. Capacitance, inductance, and a rectifier in series on a-c.

Capacitor and Inductance in Parallel. In discussing the action of resistors in parallel with one of the other two principal elements, no mention was made of the action of the combination on a sine-wave a-c voltage, since the resistor could not store energy and the two elements acted independently. But when a capacitor and an inductance are connected in parallel across an a-c source, the action becomes of greater interest. In discussing these elements separately, we found that the current supplied by the source to the capacitor reaches its positive maximum as the supply voltage is becoming most rapidly positive, just as it passes through zero and a quarter phase ahead of its maximum positive peak. On the other hand, the current in the inductance is maximum just at the end of the half cycle in which the applied voltage has been working in one direction to force the current to flow in that direction.

If we take the point in the cycle mentioned first, when the voltage is just becoming positive, the negative half cycle has just finished and so the current in the inductance is at its maximum negative value. Here at the same point, at the same instant, we require both a positive and a negative current. Thus the source need supply only the difference, the remainder being supplied by one of the parallel elements (Fig. 11.9). Whether the current supplied by the source is leading or lagging depends simply on which of the elements demands the most current. If a resonant condition exists, the current required by the capacitor will all be supplied by the inductance, and vice versa, so that theoretically the difference to be supplied by the source is zero. Under actual conditions the source will be called upon to supply the losses, which, again, will be dissipated as heat; so the loss current is resistive and in phase with the voltage. It will be noted that in parallel resonance, as contrasted with series resonance, the current supplied from the source is minimum rather than maximum. The current is again in phase with the voltage at resonance and changes from lagging to leading as the frequency increases through

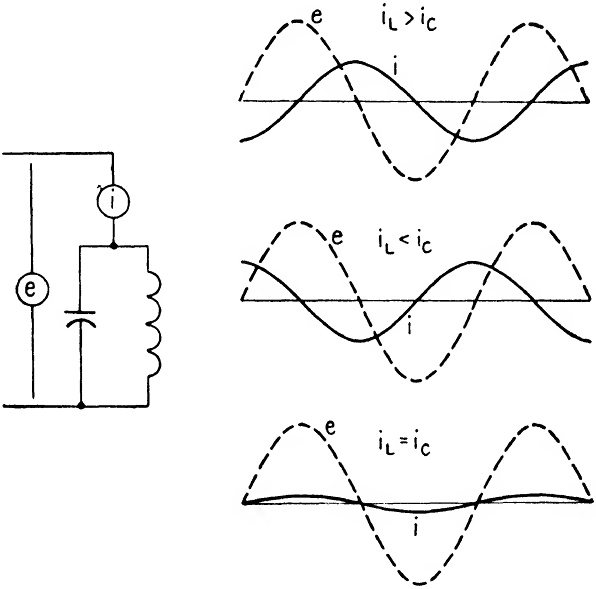

FIG. 11.9. Capacitance and inductance in parallel on a-c.

the resonance frequency. As explained under Series Resonance (page 120), for any capacitor and any inductance in parallel there is a definite frequency for resonance.

The Series Rectifier. If a rectifier is inserted between the source and this parallel circuit (Fig. 11.10), the resulting current becomes somewhat difficult to describe exactly. If the capacitor is of lower impedance than the inductance, the rectifier will charge it up on the positive half wave and start current flowing through the inductance. After the rectifier stops conducting, the current will continue to flow in the inductance, discharging the capacitor and perhaps charging it up slightly in the reverse direction before the time of the new positive half cycle and the renewal of the capacitor charge through the rectifier. It is important to note that in this case the current in the inductance does not reverse; in fact, if the capacitor is large enough, a fairly smooth d-c may flow through the inductance in spite of the interrupted contact with the source through the rectifier. This is a particularly useful feature if the inductance is an electromagnet or the

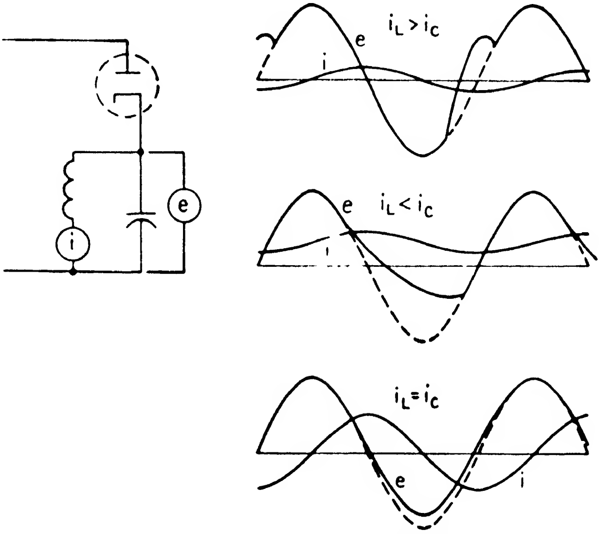

FIG. 11.10. Capacitance and inductance in parallel and in series with a rectifier on a-c.

operating mechanism of a contactor or relay that we wish to operate through a single thyratron or vacuum tube. The parallel capacitor produces results that are similar to but not quite so satisfactory as those produced by an inverse rectifier. Care must be taken to prevent the capacitor from drawing too large charging currents (by the insertion of a small series reactor or resistor) when this circuit is used with a thyratron or phanotron.

Parallel circuits in which the inductance has a lower impedance than the capacitor (an indication that the natural resonant period of the circuit is higher than the source frequency) are rarely used in series with the rectifier since by the time that the second positive cycle of the source occurs the current in the inductance has reversed perhaps once or a number of times, producing many undesirable transient currents and induced voltages.

Harmonics. Since the saturation of the magnetic circuits in iron-cored inductances and the abrupt changes in wave form caused by the insertion of a rectifier may alter radically the smooth sine wave supplied by the a-c source, the resulting wave form is assumed to be made up of a number of higher frequencies superimposed upon the original, or fundamental, frequency. Usually, these are direct multiples of the frequency. The third harmonic (three times normal frequency) is usually introduced when iron is saturated; so resonant effects of parts of the circuit at this frequency also must be guarded against.

Questions

1. If a rectifier tube feeds a parallel *RC* circuit from an a-c source, will there be a longer flow of current each cycle through the rectifier if the resistance is increased? Why?

2. If resistance and inductance in series are fed from an a-c line, will the line current lead or lag the voltage? What happens if the resistance and inductance are in parallel?

3. Sketch the form of the current wave through the inverse rectifier in the "freewheeling" circuit.

4. A capacitor and an efficient inductance each, when connected to an a-c source, draw the same current. When both are connected in parallel across the line, will the total line current be more than double that of one? Why?

5. If we connect an inductance, capacitance, and rectifier in series to an a-c source, what will happen?

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Section III

BASIC ELECTRONIC CIRCUITS

CHAPTER XII

RECTIFIER CIRCUITS AND FILTERS

No matter how complex any electron circuit may seem, it may be broken down into sections that, in themselves, are comparatively simple. Although there are an infinite number of combinations of basic circuits, if some of the more common ones can be understood and recognized the unfamiliar ones can then be studied more easily.

Electron circuits for industrial control may be classified roughly into the following general types: (1) Power conversion—rectifying of a-c to d-c or inversion of d-c to a-c at high or low frequency. This also includes frequency conversion, in which an a-c is rectified and then inverted back to a-c at a different frequency. (2) Amplification—a small incoming a-c signal or d-c difference of potential is magnified to an outgoing signal of similar character but of greatly increased power and potential charge. Some amplifiers are quite linear and reproduce an accurate picture of the input; others permit much more distortion. (3) Electron timing circuits—these prove useful for many processes. (4) Electronic switching of circuits—by far the most accurate and fastest means. It may be accomplished rapidly and continuously for long periods of time without wear of the switching element, the electron tube.

RECTIFIERS[1]

Although most of our power is distributed at present as alternating current, there are many applications for which direct current is more desirable. Motor-generator sets and rotary converters have been widely used in such cases; but for the small amounts

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[1] Quantitative data on rectifiers will be found in Appendix IV.

of d-c power needed in many control panels the electronic rectifier, now built in all sizes, is much more practical and less expensive.

Single-phase Half-wave Rectifier[1] (Fig. 12.1). This simplest type of rectifier was discussed briefly in connection with a capacitor and rectifier in series with an a-c power source (page 115).

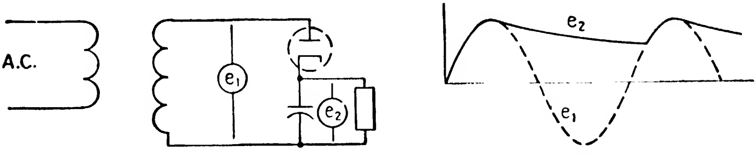

FIG. 12.1. A single-phase half-wave rectifier.

After the rise in the positive potential of the supply voltage has charged the capacitor through the rectifier, the charge is trapped when the line voltage drops lower than the capacitor potential. Then, if the capacitor is comparatively large and the load that utilizes the charge across it as a d-c source is of relatively high resistance, the capacitor will not lose much of its charge before the line voltage again becomes positive enough to replenish the charge. Thus the capacitor maintains a fairly constant d-c potential between its plates.

Single-phase Full-wave Rectifier[2] (Fig. 12.2). The next step is to "turn over" the negative half wave of the a-c voltage so that it also may be used to supply current to the capacitor and thus permit more load to be drawn with less loss of potential between rechargings. If we utilize a second transformer winding,

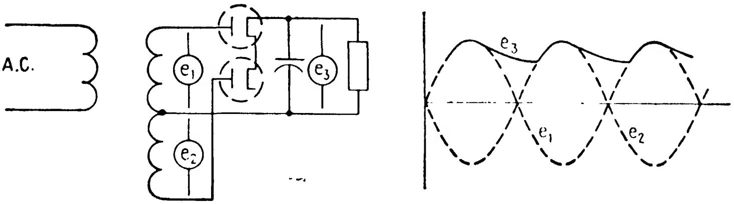

FIG. 12.2. A single-phase full-wave rectifier.

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[1] Also called "one-way" rectifier.

[2] Also called "diametric" rectifier.

with its connections to the capacitor reversed with respect to the first, and a second rectifier with its cathode also connected to the capacitor positive terminal, it will be seen that as the anode of the first rectifier becomes negative the anode of the second becomes positive and the charging action takes place twice as often.

Two respects in which this rectifier differs from the preceding one should be noted. If the same capacitor and load current are used, the *ripple*, that is, the variation in d-c potential, is less than before and occurs twice as often, or the frequency in cycles per second is doubled. In both these circuits the maximum inverse voltage on the rectifier when its anode is negative is equal to the sum of the peak a-c voltage and the capacitor potential, or roughly twice the d-c output voltage. Therefore, the rectifier elements must be insulated for this voltage. The current through the rectifier to the capacitor comes in short intervals near the voltage peaks; so the rectifiers and the transformer windings are idle more than half the time. The primary of the transformer in the first circuit was idle for half the time, but it supplies current during both half waves in the full-wave circuit. The second circuit has an advantage in that the cathodes of both the rectifiers are at the same potential and may be fed from a common heater or filament transformer winding.

Single-phase Bridge Rectifier[1] (Fig. 12.3). Sometimes a single transformer winding is used to supply both half waves. This can be done if we add two more rectifiers so that the transformer is connected to the capacitor and load only through the rectifiers and thus can be completely reversed. Since both ends of the capacitor are connected to the winding through the rectifiers, during each half cycle the inverse voltage on each rectifier can never be greater than the peak a-c voltage, or about half that in the half-wave cases above. The single winding is also used twice as effectively as either of the two windings in the half-wave case. But now the charging current must flow through two rectifiers in series each time; so the rectifiers themselves are not used so effectively. However, because the inverse voltage is

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[1] Also called "diametric double-way" rectifier.

minimum, the full-wave circuit is especially useful when extremely high voltages are to be rectified and for the copper-oxide and selenium type of dry-disk or metallic rectifiers in which the rectifier elements are small disks of limited inverse-voltage rating.

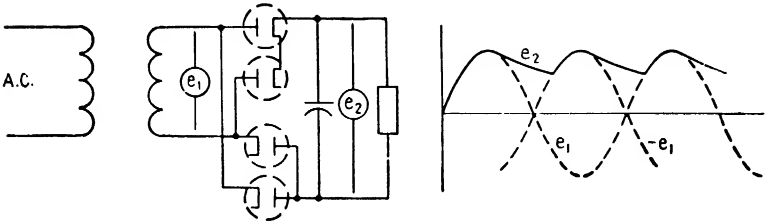

FIG. 12.3. A single-phase bridge rectifier.

Three-phase Wye Rectifiers (Fig. 12.4). If the a-c power supply is three-phase rather than single-phase and we have three secondaries, one fed from each phase, we may connect a common point on our load to one end of each of these secondaries as we did to the common point of the two half-wave secondaries in the single-phase full-wave case. Three rectifiers having a common cathode (or anode) potential are needed. The magnitude of the ripple has been further decreased, and its frequency is now the third harmonic, or three times the fundamental a-c frequency. As in all half-wave rectifiers the inverse voltage is a little over twice the d-c output voltage, and since there are now three tubes to carry the load current in rotation, the average current rating for the rectifier will be higher than in the previous cases, although each tube must carry the full current for its share of the time.

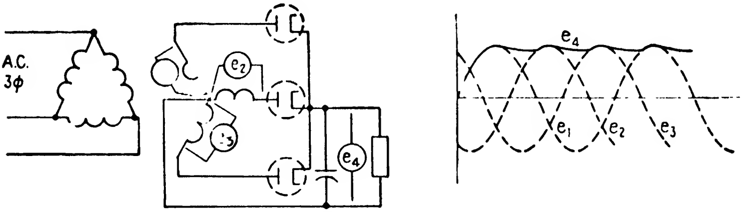

FIG. 12.4. A three-phase half-wave rectifier.

This means its cathode must be capable of supplying the electrons for the full current, although the physical size of the tube need not be more than large enough to dissipate the heat due to conduction for one-third the time.

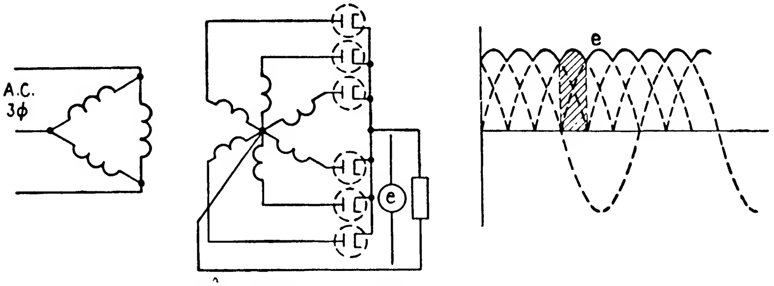

FIG. 12.5. A six-phase half-wave rectifier (shaded area is the time of current flow in one tube).

Six-phase and Double-wye Star Rectifiers. If we take two windings from each phase and connect all six to the common load point so that the potentials of the two windings in each phase are reversed, we produce a six-phase half-wave circuit (Fig. 12.5) using six rectifier tubes and having an even smaller ripple at six times line frequency. Sometimes the common load tap is taken, not directly from the junction of all six windings, but from the mid-point of a reactor, or *interphase transformer*, that joins the two sets of wyes (Fig. 12.6). As current is drawn through one side of this reactor, a voltage is induced in the other side also, through transformer action, which, added to the voltage in the other wye, causes one of the tubes on that side to pass current

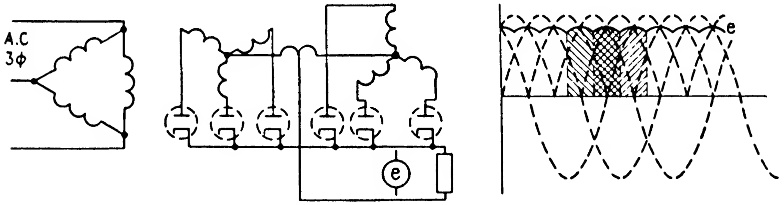

FIG. 12.6. A double-wye rectifier with interphase transformer (shaded areas are time of flow in each tube).

until the currents in the two halves of the interphase transformer are fairly well balanced. Since this means that two rectifier tubes are now conducting at all times in parallel, each rectifier tube need have only half the peak current rating it would otherwise require.

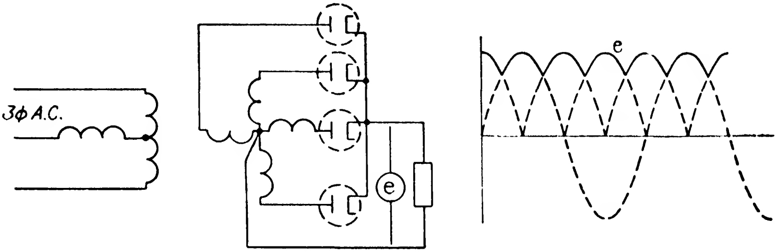

FIG. 12.7. A four-phase half-wave rectifier on a three-phase a-c supply.

Four-phase Half-wave Rectifier (Fig. 12.7). There are times when a four-phase rectifier is desirable in order to simplify the control circuit or so that the available rectifier tubes may be used more effectively. In this case two-phase power is obtained from the three-phase power by Scott-connected transformers or similar circuits, but once two-phase power has been obtained the half-wave rectifier circuit is the same familiar type, with a ripple of four times the supply frequency.

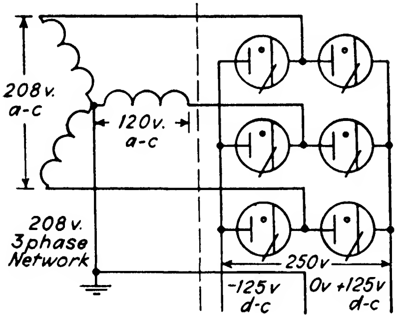

FIG. 12.8. A six-phase double-way rectifier with wye transformer input to permit three-wire d-c operation from an a-c network.

Multiphase Full-wave Rectifiers. Multiphase, as well as single- or biphase, rectifiers can be made full wave or double-way by the use of twice the number of rectifier elements to reduce the necessary inverse voltage.

We have already discussed the bridge rectifier and can now see how the same reasoning applies to multiphase circuits.

Six-phase Double-way Rectifiers. This is a three-phase rectifier in which each winding conducts current on both half waves. This requires an anode and a cathode to be connected to each winding end as shown in Fig. 12.8. The load current must flow through two tubes in series. Since the reverse current in the three-phase transformer windings is 60 deg out of phase with the other phases, the d-c wave ripple will be six times line frequency as in the six-phase star connection. Whereas we have seen that this circuit has the disadvantage of requiring that the current flow through two tubes in series, we can also note that the maximum voltage between transformer terminals is little more than the d-c output so that the inverse voltage applied to the tubes is decreased.

Double-way circuits are used extensively with metallic-oxide rectifiers because of their limited inverse-voltage rating.

If the transformer secondary winding is in the form of a wye, a mid-tap may be taken which is also the mid-tap of the d-c output. This is evident where it is noted that each half is now a three-phase half-wave rectifier. Each half has a ripple of three times line frequency although six times frequency appears across the outside lines.

This circuit with mid-tap is particularly useful for power rectifiers in metropolitan distribution networks. Many of our large cities formerly had 250-volt mid-tapped d-c networks. This meant that all of the motors for elevators, fans, and other uses were d-c motors. When the cities desired to change over to a-c, there arose the serious problem of supplying power to these motors. Fortunately, the new a-c network is often a wye circuit having 120 volts in each leg and a grounded neutral. This fits in very well with the a-c voltage input required for a rectifier having a 250-volt d-c output when using a three-phase double-way ignitron rectifier. Thus, for many applications the rectifier may be connected directly to the a-c lines without requiring intermediate transformers. The basic circuit arrangement is shown in Fig. 12.8.

Voltage-doubler Rectifier (Figs. 12.9 and 12.10). The voltage-doubler rectifier is an interesting combination of two single-phase half-wave rectifiers in which the outputs are effectively added in series. By employing two capacitors in series with their common point connected to one side of the transformer secondary winding (or even to one side of the a-c line itself) and using two rectifiers connected with the anode of one and the cathode of the other to the free end of the secondary or a-c source and the other elements to the free ends of the capacitors, the two capacitors can be charged in opposite directions on the alternate half cycles so that the output voltage taken across the capacitor ends in almost twice the peak a-c voltage. Since the energy for the output circuit for most of the cycle must be supplied by the capacitor, it is seen that this circuit is most useful for light loads at a comparatively high voltage and that it has also a definite and useful mid-potential point at the junction of the capacitors.

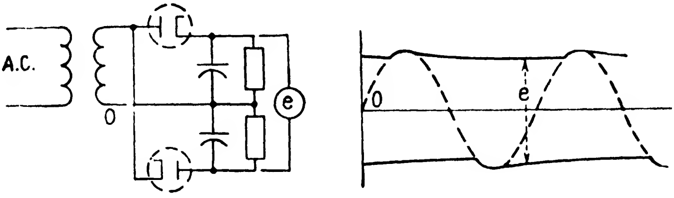

FIG. 12.9. A voltage-doubler rectifier, symmetrical about point *O*.

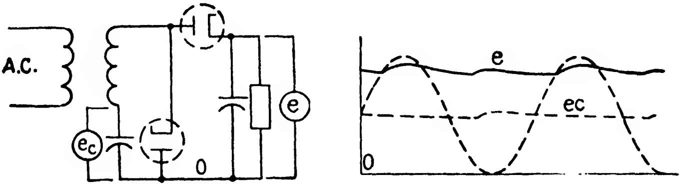

FIG. 12.10. A voltage-doubler rectifier with a single load capacitor.

Multistage Voltage Doublers. The principle used in the voltage doubler of Fig. 12.10, that of charging one capacitor so that it may act as a pedestal to "jack-up" the a-c voltage to a higher rectified value, may be extended to multiple stages as shown in Fig. 12.11.

Here two stages are shown, but the same principle could be extended to others, limited only by the basic fact that not only must each stage capacitor supply its own energy but also each cycle must store and transmit to the capacitors beyond it the energy for all succeeding stages. Hence this type of circuit is most useful for high-voltage, low-current needs, such as for cathode-ray tubes and multiplier phototubes. The circuit shown is particularly adapted for a multiplier phototube or an electrostatically deflected cathode-ray tube since the low-current, high-voltage circuit is negative with respect to the transformer winding, which may be part of the amplifier d-c supply transformer.

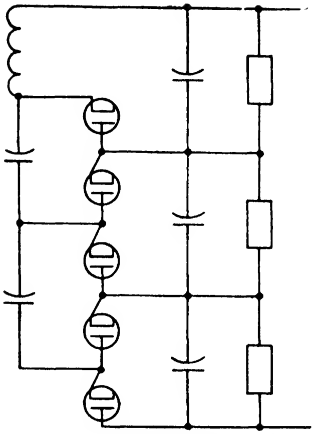

Fig. 12.11 Multistage voltage doubler. Additional stages may be added in a similar manner.

Other high-voltage, low-current rectifiers use pliotron oscillators to generate radio frequencies which may then be stepped up by air-core transformers or auto-transformers and rectified. Another form, used in some television sets, applies the saw-tooth scanning signal to the grid of a power pliotron having a high inductance in series with the anode. As the grid becomes slowly positive, the current builds up in this inductance so that when the grid is driven sharply negative a high voltage appears across the inductance. This is rectified and trapped in a capacitor as

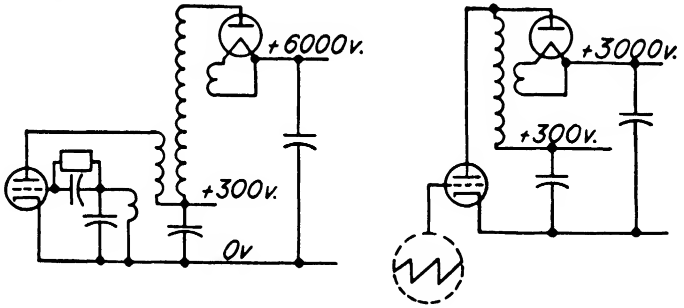

Fig. 12.12. Specialty rectifiers. Operation from an oscillator at left and from a television horizontal sweep signal at right.

above. The small power required to heat the rectifier cathode is usually obtained from an air-core secondary coupled to the main oscillator or inductance coil. These circuits are shown in Fig. 12.12.

Discriminators. Discriminators might be described as balanced rectifiers which are sensitive to a-c amplitude, frequency, or phase angle. As such they are used for detectors in frequency-modulated radio and in industry for detection of Selsyn phase shift and frequency change.

In a typical discriminator circuit the a-c voltage applied consists of a common voltage vector to which is added the incoming signal in opposite phase to the two rectifiers.

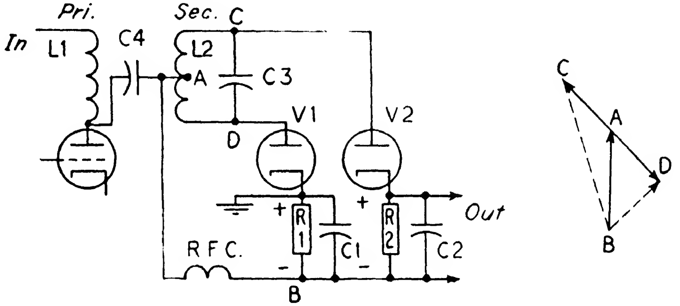

FIG. 12.13. Frequency-modulation discriminator. Output is proportional to frequency deviation.

In Fig. 12.13 we see a typical frequency-modulation discriminator in which the common vector is the practically resistive a-c drop across the input amplifier tube coupled through $C4$. The discriminated signal is received from a center-tapped tuned transformer winding, $L2$, in which the current changes phase sharply as the frequency passes through resonance. As the vector diagram shows, at resonance the a-c applied to the rectifier tubes, and the d-c output, will be balanced, but above or below resonance one rectifier output will predominate, producing a positive or negative output signal. This, in an FM receiver, varies at an audio-frequency rate.

A typical Selsyn, or autosyn, phase-reversal discriminator circuit is shown in Fig. 12.14. If the Selsyn on the transmitter and that on the receiver element, the latter often called the "control transformer," are in synchronization, the rotor winding of the receiver is at right angles to the a-c field of the stator and no voltage is induced in it. However, away from synchronization an unbalance voltage appears which reverses in phase while passing through synchronization. It is this phase reversal which is to be converted into a d-c polarity reversal. Here the common voltage vector added to the unbalance voltage must be taken from the same voltage source as that applied to the transmitter.

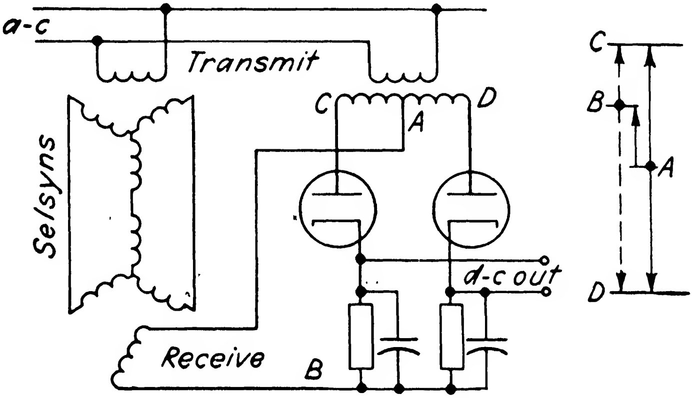

FIG. 12.14. Selsyn position discriminator. Output proportional to a-c voltage magnitude and phase.

FILTERS

For many purposes the output of the rectifier is sufficiently pure d-c. For others, particularly for vacuum-tube amplifiers, the d-c power must be further smoothed, or filtered. The capacitor across the rectifier output, mentioned above, is a fair filter for light loads, but it has the disadvantage that it may draw high peaks of current when used with gas-filled rectifiers. Usually, therefore, the filter consists of both capacitors and inductances; we thus have the advantage of the inherent constant-voltage characteristic of the capacitor and the constant-current characteristic of the inductance. For example, we might add a small inductance in series between the rectifier and the capacitor in parallel with the load to minimize the peak currents. If the inductance is sufficiently large, any tendency for the current to change appreciably will induce enough voltage to force the current through the rectifier tubes to take the form of almost square blocks. Needless to say, the absence of high peak currents means conservative operation and long life for the rectifier tubes. This type of arrangement is known as *choke input* or *inverted*-L filter (Fig. 12.15).

Of the possible objections to this type of filter the principal one is that the induced voltage in the filter inductance has leveled off the ripples of the rectifier output to the average value, so that the voltage at the output is lower than that for the capacitor input filter, which tends to charge up to the peak rectifier voltage with light loads. On the other hand, as the load increases, there will be more load voltage drop with a capacitor input filter.

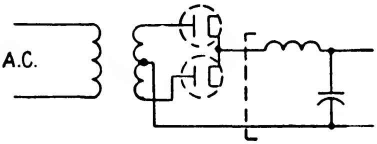

FIG. 12.15. Inverted-L filter (and rectifier).

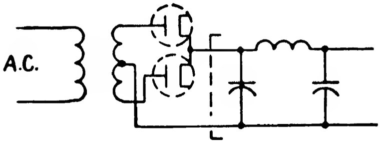

FIG. 12.16. A π filter and rectifier.

When a kenotron, or high-vacuum rectifier, is used, the element of self-protection inherent in the space-charge drop makes the matter of peak currents less serious; so it is general practice to place a second capacitor across the rectifier output ahead of the series inductance to obtain further filtering action as well as to raise the average output voltage. This arrangement is called a "pi filter" from the Greek letter π, which it resembles (Fig. 12.16). As used in radio-receiver d-c power supplies, the two capacitors are of the electrolytic type, 8 to 40 μf each, in a common container. The inductance may be the field-magnet winding of the loud-speaker used. Since these are "brute-force" filters, the filtering action is affected but slightly by wide changes in the actual values of inductance and capacity.

Although the inverted-L and pi types of filter are the most common, there are a few other types that should be mentioned. For example, if extremely smooth d-c is required, additional inverted-L sections may be added to obtain any desired degree of smoothing. On the other hand, if it is felt that the required filtering does not warrant the expense of an inductance, a resistor may be substituted, with similar, but not quite so satisfactory, results (Fig. 12.17). We do not have both the positive and negative induced voltage characteristic of the inductance, but only the *IR* drop change due to the rise and fall of current charging the second capacitor.

From the discussion of series and parallel resonant circuits (page 121) it will be remembered that, at the resonant frequency, the parallel resonant circuit acted as an extremely high impedance and the series circuit seemed almost a short circuit. So if for the inductances we substitute circuits parallel-resonant to the ripple frequency and for the capacitors substitute series-resonant circuits also tuned to this frequency, we obtain a filter that is many times as effective as the component parts taken alone. A resonant filter of this type (Fig. 12.18), of course, requires much more careful matching of elements than the brute-force filters discussed above.

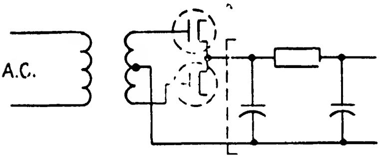

FIG. 12.17. Resistor π filter and rectifier.

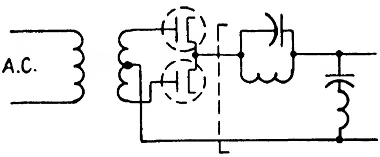

FIG. 12.18. Resonant filter and rectifier.

Voltage Dividers. When various parts of the circuit have widely different demands for direct current, it is often best to supply separate rectifiers to suit each particular need. However, there are often needs for small amounts of current at intermediate potentials of the rectifier output. These may be best met by a *voltage divider.* This device consists merely of a series of resistors or a single-tapped resistor connected across the rectifier output and carrying five to ten times as much current as is expected to be bled off at the tapped point (Fig. 12.19). If the current to be drawn is intermittent or varying, a capacitor connected between the tap point and one side of the divider will help to hold the potential steady. The actual change in the potential of the tapped point as the load changes can be calculated easily from Ohm's or Kirchhoff's laws. Voltage dividers are especially suitable for phototube potentials and for the screen and other grid potentials for voltage-amplifier tubes.

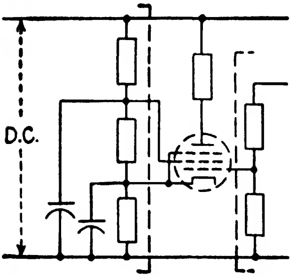

FIG. 12.19. Voltage dividers. Left, potential for cathode and screen grid. Right, divider on grid input.

Voltage dividers are also used in many types of control circuit to obtain a definite fractional voltage output from any voltage, a-c or d-c, applied across its ends.

Questions

1. Draw a diametric, or single-phase, full-wave rectifier feeding a resistance load only. Sketch the wave form of current in the resistor.
2. What is the ripple frequency of a three-phase half-wave rectifier on a 60-cycle a-c supply?
3. What is the principal advantage of a double-wye rectifier with interphase transformer over the six-phase half-wave rectifier?
4. Draw the circuit for a four-phase rectifier operated from a three-phase a-c supply.
5. What is the frequency of the ripple of a voltage-doubler rectifier output on a 60-cycle supply?
6. Sketch a circuit suitable for obtaining three-wire d-c power from an a-c three-phase circuit using a wye transformer.
7. What is the general purpose of a "discriminator" circuit?
8. Name a contrasting advantage for a pi filter and for an inverted-L filter.

CHAPTER XIII

AMPLIFIERS

Class A Amplifiers. The fact that a small change of potential on the grid of an electron tube can influence the flow of a much larger amount of power in the cathode-anode circuit is the most important characteristic of a tube. The practical application of this characteristic is the electronic amplifier. Let us look at a few of the most common types.

In the discussion of tube-characteristic curves on page 50 a brief description was given of the possible gain in voltage change in a single tube and its relation to the amplification factor (mu) of the tube and the anode resistor. It has been found for the modern pentode tube that *maximum voltage amplification* per stage occurs when the *IR* drop in the anode resistor is about four-fifths the available anode voltage. For attaining the *maximum power change* in the anode load the anode voltage supply is equally divided between the resistor and tube. However, these are general rules and special circumstances may alter them somewhat.

In any conventional amplifier the changes in grid and anode potentials are always in opposite directions. This may be checked by noting that as the grid becomes more negative, decreasing the cathode-anode current, the decreased *IR* drop in the anode resistor permits the anode potential to rise nearer the positive supply potential.

In radio practice, amplifiers are divided into three classes (with a number of subdivisions) depending on how the grid is made to swing with respect to the cathode potential (at the positive end) and the potential at which the cathode-anode current is completely cut off (at the negative end). If the grid potential always remains between these two potentials so that the main current flow is not cut off and the grid does not go positive and require appreciable power to drive it, the circuit is called a *Class A amplifier* (Fig. 13.1). Its characteristics are good linearity between input- and output-voltage wave shapes, good power and voltage amplification (since the theoretical power input is zero), but a poor over-all efficiency, or ratio of power output to the power required from the d-c anode supply. This type of amplifier is most used for electronic control circuits.

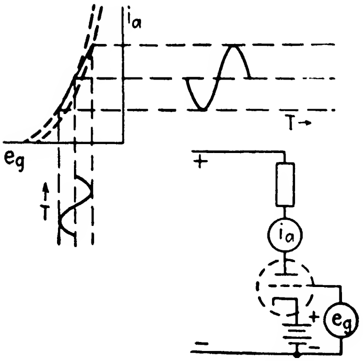

FIG. 13.1. A Class A amplifier. (E_d and I_a are plotted on tube-transfer characteristic curves; see page 50.)

Push-pull Amplifiers, Class B. In those cases where it is desired to obtain greater efficiency from the available d-c power, Class B or C amplifiers are used. In both these types two tubes are used in parallel in circuits that are similar in some ways to a single-phase full-wave rectifier working backward. The grids of the tubes are biased so far negative that little if any current flows when there is no signal on the grid. An a-c input signal

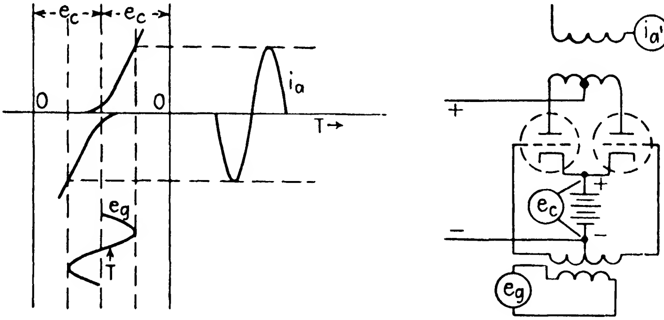

FIG. 13.2. A push-pull Class B amplifier. (Transfer curves for second tube read down and to left.)

on the grids permits first one tube and then the other to pass current into the halves of the output transformers so that the magnetic flux reverses and the effect on the secondary winding is similar to that of a true a-c on the primary. Class B amplifiers (Fig. 13.2), biased to the proper point above current cutoff, may have excellent linearity characteristics as well as good power efficiency. The grid may or may not be permitted to swing above cathode potential and draw grid power. Better circuit efficiency and higher power output can be obtained with a positive grid, but the input grid power is greatly increased.

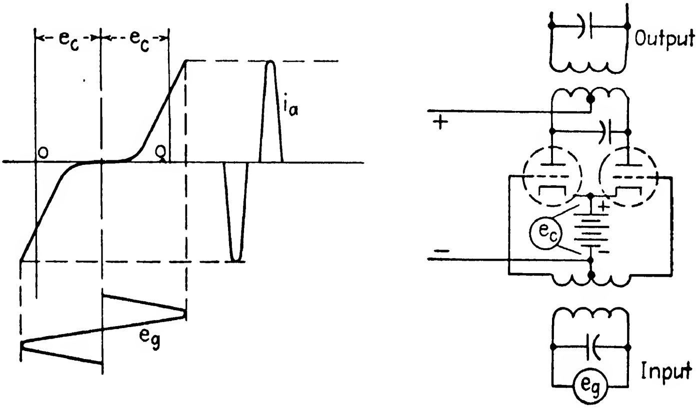

Fig. 13.3. A push-pull Class C amplifier. Note intermittent anode current. A single tube circuit may also be used.

Class C Amplifiers (Fig. 13.3). Class C amplifiers are used when it is desired to obtain the maximum amount of power from the tubes and the available d-c supply. Linearity is not a consideration since the output load is always a resonant circuit whose flywheel effect is sufficient to smooth out the effects of the intermittent power pulses applied. The grids are swung from well below cutoff to well positive, perhaps so positive, indeed, that the potential of the decreasing anode potential is approached. If the frequency of the a-c applied to the grids is correct, the short high peaks of current fed into the resonant load utilize the tubes and d-c supply at maximum efficiency.

Class B and C amplifiers will be found in industrial uses in such services as public-address systems and induction heating.

Direct-coupled Amplifiers. Since it is often not possible to obtain sufficient amplification in a single stage, it is necessary to couple two or more stages together to cascade the effect. The simplest arrangement is the direct-coupled one in which the grid of the second tube is connected directly to the anode of the first. Obviously, then, the cathode of the second tube must be at a potential more positive than that of the first since the anode of the first tube must be positive with respect to its cathode, and the grid of the second tube must be negative with respect to its cathode (Fig. 13.4).

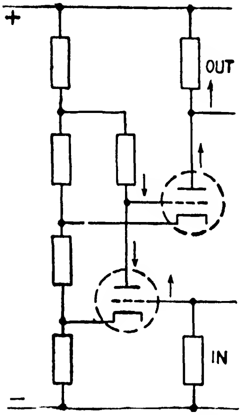

FIG. 13.4. A direct-coupled amplifier.

A properly designed direct-coupled amplifier amplifies faithfully any signal applied to the input, from a d-c voltage change to high radio frequencies, but it has some practical drawbacks. One is the necessary difference in cathode potentials of the succeeding stages. If a number of stages are used, this means that an abnormally high d-c supply is required. Another and more important disadvantage is that unless all cathode-heater and anode potentials are regulated extremely closely there will be considerable drift in the output voltage, so much so in fact that usually not more than two stages of high-gain direct-coupled amplification are practical.

Provisions for stabilizing the amplifier are made by placing a glow tube in parallel with the anode supply to hold it constant, placing a current-regulating or ballast tube in series with the tube heater windings, and feeding rectifier and heater transformers from a closely regulated a-c source such as a voltage-regulating transformer.

The Long-tailed Pair. Another attempt to minimize the effect of drift in a direct-coupled amplifier is the descriptively named *long-tailed pair* (Fig. 13.5). This consists of two matched tubes, in a single envelope if possible, having their cathodes connected to a cathode resistor of rather high value. The anode resistors for both tubes are equal. The grid of one of the tubes is connected to a fixed potential, and the grid of the second tube is permitted to vary with respect to this potential. The output is taken between the anodes of the two tubes. If desired, it may feed the two grids of a second long-tailed pair; or if the circuit is to be used as a vacuum-tube voltmeter, the load may consist of a meter element.

The action of the circuit is as follows: As long as the two grids are kept at the same potential, changes in cathode heating and anode potential in the two tubes should balance and the currents in both halves should change equally, producing an equal change in anode potentials and no loss of circuit balance. However, when the potential of one grid changes slightly with respect to the other, the current in that half, as well as the IR drop in the common cathode resistor, is changed, producing a change in the opposite direction in the other half. For example, suppose the first grid becomes more negative. The current in that half will decrease, causing the voltage across the cathode resistor to decrease, bringing the cathodes down nearer the fixed grid, and thus causing an increase in the current on the second side to stabilize the total cathode current again.

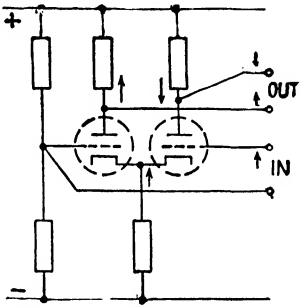

Fig. 13.5. The "long-tailed" pair. (Arrows show direction of potential change if input grid changes as shown.)

The amplification obtained from this circuit is almost that of one of the tubes used in a conventional circuit. It is the basic circuit used in the RCA VoltOhmyst and other similar vacuum-tube voltmeters.

Attenuation Circuits for the Long-tailed Pair. Because of the balanced action of the above circuit, it is somewhat difficult to change its effective amplification without also changing the balance point; however, the two circuits of Fig. 13.6 (nicknamed the "zipper" and "shoestring" for obvious reasons) overcome this difficulty. When the cathodes are no longer tied solidly together, each becomes partially degenerated and its stage amplification becomes less as the *IR* drop in the series cathode resistor subtracts from the effect of the grid-voltage swing. This becomes obvious if we consider the "zipper" opened all the way down to the negative bus so that there is no longer any coupling between the two tubes of the pair.

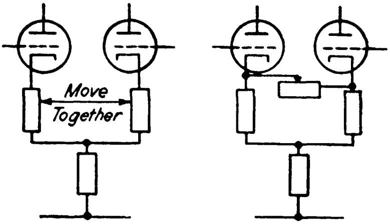

FIG. 13.6. "Zipper" and "shoestring" circuits for attenuation of long-tailed pair.

Cathode Coupling (Fig. 13.7). Sometimes it is desired to increase the power available from a change in grid potential without reversing the polarity. If voltage amplification is not necessary, this can be done by connecting the anode to the positive side of the d-c supply and placing a resistor in series with the cathode. The cathode now varies up and down with the grid, trailing behind just sufficiently to permit the change in grid-cathode potential necessary for the change in cathode current. The output is taken at the cathode potential.

Again it may be desired to obtain both a positive and a negative voltage change of equal value. This can be done by using an anode resistor also equal in value to the cathode resistor (Fig. 13.8). A phase-inverting circuit of this sort might be used to feed the two tubes of a Class B amplifier coupled through capacitors as required to allow for difference in d-c potential. This action is described below.

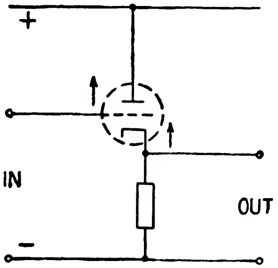

FIG. 13.7. Cathode coupling.

Capacitor Coupling. It has been pointed out (page 148) that the two disadvantages of direct-coupled amplifiers are the effect of drift and the difference in cathode potentials of succeeding stages. Both these defects can be overcome by capacitor coupling if the rate of change of input grid potential is not too low. Capacitor coupling is adapted from direct coupling simply by inserting a capacitor between the anode of the first tube and the grid of the next (Fig. 13.9). So that the stray charges which may be picked by the grid may not charge the capacitor to erratic potentials, we connect the grid through a high resistance to a potential properly negative to its cathode.

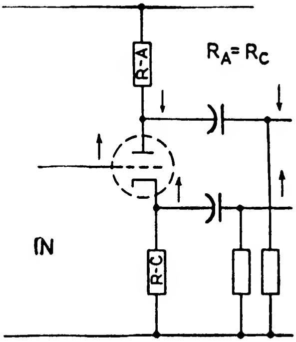

Fig. 13.8. A cathode-coupled phase inverter.

If the capacitor has sufficiently low impedance at the desired frequencies compared with the effective anode resistance of the first tube and the grid resistor of the second, it will lose little of its charge while the anode of the first tube is swinging about its mean potential and will transmit a faithful picture of this change to the second grid. Because the grid resistor is effectively in parallel with the anode resistor of the first tube for anode potential swings and because it also acts as the discharge path for the capacitor, it should be as high as practical, usually about 1 megohm, although it may be as high as 5 megohms in some very sensitive circuits or as low as 50,000 ohms in the case of large tubes.

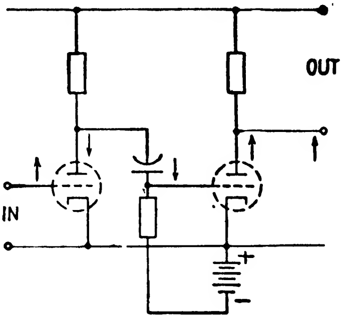

Fig. 13.9. Capacity coupling between stages.

Now that the coupling capacitor insulates the two stages, the second cathode can be placed at any convenient potential, usually the same or nearly the same as that of the previous stage, so that it may use the same d-c anode-potential supply most effectively. Since the potential of the charge on the capacitor has a chance to accommodate itself to the comparatively slow changes in the first tube *anode potential due to drift from any cause, the average grid potential of the second tube becomes that of the fixed end of the grid resistor, and changes due to a slow drift in the first tube are no longer a problem.*

Transformer Coupling. If the range of frequency to be transmitted through the amplifier system is reasonable, transformers may be used to couple the stages (Fig. 13.10). For example, the audio range of 50 to 5000 cycles can be easily handled by a transformer with a laminated iron core. Even wider ranges may be covered by careful design. The transformer coupling has the advantage that, by having more turns on the secondary than on the primary, a gain in voltage may be obtained in the transformer itself. A turn ratio of about 3 is common, although up to 10 is sometimes used.

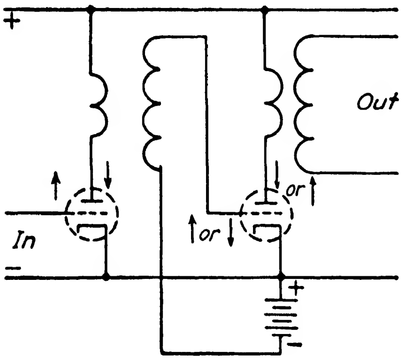

FIG. 13.10. Transformer coupling.

The primary of the transformer and the magnetic circuit must be designed to stand the saturating effect of the direct anode current if the transformer is used with a single amplifier tube. This is not necessary if two tubes are used in a push-pull, or Class B, circuit, for they tend to magnetize the transformer in opposite directions. On the other hand, transformers are relatively expensive and hard to wind for extremely high impedances at low frequencies to match the tube impedances. Therefore, for low-frequency work, capacity-coupled amplifiers using voltage-amplifier pentode tubes have supplanted this type to a great extent.

Tuned Transformers (Fig. 13.11). At high frequencies the situation is different from that described in the foregoing. By combining air-cored transformers and parallel capacitors to tune the two windings to resonance, high impedances for both primary and secondary are obtained, as well as a selective transfer of energy at or near the resonant band. This is the accepted method of coupling radio-frequency amplifier circuits in which usually only a comparatively narrow band of frequencies near the resonant frequency need be passed. In some of the most modern radio frequency transformers it has been found possible to use iron-dust cores to increase the efficiency and reduce transformer size and stray fields.

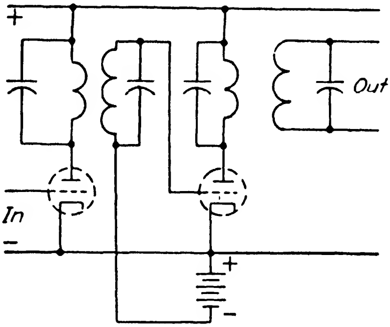

FIG. 13.11. Tuned transformer coupling.

Other forms of amplifier will be found occasionally, such as those using an anode inductance or a second tube as an anode impedance, rather than a resistor. However, these types are so varied and so rare that they will be omitted in this discussion.

Decoupling Means. In a direct-coupled amplifier or one in which very low frequency signals must be transmitted faithfully, the most usual way to obtain the various potentials needed is to tap them off of a resistance voltage divider. However, as the frequency increases to the point where the potential may be held fairly constant over the signal cycle by a practical-sized capacitor, another means is available. A resistor may be placed in series with the cathode of the proper number of ohms so that the *average* current through it produces an *IR* drop equal to the required grid bias (Fig. 13.12). If a capacitor of sufficient size is connected in parallel with this resistance, the cathode will remain

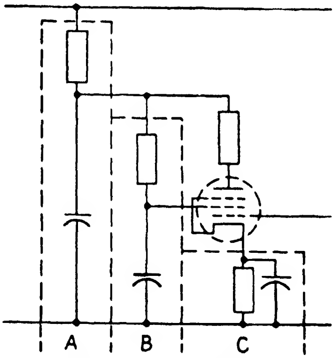

FIG. 13.12. Decoupling resistors and filter capacitors. *A*, stage decoupling; *B*, screen-dropping resistor; *C*, cathode resistor and capacitor.

at a fairly constant potential, even though the instantaneous tube current varies widely. In a similar manner, the current for a screen grid may be obtained by a dropping resistor connected to the positive supply potential, with a capacitor connected across it, or, more commonly, from screen to cathode or negative bus to hold the screen potential steady.

These methods of obtaining potential have two other desirable features. Since the varying tube circuit is connected to the voltage supply only at its positive and negative terminals, there is the least interference with other circuits; and, because of their self-regulating feature, if the whole d-c supply changes, the cathode and screen potentials change with the changing average current values to compensate partly for the supply change. Sometimes, for very sensitive circuits, a dropping resistor and capacitor filter are used to isolate a whole stage from the rest of the circuit and thus shield it from possible voltage surges.

Amplifiers Operated Directly from A-C Supplies. All the amplifiers discussed previously in this section have been supplied with power from a d-c source. Direct current is preferable to alternating current for an amplifier supply for two reasons: (1) A constant-potential source permits the accurate amplification of a wide range of frequencies. (2) When the supply is a-c the varying and intermittent positive potential of the a-c source distorts the instantaneous wave form badly so that only the average value of the individual wave or the envelope of a very low frequency signal may be amplified. Also, because of the extreme power amplification of the thyratron, large voltage amplification on a-c circuits is usually unnecessary.

However, one a-c amplifier has seen much use and is worthy of consideration here (Fig. 13.13). In this the cathode of the first stage is connected to one side of the line and the cathode of the following stage to the other side. The grid of the second stage is connected directly to the anode of the first tube, and a capacitor is placed in parallel with the first tube anode resistor. This retains the grid potential negative with respect to that line which was positive when the first tube was conducting and is negative when the second tube is to conduct. But the capacitor is holding the second tube grid negative with respect to this line, no matter what its relation to the rest of the circuit. Since the second tube cathode is at the potential of this line, its current also is dependent only on the relation of the grid potential to that one point. Thus it follows that, if the first tube is permitted to pass a larger current, the capacitor will receive a larger negative charge and the second tube will be permitted to pass less current when it conducts on the next half cycle. The increase in current in one stage causes an amplified decrease in current in the next stage that is similar to the general action in an amplifier operated from a d-c supply. A third and more stages may be added, although this is usually not necessary.

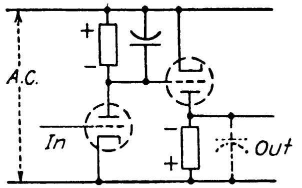

FIG. 13.13. An amplifier on an a-c supply.

A long time constant in the anode resistance-capacitor circuit is desirable for maximum amplification, but it slows down the speed of response.

The Mallory Bias Cell and Mercury Battery. An interesting device for furnishing a small amount of grid bias in sensitive circuits is the *bias cell* made by P. R. Mallory & Co., Inc., Indianapolis, Ind. This small cell is made in two types, having potentials between elements of 1½ and 1¾ volts, respectively. No current can be drawn from them, but when used to furnish negative grid bias they have a very long life and fill a unique need (Fig. 13.14).

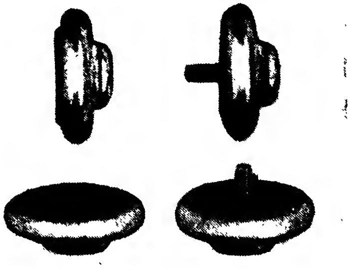

Fig. 13.14. The Mallory bias cell. These small potential supplies have a diameter of less than ½ in.

The Mallory mercury battery is another development which shows promise in industrial electronics. Although designed as a cathode supply for hearing aids, etc., it has been found to have an extremely long shelf life and low internal noise, two fundamental requirements for a voltage-reference standard for regulating systems. For best results the battery reference composed of mercury cells should be used in a cathode-follower circuit wherein no current is drawn from the battery.

Questions

1. Give an advantage and a disadvantage of the Class A, B, and C amplifiers.
2. Sketch a "long-tailed pair" and tell why it is well adapted to fluctuating supply voltages.
3. What is a typical value of voltage amplification from a cathode-coupled stage?
4. Name and sketch three means for coupling a-c signals between amplifier stages.
5. Draw a typical pentode a-c amplifier stage with decoupling by filter circuits for cathode and screen grid.

CHAPTER XIV

TIMING AND WAVE-SHAPING CIRCUITS

RESISTANCE-CAPACITOR TIMING CIRCUITS

The simple process of discharging a capacitor through a resistor connected across its terminals, directly or indirectly, is one of the most useful in industrial electron circuits and as such deserves careful study. Let us start with a typical circuit. One microfarad of capacity is charged to a potential of 100 volts. A resistance of 1 megohm is connected across the capacitor terminals and a record is made, by cathode-ray oscillograph or other means, of the instantaneous voltage across the resistor (or the current flowing through it) as the capacitor is discharged (Fig. 14.1). It will be seen that the potential, starting at 100 volts, first drops sharply and then more slowly, for as it becomes lower it forces less current through the resistance. At the end of 1 second the

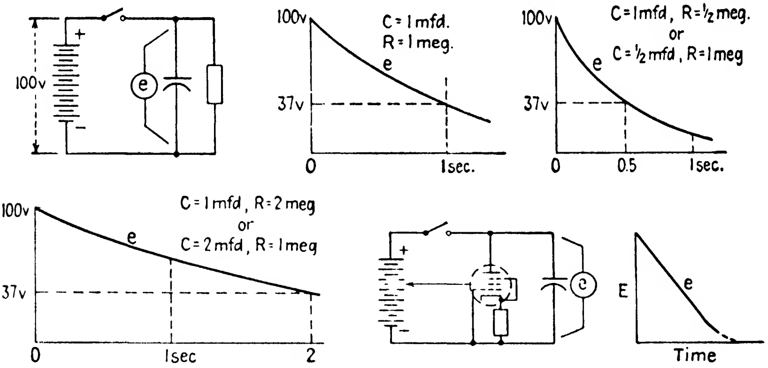

FIG. 14.1. The resistor-capacitor timing circuit.

potential has dropped to about 37 per cent of its original value, or 37 volts; at the end of the next second, the value is 37 per cent of this amount, or about 13 volts. The end of the third second sees another reduction to 37 per cent of this value, or about 4.7 volts. It follows that, no matter when we start our timing, no matter what the original charge on the capacitor, for a combination of 1 μf and 1 megohm the potential will always drop to 37 per cent at the end of a second.

Change of Component Values. Suppose the capacitor is increased to 2 μf and the resistor remains 1 megohm. There will be twice as many electrons to flow through the resistor and only the same potential to drive them; so it may be assumed correctly that it will take twice as long, or 2 sec, for the potential to drop to the 37 per cent value. The same is true if we use 1 μf but increase the resistor to 2 megohms. Twice the resistance means half the current at any potential; so again 2 sec will be required to discharge to 37 per cent. If either the resistance or the capacity is made smaller, say, the resistance is reduced to ½ megohm or the capacity to ½ μf—but not both—the current flow will be doubled in the lower resistance path, or there will be half the electrons to flow. In either case, the time to reach 37 per cent voltage will be ½ sec. If we had reduced both to half value, the 37 per cent point would have been reached in ¼ sec.

The Time Constant.[1] In each case it may be noted that the product of the capacitor in microfarads times the resistance in megohms equals the number of seconds required to reach the 37 per cent potential point. This is a very simple and useful formula and one well worth remembering:

$$C\ (\mu\text{f}) \times R\ (\text{megohms}) = T\ (\text{sec}) \text{ to reach 37 per cent volts}$$

This time is often called the "time constant" of a resistor-capacitor combination.

Another way of expressing the time constant is that time in which the complete voltage change would have taken place if it had continued always at its initial rate (*i.e.*, the intercept to the tangent at the start of the discharge curve).

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[1] A typical voltage decay curve and table will be found in the Appendix.

In the above explanation we have assumed that there were no other potentials present and the capacitor discharged to zero volts. In many cases there will be other potentials present, and the final charge will be not zero but some definite d-c potential. The same reasoning holds whether the final potential is higher or lower than the original charge potential. The time constant is always the time required to change the potential across the capacitor to 37 per cent of the differential voltage between the original and final states (Fig. 14.2).

Variations of the Resistance-capacitor Timing Circuit. The use of a nonlinear resistance in the place of the pure resistance will produce a different-shaped discharge curve. One such circuit is a pentode-tube circuit designed to pass constant current for any value of anode potential. This particular circuit will give a potential-time curve that is a straight line, which makes it a very useful one for the timing sweep on a cathode-ray oscillograph. Other resistors, in series with rectifiers, may be connected to parallel the principal resistor over selected portions of the potential range in order to modify the timing curve, which must then be calculated separately for each portion between discontinuities.

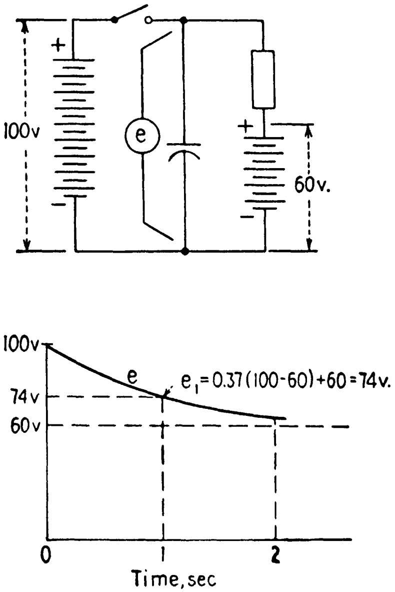

Fig. 14.2. Resistor-capacitor timing circuit. Final volts not zero.

Factors Affecting Accuracy of Timing. The two elements, the resistor and capacitor, are sturdy devices not subject to great change in service; thus, timers based on the fundamental capacitor-discharge timing circuit are reliable and consistent. The care required in the selection of components depends on the accuracy desired. For very accurate work, precision resistors, noninductively wound of low-temperature-coefficient wire and mica, or liquid-filled capacitors are preferable to carbon resistors or electrolytic capacitors. However, all capacitors have a slight dielectric hysteresis effect, which may cause slight errors if the circuit is required to time to a number of times the time constant.

The only other factor influencing the timing is the potential to which the capacitor is charged. Since the discharge in unit time is always on a strictly percentage basis, the final potential is dependent directly on the original potential and will vary in proportion to it. Because most precise timing circuits arrange to discharge toward zero, the final potential is usually fixed at this value and is unaffected by variations in supply voltage. The charging voltage is often held constant by voltage-regulating tubes or similar means, or the control point is made to vary in proportion to the charging potential and thus to compensate for the variation in charging.

The Time Constant of an Inductive Circuit. In a similar manner if the source of energy is applied, or removed, from a circuit having inductance and resistance in series, the time required for the current to reach within 37 per cent of its final value will be

$$\frac{\text{Inductance (in henrys)}}{\text{Resistance (in ohms)}}\ \text{seconds}$$

Relaxation Oscillators. A gas-filled tube may be connected in series or parallel with a resistance-capacitor timing circuit to recharge the capacitor after the discharge has reached a certain

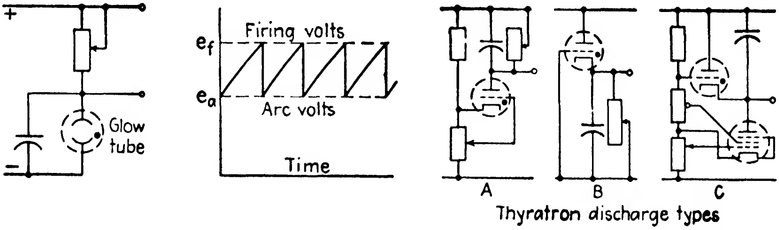

Fig. 14.3. Relaxation oscillators.

potential. After the capacitor voltage has risen to a potential near enough to the supply potential, the arc through the tube can no longer be maintained and the tube ceases to conduct. This permits the discharge through the resistor to begin. If the gas-filled tube is one of the cold-cathode glow type or a hot-cathode phanotron, the discharge will continue until the striking voltage is reached across the tube, when conduction will begin once more (Fig. 14.3). If the tube is a thyratron, more freedom of action is permitted. By adjusting the grid potential the striking voltage may be set over a wide range, or the cathode may be connected to the negative (varying) potential of the capacitor and brought down to meet the grid, which is held at fixed potential.

The relaxation oscillator is useful as a linear time sweep for the cathode-ray oscillograph because of the saw-tooth shape of the potential-time curve, which permits the spot to move at constant speed across the screen and then jump back to the beginning for another sweep. Any cyclic phenomenon applied to the vertical plates and of the same frequency as the oscillator will appear as a standing wave spread on a linear time axis for study.

The relaxation-oscillator output may be amplified and filtered to refine its unusual wave form in order to provide a simple source of a-c power from a d-c source.

MULTIVIBRATORS

Multivibrators are also called "square-wave" or "suicide" circuits. They are two-tube combinations in which the output of the second tube is fed to the input of the first to force it to saturation or cutoff when a critical point has been passed. If each anode transmits its potential change to the grid of the opposite tube through a time-delay circuit, it is clear that the re-occurring suicide action will cause the tubes to conduct alternately to produce self-excited oscillations of essentially square-

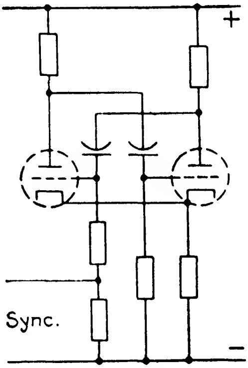

FIG. 14.4. The multivibrator with synchronizing signals.

wave shape (Fig. 14.4). Although the length of time that both tubes conduct may be the same, this is not necessarily so. For example, in some television circuits where this circuit may be used in place of the relaxation oscillator, the difference in time of conduction may be 10 to 1. It all depends on the time constant of the timing circuits.

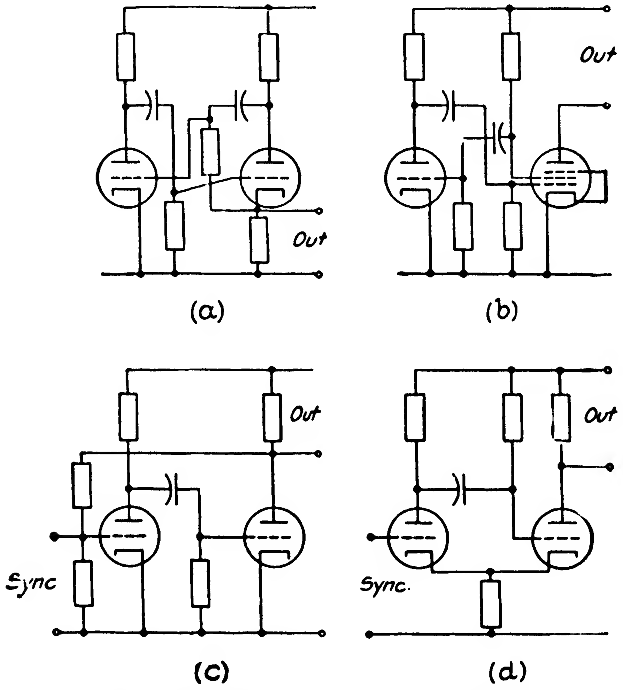

FIG. 14.5. Various forms of multivibrators.

Another feature of the multivibrator circuit is the possibility of applying a small outside potential to one of the grids to assist in holding the oscillation frequency in step with an external signal. Then, as the timing circuit permits the grid of the controlled tube to come near the critical voltage, the small additional voltage from the external signal will cause the tube to trip at the correct time. In this way the multivibrator may be made to run at some subharmonic, say one-fifth or one-tenth, of the tripping-signal frequency. By utilizing a number of stages of multivibrators in this manner, precise low frequencies can be obtained from high-frequency standards such as might be obtained from a crystal oscillator.

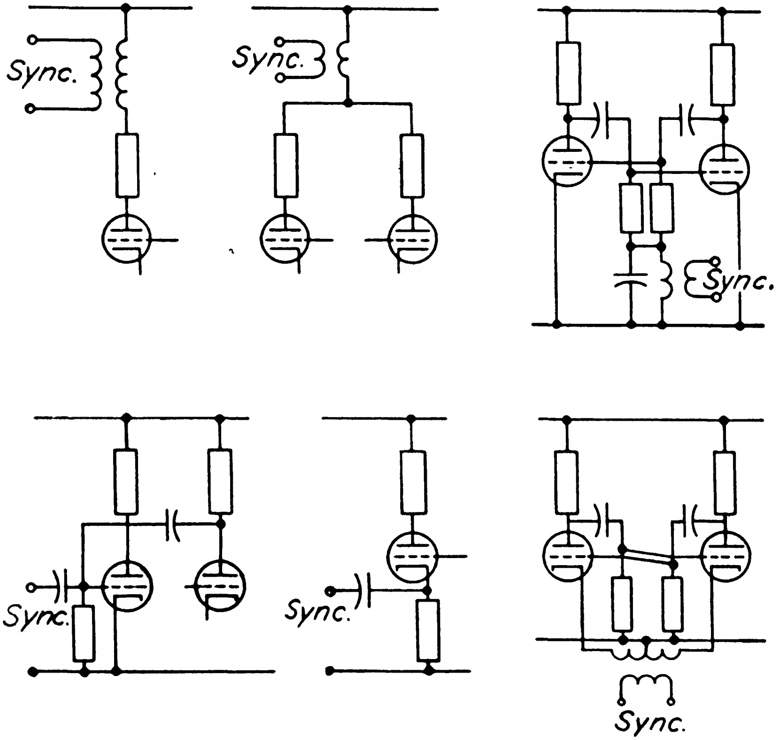

FIG. 14.6. Multivibrator synchronizing means.

As in the case of the relaxation oscillator, the square-wave output of the multivibrator requires considerable filtering to round off the corners if a pure sine wave is required.

Other Multivibrators. Although the basic multivibrator consists essentially of two pliotron tubes having their anodes and grids cross-connected through *RC* time-delay circuits, the exact form may vary widely as seen in Fig. 14.5. In (*a*) the output is cathode-coupled. In (*b*) a tube having a screen grid is used as the second tube, and the drop in its series resistor is used to trigger the first tube, leaving the second anode completely free for other uses. "One-shot" circuits such as (*c*) and (*d*) go through a cycle only once each time a synchronizing signal is received.

Various methods of synchronizing are illustrated in Fig. 14.6. Inspection will show that each circuit operates to permit the "off" tube to begin conduction a little more readily when the synchronizing signal is in the proper part of its cycle.

Counting Circuits, Count of Two, or "Binary." The multivibrator is self-excited and continues to operate at a fairly constant frequency, subject to only a slight delay or speed-up due to the synchronizing signal. Of almost equal importance is a very similar circuit in which the coupling is made direct through voltage dividers, rather than through capacitors, so that an input signal is needed for each transfer of current. This circuit, shown in Fig. 14.7, is extremely useful for high-speed counting. Although it has only two possible conditions or modes of operation, its output can be used to trigger another similar pair in cascade for a count of four. For each pair the count increases as a power of 2. Five pairs, for example, permit a count of 32 in this so-called "binary" system.

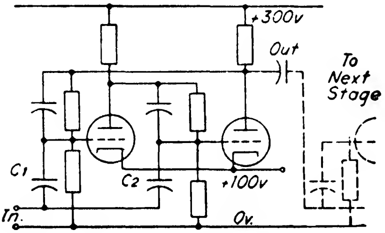

FIG. 14.7. Count-of-two, or "binary," circuit.

The action of each stage is as follows: Assume the left-hand tube conducting and the right-hand tube cut off due to its grid potential being carried sufficiently negative on the voltage divider between the left anode and ground. The input signal is a brief negative pulse, drawing the left grid negative before capacitors $C1$ and $C2$ can change their charge appreciably. A negative left grid decreases the current in the left tube, its anode potential rises, drawing the right grid positive and permitting conduction in the right tube. As the right anode is drawn down, it forces the left grid down further, accelerating the current transfer in a manner similar to that in the multivibrator. The capacitors quickly recharge to the new condition; and the circuit is again stable but with the right-hand tube conducting.

Since the right and left circuits are symmetrical, the next sharp negative pulse will be effective on the right grid only to transfer the current again to the left tube. It is seen that the time constants of the capacitor circuits must be so related to the input-pulse wave shape that the proper grid-voltage swing is attained through the charged capacitor, but the capacitor must be recharged almost up to its new equilibrium condition before the next pulse arrives.

The input trigger pulse for the next stage may be obtained by capacity-coupling the potential change of the right tube as shown in dotted lines. Twin triodes, such as the 6SN7, permit combining the two tubes of one stage into a single envelope.

In large electronic computers pulses as short as 0.1 microsec at frequencies greater than 100,000 per second are used. Sometimes after a count of eight a feedback circuit resets the previous circuits so that two more pulses will trip the next stage, permitting a count of 10, which is better adapted to our decimal system. Small neon lights indicate conducting tubes and permit the count to be noted at any time.

Some variations of the binary counting circuit apply input pulses to the cathodes or to the positive or negative bus, but the basic principle is still that of changing the critical cathode-grid relation of one tube as set up by the charge on the grid-divider capacitors.

Counting Circuits, Count of Three or More. The principle may be extended to a stage having more than two tubes; for example, a ring of five tubes is common. This can be used with a binary pair to give a decimal system. In Fig. 14.8 a ring of three shows the typical circuit. Here note that each anode has a voltage divider to each grid except its own, but its anode is capacity-coupled to only one adjacent grid. The divider resistances are so selected that only two of the three tubes can conduct at once in a stable state. If, for instance, tubes 2 and 3 are conducting, their anodes will be at such a low potential that the grid of tube 1 will be too negative to permit its conducting. However, if the input signal pulse should draw all grids momentarily negative, the combined action of the anodes 2 and 3 will raise the potential of grid 1, causing tube 1 to conduct, lowering its anode potential, and thus driving the grid of tube 2 more sharply negative because of the capacity coupling. So as a result of the pulse, tubes 1 and 3 will be left conducting and tube 2 cut off. As each pulse is received, the tube cut off rotates around the ring.

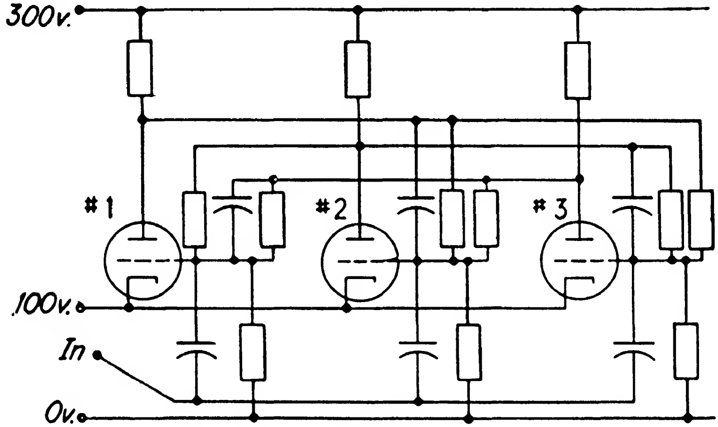

FIG. 14.8. Counting ring of three.

For a ring of five wherein each anode is coupled to four grids, resistors of accurate value must be used for circuit reliability. Numerous circuit variations have been devised to overcome this and other handicaps of the basic circuit. Also in practical circuits, some reset means must be provided. This might, for example, consist in removing anode power momentarily from one tube of each pair in the binary circuit.

Count of Five by Energy Storage. The above counter circuits will count accurately input pulses of completely random time interval and record the count to the last digit. However, if the pulses are occurring rapidly at a fairly equal time interval, a much simpler form of counter may be used. Fig. 14.9 shows a typical count-of-five circuit used in radar and loran timing circuits to count cycles from a crystal oscillator. It operates on the principle of transferring a definite electron charge at each pulse from the input capacitor $C1$ through the rectifier $V1$ to the storage capacitor $C2$. $C1$ is recharged on each negative cycle of the input pulse through the action of rectifier $V2$.

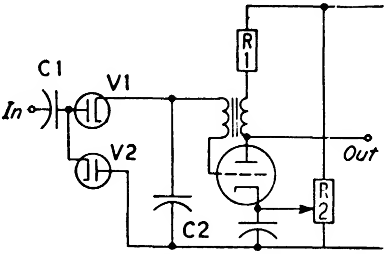

Fig. 14.9. Count by energy storage. A fixed charge from $C1$ is transferred to $C2$ at each count.

When $C2$ has been charged sufficiently to permit the triode $V3$ to conduct, the transformer action between anode and grid circuits drives the grids further positive. The resulting feedback action discharges $C2$ by grid rectification, and the sudden drop in anode potential provides the signal for the next stage.

Wave-shaping Circuits. It has been indicated that the pulse applied to a counting circuit must have a definite shape. In Fig.14.10 are shown typical circuits which might be used to convert a sine wave to the sharp negative pulses suitable for triggering a counter. Circuit A is often called a "clipper" circuit since its anode voltage is so low that the tube is driven from cutoff to saturation during a very small portion of the input wave so that the output is almost a square wave. A protective resistor in series with the grid prevents drawing of excessive grid current as the input signal rises far positive. Clipping can also be obtained without amplification by diodes placed at the upper and lower voltage level desired. The name is descriptive of the clipping, or rendering ineffective, the portion of the input wave outside of the narrow control-voltage range.

The B circuit may take the square wave from A and, by using a very small coupling capacitor, will respond only to the rapid voltage changes, which will be succeeded by a rapid return to normal condition. This results in output pulses alternately positive and negative if the whole of the input wave voltage lies within the grid control range. If the bias is so set that the normal grid potential is at the cathode or above, only the negative grid swings will be effective, while if the grid is normally biased to cutoff, only the positive swings will be used.

The circuit *C* biases the grid to cutoff or below so that only the positive pulses are effective to produce the sharp negative swings needed for counter pulsing.

A Two-tube Pulse-forming Circuit. A pulse-forming circuit using two tubes with feedback is adaptable to almost any form of varying input signal. In Fig. 14.11 we see that it is a cathode-coupled pair with direct coupling through a voltage divider from the first anode to the second grid. The anode resistor of the second tube is less than that of the first tube, and the first grid is actuated by the input signal.

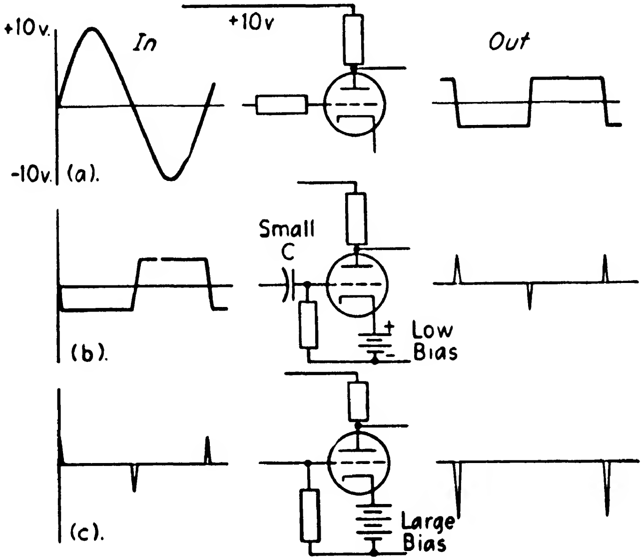

FIG. 14.10. Typical wave-shaping circuits.

Assume that the first grid is so far negative that the first tube is cut off. As the first anode is at maximum potential, the second grid is also at its most positive point. The second cathode (and with it the first cathode) rises slightly above its grid potential as a cathode follower. The second anode is at its most negative potential with full current flowing.

As the first grid rises, whether fast or slowly, it eventually reaches a potential at which tube 1 begins to conduct. Its anode voltage drops, forcing the second grid negative and decreasing tube-2 current. Because of the difference in anode resistors, tube-2 current decreases faster than the current in tube 1 rises, resulting in a net loss of current through the cathode resistor and a slight drop in cathode potential with respect to the first grid. This insures that the current transfer, once begun, will carry on to the limit, producing the square wave. The reverse action occurs when the input grid passes the critical voltage in a negative direction, at which the first tube current starts to decrease. The abrupt changes in potential of the second anode may easily be capacity-coupled to form the input signal to a counter or similar circuit.

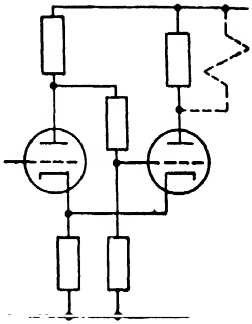

FIG. 14.11. A pulse-forming circuit using two tubes. A positively acting relay may be made by using a contactor coil in the dash-line location.

If the anode load of the second tube is a contactor coil rather than a resistor, an electron relay results which has a definite "snap" action even though the input signal varies quite slowly.

Clamping Circuits. A clamping circuit is one which adds a d-c voltage component to an incoming a-c signal. The incoming signal is introduced through a series capacitor and discharge resistor having a sufficiently long time constant so that there is little loss or attenuation of the a-c signal. If the positive or negative peak or maximum of the a-c signal is sufficiently constant, rectification will permit current to flow each time the a-c wave tends to rise above (or fall below) the set potential. The coupling capacitor will be charged to bring the desired d-c component to the required value. In Fig. 14.12 circuit *A* acts on the positive maximum, while circuit *B* acts on the negative maximum. Circuit *C* is similar to *A* but uses grid rectification and permits amplification with phase reversal in addition to the clamping action.

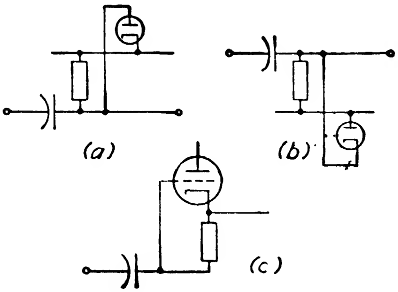

Fig. 14.12. Simple clamping circuits.

If the incoming signal has no consistent maximum or minimum but it is desired that at a definite moment it have a definite potential and change freely from that instant, the clamping circuit of Fig. 14.13 may be used. If the clamping tube permits the grid point, *A*, to rise equal in potential to *B*, the outgoing circuit is clamped closely to potential *B*. This is seen to be true, for if *D* tends to fall below *B* the cathode follower action of tube 2 will cause sufficient electron flow to charge the capacitor *C* quickly to the *B* potential. On the other hand, if *D* tends to rise above *B*, tube 2 will cut off and all of the electron flow from tube 1 will flow into the capacitor, charging it back up to potential *B*.

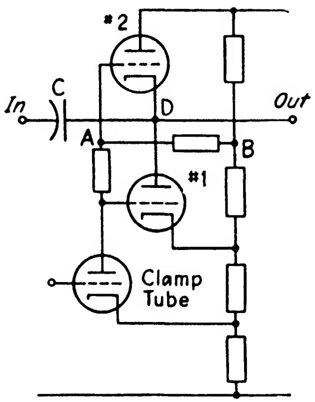

Fig. 14.13. Double clamp with grid release.

However, when the clamping tube conducts to drive both grids below the tube-1 cutoff potential, neither tube conducts and the circuit from *C* to the output is unrestrained.

Gating Circuit, Series Type. A gating circuit may be considered an electronic switch which can interrupt the principal signal at some point along its path. For example, the two-tube clamping circuit (Fig. 14.13) is one form of gating circuit, since when the grids are positive the signal is not effective in the output circuit. The simplest form of gate is a multigrid tube as shown in Fig. 14.14. If the signal voltage is applied to the first grid and the gating signal to one of the other grids, forcing the gate grid far enough negative will cut off the electron flow in the tube and make the first grid ineffective. Such a circuit is often used to check the coincidence of two signals, as for example, the cutter and register mark position in a web register control.

As the anode potential is definite when no current flows in the tube, this circuit is somewhat more consistent than the parallel type of gating circuit described below.

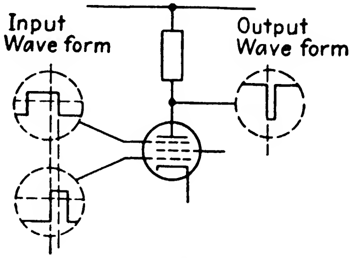

Fig. 14.14. Series gating circuit. No tube current unless both signals are present.

Gating Circuit, Parallel Type. This form of gate uses two tubes with anodes in parallel and a common anode resistor. The gating tube may be a pentode and the signal amplifier a triode as shown in Fig. 14.15. Here the gate grid is held positive or at cathode potential to draw the anodes almost to cathode potential and render the triode grid ineffective. A gate grid negative enough to cut off the gate tube permits the anodes to rise to a potential suitable for proper operation of the signal triode amplifier. This circuit may be used with a much smaller gating voltage swing than the series type above.

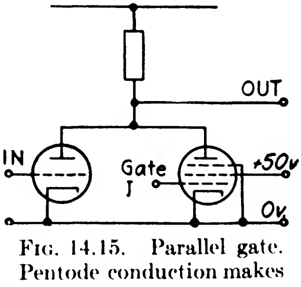

Fig. 14.15. Parallel gate. Pentode conduction makes triode ineffective.

Variations and Combinations. The variations and combinations possible on even these few circuits are endless. It would be impossible for anyone to describe them all. At times circuits will be found in which even the circuits included here will be so surrounded by refinements such as filter and decoupling circuits, etc., that it may be difficult to trace the fundamental circuit. But if a sincere attempt is made to learn the how and why of the functioning of these circuit elements, a long step will have been made toward an understanding of the over-all circuit.

Questions

1. What factors affect the accuracy of an *RC* electron-timer circuit?
2. Determine a capacitor and resistor value for a time constant of 3 sec.
3. Draw a multivibrator circuit indicating a point for application of a synchronizing signal.
4. What is a "binary" circuit? How is it used in a decimal system?
5. Draw a simple clamp circuit.
6. What is meant by a gate circuit?

CHAPTER XV

A-C PHASE-SHIFT AND SWITCHING CIRCUITS

Alternating-current Bridges and Phase-shift Circuits. In the discussion of the fundamentals of the primary elements of resistance, capacitance, and inductance (pages 83–101), the fact was brought out that when an a-c potential is applied to each of these elements the current in the resistance is in phase with the applied voltage, the current in the capacitor reaches its peak values a quarter phase ahead of the voltage, and the current in the inductance lags a quarter phase behind the voltage. We will now see how these phase relations may be used to obtain desired grid-control effects.

Vectors.[1] If we represent the a-c voltage as the vertical projections that a constant-length vector makes when revolving at a constant speed around its axis in a counterclockwise direction, then the current in the resistance may be represented by a current vector lying along the voltage vector, while the current in the capacitor becomes a current vector 90 deg ahead of the voltage vector, and the inductance current by a current vector 90 deg behind the voltage

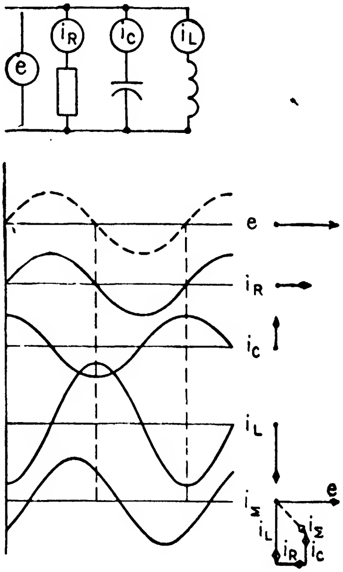

Fig. 15.1. Current vectors in a parallel circuit (*e*, common).

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[1] See summary of vector mathematics in Appendix VI.

vector (Fig. 15.1). The sum of the currents in all three elements may be found by adding the instantaneous values or, more simply, by plotting all three current vectors to the same amperes-per-inch scale and adding the vectors. The graphical addition of vectors is simple. Each vector must be kept its original length and pointed in the original direction but is moved so that all three vectors are touching, tip to base. The sum, or *resultant*, is then one long vector drawn from the base of the last to the tip of the front one; its direction points as the front vector points, not in the reverse direction.

Vectors, Series Circuit. In a series circuit the current is the common factor and hence is the common vector to which the voltage vectors of the potential drops across the elements must be matched. Here the drop across the resistor will lie along the current vector, the drop across the capacitor must lag the current by 90 deg, and the voltage across the inductance will lead the current by 90 deg (Fig. 15.2). The total voltage across the whole series circuit may be found by vectorial addition of the three individual voltages just as the total current was found in the case of the parallel circuit.

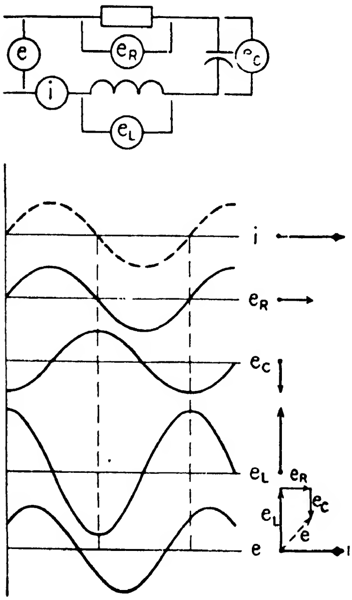


Fig. 15.2. Voltage vectors in a series circuit (*i*, common).

Often the values that are known are the a-c voltage, the frequency, and the resistance, inductance, and capacity of the elements. From the frequency and *R*, *L*, and *C* values the effective impedance of each element to the current flow is found, and, assuming unit current, the vectors are drawn to find the resultant total-voltage vector. By measuring this and dividing the known supply voltage by the number of inches, a volts-per-inch scale can be found by which the individual voltages may be measured. The current can be found by dividing the voltage across any one of the vectors by the calculated impedance in ohms.

This vectorial method of solution may be used to show resonance and other physical phenomena discussed previously, and the reader may find it an interesting exercise to do so. However, the use of vectors is a form of shorthand that must be used with great care in any circuit containing a rectifier. For this reason it was thought more desirable to gain an insight into the actual physical action that is taking place.

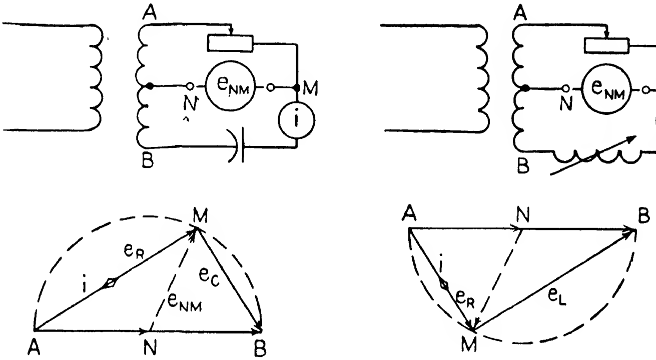


FIG. 15.3. The phase-shift semicircles.

Phase-shift Circuits for Grid Control. The most useful phase-shift circuit combines a series resistor and capacitor or inductance, at least one of which may be varied, and a center-tapped transformer winding. The series circuit is connected across the whole winding, and the output circuit is taken from the center tap and the junction of the two series elements (Fig. 15.3).

Let us consider the value of this output voltage and its vector relation to the transformer-winding voltage. We know that the voltage across the resistor and the other element must be 90 deg out of phase and that their vectorial sum must be that of the transformer winding. From plane geometry it can be shown that the location of the series junction of two voltages at right angles must lie on the circumference of a circle having the total voltage at a diameter. The output voltage becomes a vector from the mid-point of the total-voltage vector to this junction point, so that by variation of the series elements we may change the direction of this vector over a theoretical 180 deg. Since it always extends from the center of a circle to the circumference, it stays constant in voltage. Under practical conditions, if only one of the elements can be varied, the whole 180-deg range is not available.

Some control circuits permit the above-described phase-shift circuit to be used directly in the thyratron grid circuit. In others it is necessary to insert a transformer to insulate the grid circuit or circuits. If this is done, it must be remembered that the transformer is not 100 per cent efficient and energizing the transformer will add a parallel inductive load. Also, any grid current drawn will tend to load up the phase-shift circuit. To keep this grid current at a minimum, a protective resistor is usually placed in series with the grid. This resistance cannot be too high, or a small grid contamination current will cause erratic operation. If a capacitor is connected between grid and cathode to protect the grid circuit from picking up any high-frequency fields, care must be taken that this is kept small so that its charging current is not an appreciable load on the circuit.

A number of the means for varying the impedances of the bridge elements have already been discussed. For manual control a rheostat is the simplest means for changing the resistance. Electronic means for achieving the same effect are inverse-parallel high-vacuum-tube circuits, the series-impedance transformer, and a bridge circuit in which the current on both half waves is rectified to pass through the single tube in the correct direction (Fig. 15.4). A similar bridge circuit is used for a special purpose in the Reliance VSC Drive (see page 265).

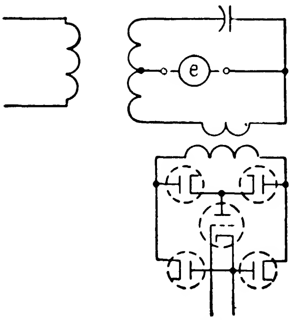


FIG. 15.4. The bisected rectifier square, a single pliotron as an a-c resistance.

Variation of Capacity. Variation of capacity is not easy in the values normally associated with power-frequency circuits. Blocks of capacity may be switched in and out by standard tap switches. At high frequencies or when extremely high impedances are permissible at power frequencies (as in photoelectric circuits), the variable air capacitor of the typical interleaved-plate design may be used. Generally, though, control of phase by change of capacity at power frequencies is subject to too many disturbing factors and is not often used.

Variation of Inductance. Variation of the inductance element is easily accomplished by the use of the saturable reactor previously discussed (page 106). This has become one of the most often used phase-shift means (Fig. 15.5). It has two advantages: (1) The d-c winding in the control circuit is insulated from the thyratron circuit, and (2) the inherent insensitiveness of an inductive circuit to high-frequency transients permits this type of circuit to be unaffected by disturbances that might cause false operation of the thyratrons.

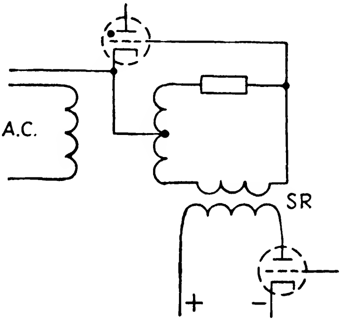


FIG. 15.5. A saturable reactor and a variable inductance to shift grid phase and a typical connection to the thyratron grid.

Although one might think of the saturable-reactor circuit as being slow, the d-c power requirements are small so that most of the d-c supply voltage will appear in the cathode-anode drop of the tube controlling the reactor current. This can force a relatively high effective potential across the reactor when the tube grid calls for a current change. By this means the current can be varied over its whole range in 0.03 or 0.04 sec. Sometimes series or parallel capacitors may be added to the a-c circuit to obtain partial resonance for special control effects.

Phase Shifts from Three-phase Power. If two- or three-phase power is available, we find ready-made those out-of-phase vectors that previously had to be created by the out-of-phase current flow in an inductance or capacitor. If an electromagnetic device is available such as the Selsyn in which a three-phase field may be applied to the stator and an output voltage of any phase relation may be taken from a rotatable secondary, the problem of obtaining a manually adjusted phase shift becomes a simple one (Fig. 15.6). Inexpensive means, such as a potentiometer across one phase, will permit a phase shift adequate for many needs (Fig. 15.7). Of course, any of the phase-shift circuits used with

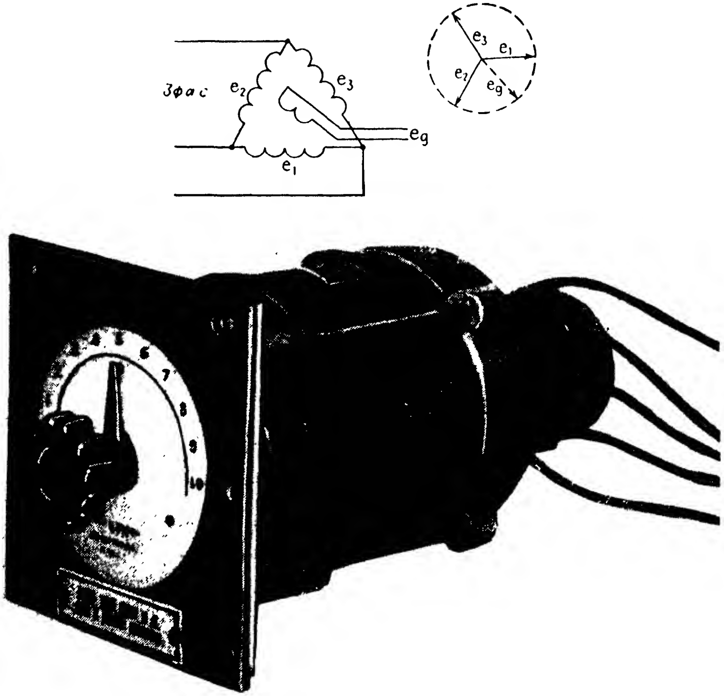


Fig. 15.6. A Selsyn phase shifter from three-phase a-c.

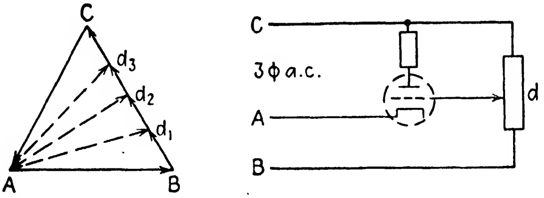


Fig. 15.7. A phase shift obtained by the change in length of a fixed-phase vector.

a single-phase source can be adapted to the three-phase source for greater flexibility.

The Quadrature Phase and Variable D-C Control. The combination of a variable d-c voltage and an a-c voltage lagging 90 deg behind the anode voltage is one of the fastest acting thyratron grid-control circuits available. The a-c portion of the circuit may be obtained in many ways, although the simple resistor-capacitor square is one of the neatest (Fig. 15.8). This may be used with a transformer winding, with or without a center tap. If no center tap is available, the common point is taken from the mid-point of a high-resistance voltage divider across the winding. By reference to the normal phase relations between grid and anode voltages, it will be noted that if the common point is connected directly to the thyratron cathodes the thyratrons are fired at approximately the mid-point of the positive cycle. The addition of a positive potential between the common point and the cathodes will cause the thyratrons to fire earlier, and a negative voltage will cause them to fire later. If the d-c potential is obtained as the anode potential of a high-vacuum control tube, extremely fast control action is possible since there is no appreciable capacitance to charge or inductance current to change.

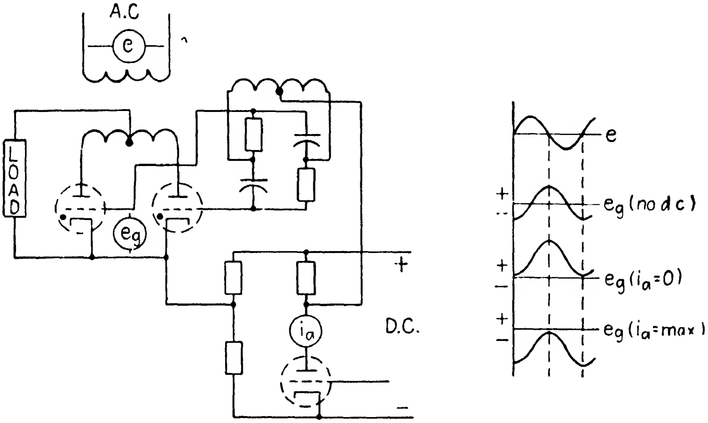
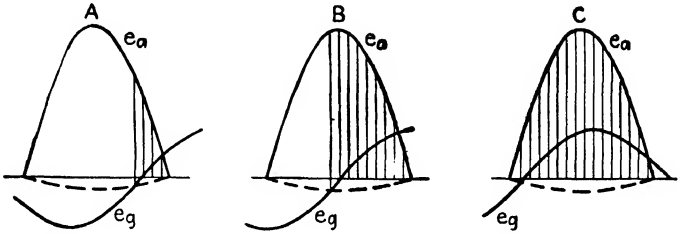


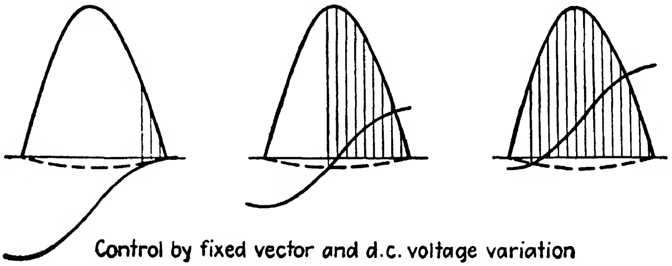
FIG. 15.8. Phase shift obtained by a fixed quadrature lagging phase shift and a variable d-c voltage.

(The quadrature-phase circuit moves as a unit; the only retarding action here is the capacity of its elements to ground.)

In addition to the advantage of speed, this circuit has the advantage for some applications that failure of the control tube will cause the thyratrons to turn partially on rather than to turn off. It has the disadvantage that the control circuit is not insulated from the thyratron circuit; and, unless it is deliberately slowed by the addition of shunt capacitors, it is very susceptible to high-frequency transients. This is especially true near the top and bottom ends of its range where the intersection between the control voltage and the thyratron critical voltage is least steep. [Contrast this with the steep wave front presented by the phase-shift form of control at all times (Fig. 15.9).]



Control by phase shift of constant voltage vector



Control by fixed vector and d.c. voltage variation

FIG. 15.9. Contrast of two forms of thyratron grid phase control. (Note poor angle of intersection between control and critical voltage in lower form.)

Standard Wheatstone bridge circuits, in which one or opposite legs are composed of a nonlinear element, such as a tungsten filament, thyrite, or one of the temperature-sensitive materials, lend themselves well to voltage or temperature-sensitive control of such phase-shift circuits, either directly or when amplified.

Inverse-parallel Kenotron and Pliotron as Resistance Element in Resistance-capacitance Phase-shift Bridge. Another circuit combining phase-shift and d-c components is shown in Fig. 15.10. If the potential of the pliotron grid is at about the mid-point in its range, the pliotron will conduct as much electron current in its positive half cycle as the kenotron and series resistor conduct in the inverse half cycle and the circuit acts as the simple resistance-capacitor bridge on Fig. 15.3.

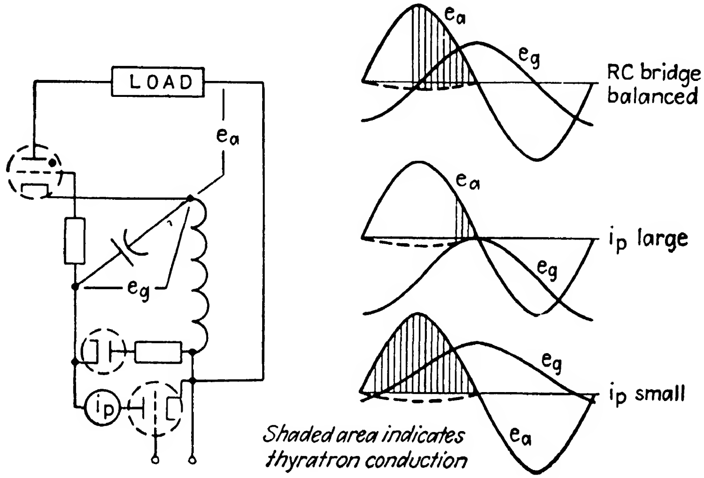


FIG. 15.10. Resistor-capacitor phase shift circuit using kenotron and pliotron as the resistance element.

The size of the capacitor is such that the major voltage vector of the phase-shift semicircle is the effective resistive drop across the tubes. Thus the capacitor reactive drop—which is the thyratron grid voltage—lags the thyratron anode voltage almost 90 deg, even though the thyratron cathode is connected to the end of the bias transformer rather than the midtap (as shown previously).

However, should the grid bias of the pliotron change so that its effective resistance decreases, more electrons will reach the capacitor than are drained by the kenotron on the inverse cycle; so the capacitor will build up a basic d-c charge in addition to the normal ebb and flow of electrons due to the a-c potential. The negative d-c potential on the capacitor is added directly in the thyratron grid circuit and delays the thyratron firing angle. This action is similar to that shown in Fig. 15.8.

In a similar manner, if the pliotron conducts less than the kenotron, the d-c charge on the capacitor will reverse, and the thyratron firing angle will be advanced. (Should the pliotron cease conducting completely, the capacitor would charge up to the positive peak of the bridge winding voltage, but the thyratron will be fully conducting well before this condition is reached.)

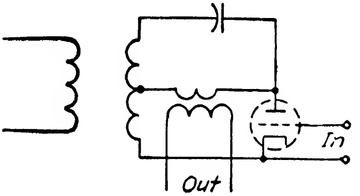


FIG. 15.11. Phase shift by a single pliotron as a resistor (see also Fig. 15.4).

Half-wave Pliotron Rectifier and Series Capacitor to Obtain a Phase Shift. This circuit, shown in Fig. 15.11, has been used for phase shifting in the same manner as the circuits described above, the capacitor discharging through the grid transformer. It has proved satisfactory for a limited phase shift; but its action is difficult to predict, since it is dependent on the stray reactance of the transformer and possible resonant effects.

Series Pliotron-kenotron Phase-shift Circuit. As shown in Fig. 15.12 this ingenious grid-control circuit is used to control two thyratrons in a regulator or motor control supplied by a single-phase full-wave rectifier. It is a variation of the quadrature-lag and d-c shift circuit of Fig. 15.8. The a-c component of the grid voltage is made up of the transformer secondary $4TS$, the resistor $4R$, the capacitors $4C$ and $1C$, and the resistor $3R$. A vector presentation of the voltage distribution indicates that, neglecting d-c effects, the voltages across the capacitors $1C$ and $4C$, and hence the voltage on the thyratron grids, are of opposite phase and lagging the line and transformer voltage by nearly 90 deg. But capacitors $1C$ and $4C$ may be charged with d-c also. This is the function of tubes 4 and $6A$. If pliotron $6A$

is not conducting, the electron flow through kenotron 4 charges 1*C* and 4*C* up to a maximum positive grid voltage, the peak of the voltage across the winding 4*TS*. But when 6*A* conducts, its tube drop is much less than that of 4 and its series resistor 5*R*, so that the net d-c charge on 1*C* and 4*C* is negative. So control of the current through 6*A* controls the d-c charge on 1*C* and 4*C* and the thyratron grid phase.

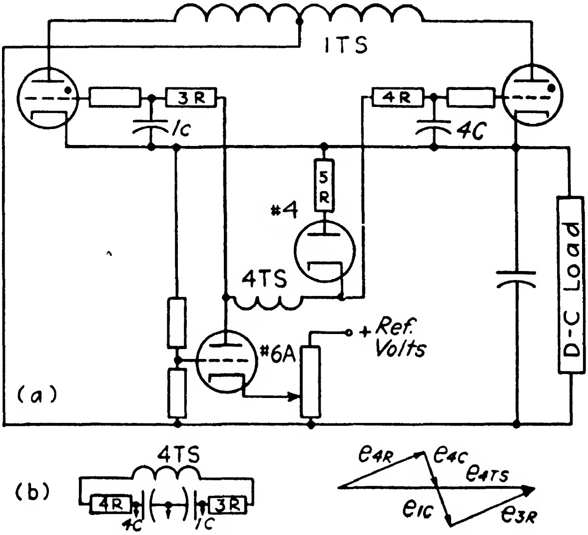


FIG. 15.12. A phase-shift circuit using a kenotron and pliotron in series.

The cathode of 6*A* is connected to an adjustable point on the reference voltage, the grid to a voltage divider across the load. Therefore, as the load voltage tends to rise, the grid of 6*A* rises with respect to its cathode, 6*A* conducts more current, the d-c charge on 1*C* and 4*C* tends to become more negative, and the average load voltage is closely regulated.

This is the basic circuit for the General Electric Co. Thymotrol CR7507F101 and similar controls.

Peaking Transformers. One of the advantages of the phase-shifting control circuit over the d-c quadrature-shift circuit is the steepness with which the control voltage cuts the thyratron critical voltage and thus the consistency with which the thyratron is fired in spite of slight variations in thyratron characteristics due to anode-voltage change, temperature, or slight tolerances between thyratrons of the same type. The steeper the wave front, the more accurate is the firing point; so for those applications requiring the greatest accuracy a special transformer having an extremely steep wave front has been designed. This is the *peaking transformer* discussed on page 105.

Besides its accuracy, another advantage of the peaking transformer lies in the narrowness of its voltage wave. For example, suppose a peaking transformer is superimposed on the slowly changing potential of a capacitor-resistor discharge curve. If the peaking voltage is greater than the discharge potential change over a full a-c cycle, this will ensure either that the thyratron will be fired at the correct point on the cycle or that it cannot be fired again until the following cycle (Fig. 15.13). In precise timing circuits this prevents partial cycle conduction and the inaccuracy due to the poor intersection between the discharge timing curve and the thyratron critical control-voltage curve.

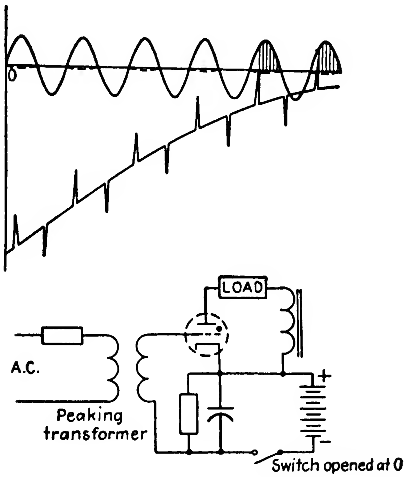


FIG. 15.13. A peaking transformer voltage superimposed on an *RC* timing wave.

Peaking Transformer and Series Out-of-phase Transformers. A typical means for energizing a welding transformer by ignitron and thyratrons is shown in Fig. 15.21. One way to control the grids of these thyratrons to ensure that the welder is operated at the desired phase angle is by a combination of a peaked voltage and an out-of-phase bias voltage in series (see Fig. 15.14). Actually, it is seen that the grid circuit for the thyratrons (one only is shown) consists of the secondaries of three transformers. One is the peaking transformer, *T*1. The primary of this transformer is energized continually from a phase-shift bridge, which may be adjusted to bring the peaked voltage to the desired firing angle

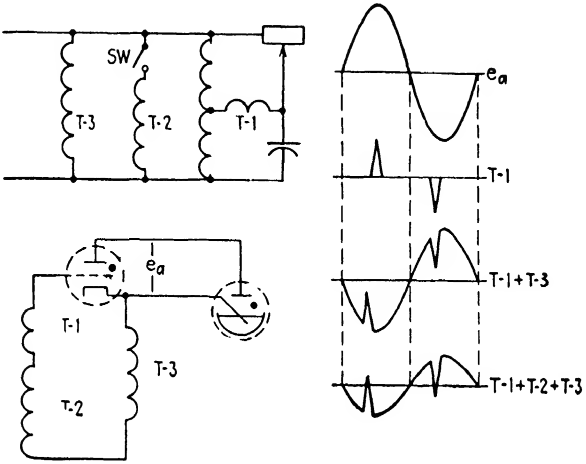


Fig. 15.14. Peaking transformer and opposed-phase transformers in series for welder control. (Only one-half the circuit is shown. See Fig. 15.21.)

(usually somewhere between 50 and 150 electrical degrees). Another secondary is that of the continuously excited out-of-phase bias transformer *T*3, which is of sufficiently high potential to prevent the peaked voltage from firing the thyratron. Finally, there is the in-phase winding of transformer *T*2, which is energized only when a weld is to be made. When this winding is energized, its in-phase voltage—although less than the out-of-phase voltage of *T*3—balances out enough of it to permit the peaked voltage to rise above the thyratron cathode potential and fire the thyratron.

Magnetic-impulse Circuits for Firing Large Ignitrons. This circuit is used to ignite some of the largest pumped-tank type of ignitron rectifiers. It combines the principles of a number of basic circuits just studied but, instead of the usual saturated-core peaking transformer, uses a special saturating-core reactor (Fig. 15.15).

The proper phase range for the firing voltage is first selected for suitable voltage and phase from the three-phase power. This is similar to the action shown in Fig. 15.7.

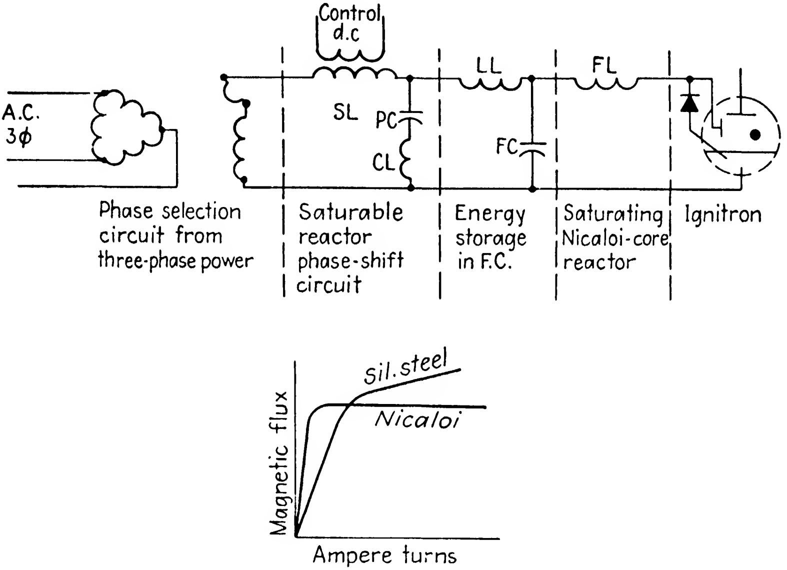


FIG. 15.15. Magnetic-impulse firing of an ignitron.

The voltage thus obtained is next shifted in phase, as the load or output voltage requires, by a bridge circuit composed of the saturable reactor *SL* and the series reactance circuit, the reactor *CL*, and the capacitor *PC*. The action of the use of *PC* and *CL* in place of the resistor permits a greater phase swing and a somewhat better wave form.

The shunt capacitor *FC* acts somewhat as the energy-storage capacitor of the relaxation oscillator of Fig. 14.3, whereas the reactor *LL* acts as a series impedance replacing the resistance of Fig. 14.3. However, since this is an a-c rather than a d-c circuit these components also act as a series reactive circuit so that an a-c voltage appears across the capacitor *FC*.

The saturating-core reactor *FL* is the most essential part of this circuit. Its core is made of Nicaloi or other such magnetic material that has a saturation curve with a very sharp knee and flat top, so that once the circuit has built up to the saturation point the reactance drops to a very low value. (Note its saturation curve in Fig. 15.15, as compared with typical silicon transformer steel.)

As the voltage builds up across the capacitor *FC*, a very small current flows through the high reactance of the unsaturated reactor *FL* and the ignitor, which form a parallel circuit. However, as soon as the current has reached a value sufficient to saturate *FL*, the sudden drop in reactance permits a large surge discharge current to flow from *FC* through the ignitor to fire the ignitron. This is similar to a relaxation-oscillator action, the impedance of *LL* limiting the current after *FC* has discharged. By proper design the time of the discharge current surge can be kept shorter than 15 electrical degrees.

The usual metallic rectifier in series with the ignitor prevents reverse current flow during the inverse half cycle. The auxiliary anode shown in parallel with the ignitor and rectifier is called the "relieving" anode. As soon as ionization occurs and the arc is established, the major part of the ignitor current transfers to the relieving anode, thus preventing heating and injury of the ignitor.

Although the rectifier prevents the inverse current from flowing through the ignitor shown, if there is another ignitron to be fired 180 deg out of phase with this one, the same circuit may be coupled through transformer action to make use of the inverse pulse.

Grid-control Rectifier Tie. The inverse-parallel thyratron control circuit is a useful one, but it imposes a serious problem of grid control since the cathodes are not at the same potential. A circuit has been devised for the phase-shift type of control that solves this nicely (Fig. 15.16). Rectifiers, usually of the metallic, or dry-disk, type, are connected with anodes to the opposite ends of the grid-transformer output winding, and cathodes are connected to each of the thyratron cathodes. In this manner the winding will be effectively tied to whichever cathode is negative, permitting the grid to be fired at the proper time in the normal way while the grid of the opposite tube is held negative. This is true even though the load characteristics may cause the potential between the thyratron elements to be well out of phase with the a-c supply.

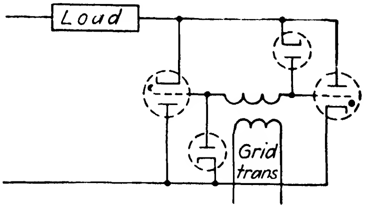


FIG. 15.16. A rectifier tie for a single-grid transformer used with two thyratrons.

A Split-primary Current Transformer for Indication of Rectified Current. For current-limiting control, constant-current operation, regulation proportional to load current, and so on, it is desirable to obtain an accurate insulated indication of the rectified current. This is done in some circuits by means

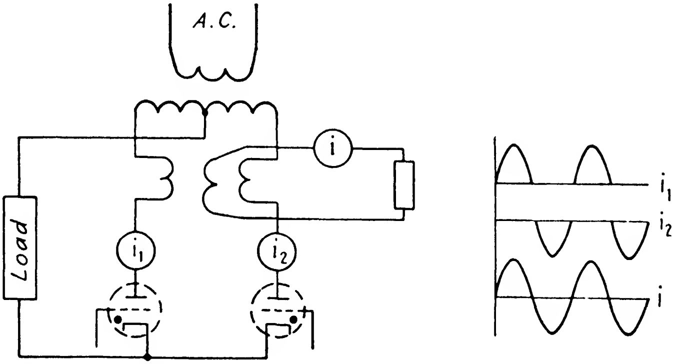


FIG. 15.17. A split-primary current transformer for reading rectifier output.

of a split-primary current transformer as shown in Fig. 15.17. Balanced half waves flowing in the two halves of the primary combine to produce an a-c voltage in the common secondary.

Series Impedance Transformers. A transformer having an open-circuited secondary acts as any iron-cored inductance in presenting a high impedance to the flow of an alternating current. Therefore, if such a transformer is placed in series with a load and the a-c supply, it will permit only a small current to flow. However, if the transformer secondary is short-circuited, the short circuit will reflect a low impedance back to the primary, permitting a much larger current to flow through the load. One way to provide this short-circuit effect is to use two secondaries or a center-tapped secondary and short-circuit each of these on alternate half cycles by two thyratrons (or pliotrons) suitably connected (Fig. 15.18). If the center-tapped winding is used, the result will be the same as that of the biphase half-wave rectifier with a zero load resistance. This circuit places both cathodes at the same potential and simplifies the control of their grids.

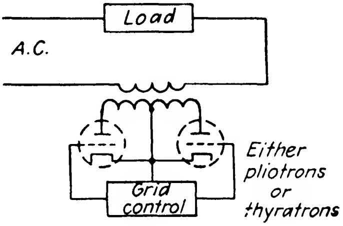


FIG. 15.18. The series-impedance transformer.

There are two advantages and one drawback to the circuit described. As the turn ratio of the transformer may be varied over a wide range, the low-current high-voltage characteristic of the electron tube may be used most effectively to control a low-voltage high-current load. As the thyratron circuit is insulated from the load circuit, the thyratron cathodes may be connected into the control circuit as desired. However, even when no current is flowing in the secondary circuit, the transformer primary impedance is not infinite and the current flowing through the load cannot be stopped completely.

The average effective impedance of the transformer can be adjusted by shifting the grid phase of the thyratron or, on low power circuits, by controlling the grid to vary the current flowing in the high-vacuum tube, if this type of tube is used.

Ignitron Contactors. Two electron tubes connected in inverse-parallel in series with a load comprise the simplest form of electronic switch for an a-c circuit. If the tubes are ignitrons or thyratrons requiring a positive grid for conduction, a simple control circuit may be devised by joining and disconnecting the grids or ignitors (Fig. 15.19). Series resistors are added to protect the

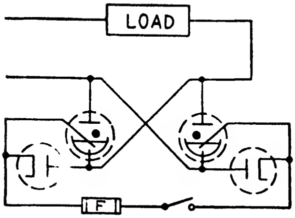


FIG. 15.19. An ignitron contactor (random-phase switching by grid-circuit switch).

thyratron grids, or rectifiers are used to prevent reverse current on the ignitors. The action when the control circuit is closed is as follows: Each grid or ignitor is effectively connected to the anode of its own tube through a rectifier so that, when in the a-c cycle the anode tends to go positive with respect to the cathode, the grid or ignitor is drawn positive, starting the arc and reducing the potential between

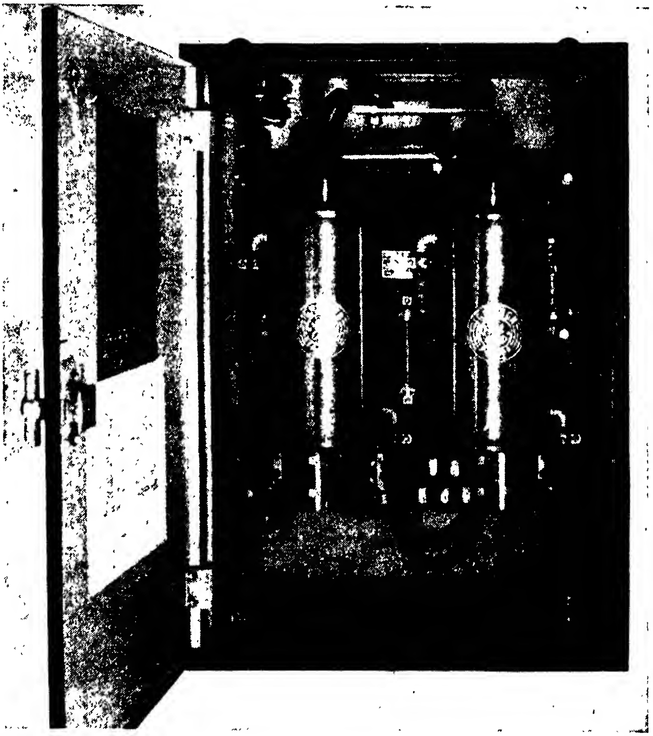


FIG. 15.20. An ignitron contactor using the circuit of FIG. 15.19. (*Courtesy of General Electric Company*)

the grid and the cathode to the arc-drop potential. The grid current drawn at this low potential should not harm the ignitor.

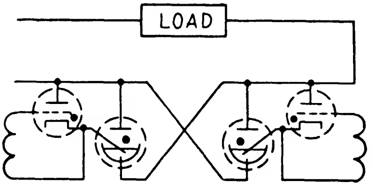


FIG. 15.21. An ignitron contactor. Thyratron firing control through grid transformer.

The above-described simple circuit will permit passage of only full current or zero current. If adjustment of firing to permit current flow over partial phase is desired, it is necessary to control the ignitors with hot-cathode thyratrons added to the control circuits (Figure 15.21 and page 185, Fig. 15.14).

Questions

1. Draw a phase-shifting circuit using a center-tapped transformer, an inductance, and a resistance. Will the phase-shift vector lag more or less as the resistance is decreased?

2. Compare the saturable reactor bridge and the quadrature-phase and d-c phase-shift circuits, giving an advantage and disadvantage of each.

3. Describe the action of an *RC* bridge using a kenotron and pliotron as the resistance element.

4. On what principle is based the magnetic-impulse circuit used to fire ignitrons?

5. What is the advantage of adding a peaking transformer to a phase shift on timing circuits?

6. Draw the circuit for an ignitron contactor with a simple firing circuit.

CHAPTER XVI

OSCILLATOR CIRCUITS

Degeneration and Regeneration. When amplifier tubes were first used, their amplification factor was so low that the most important consideration was that of maximum output per stage. However, with the extremely high gain possible in today's tubes it has been found desirable at times to sacrifice amplification for other qualities, such as fidelity of output. This can be done in two ways. Each stage may be degenerated within itself. The simplest way is to fail to by-pass all or part of the cathode resistor so that the cathode is forced to rise and fall in potential with the grid as the cathode current changes (Fig. 16.1). Again, part of the output power may be fed back in series with the grid potential to neutralize its effect (Fig. 16.2). In each of these actions will be seen the desired effect of increased linearity of response at the expense of amplification.

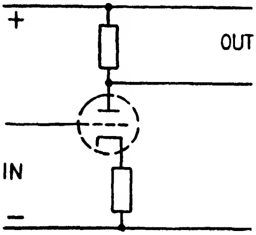


FIG. 16.1. Degeneration (swinging cathode).

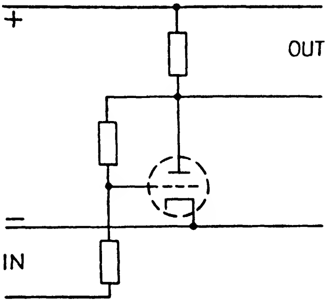


FIG. 16.2. Degeneration (output feedback).

In some laboratory amplifiers intended for precise work the signal may be amplified for a number of stages before a part of the final output signal is brought back to compare with the input signal. For example, if an amplifier has a normal gain of 10,000 but $\frac{1}{20}$ part of the output is brought back to balance out the input signal, the reproduction of the input signals at the output will be accurate to better than 20/10,000, or 0.2 per cent, but the whole amplifier gain will be slightly less than twenty times. The whole subject of feedback amplifiers as closed-cycle control systems is discussed at length in Chaps. XVII and XVIII.

Opposed to degeneration we have regeneration, in which the output is used to assist the input signal. To increase the effect of the input signal is desirable, but the big problem lies in controlling this cumulative effect. If only part of the losses of the amplifier circuit can be supplied, satisfactory operation is obtained, but it is extremely difficult to control the action. An increased input means an increased output, which fed back means a still larger input, a larger output, and so on, until control by the input signal is completely lost and the output-input loop takes the action to its limit. If the amplifier consists of an even number of direct-coupled stages, the result is to cause some stages to pass maximum current while the stages between pass minimum current. If the input circuit can again regain control, causing the current to begin to change after a critical point is reached, the whole current pattern may instantly reverse, causing extremely sharp wave fronts and approximately square waves each time the input signal passes through the critical voltage range.

This *suicide*, or *square-wave, circuit* has a number of useful applications in electronic control since it duplicates in some ways the trigger action of the thyratron. One of the most familiar of these circuits is the *multivibrator*, described previously.

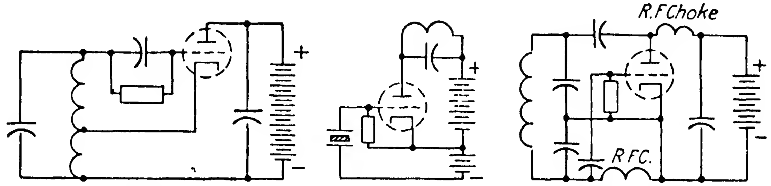
Oscillators. In the discussion of the fundamentals of capacitors and inductances (page 122), it was found that they stored up energy given them so that the input and output energy were not equal at any instant. Now suppose one or both of these elements is added to our regenerative feedback circuit. The impetus added to the input signal may be a little late in becoming apparent in the output circuit (rather than instantaneous, as in the case of a wholly resistive circuit) so that the maximum effect is reached more slowly. However, once it has been reached, the energy stored in the system begins to return. We know that this means a reversal of voltage across the inductance or a reversal of current to the capacitor. This results in a reverse signal's being transmitted to the input; so the grid swings to the opposite extreme. This periodic surging of energy naturally occurs at a fairly constant frequency determined by the values of inductance and capacity in the circuit. Since the circuit is continually supplied with energy from the anode supply at the dictates of the swinging grid, it can continue indefinitely as a sustained oscillation. This type of oscillation may be contrasted to those described earlier (page 94), which were shock-excited damped oscillations and which died out as the original energy was dissipated.

When undesired oscillations develop in a circuit, they can be very annoying. In sensitive circuits special care must be taken to prevent output signals from affecting the input. Decoupling filters are placed between the circuits, and metal shields are placed to prevent stray electromagnetic or electrostatic fields from coupling input and output circuits.

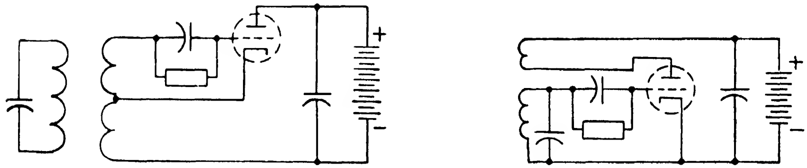
Properly designed, the vacuum-tube oscillators are the most important source of high-frequency power. Some of the most useful oscillator circuits are shown in Fig. 16.3. In all circuits, except the crystal oscillator, it will be seen that the tube output is coupled back in reverse phase to the input by transformer, autotransformer, or capacitor coupling. In the crystal oscillator the only coupling is that within the tube itself. The load is usually coupled to the anode inductance.

Two details are of especial interest. The resistor-capacitor parallel circuit in series with the grid draws grid current and charges up when the grid tends to go positive, thus holding an automatic grid-bias potential at an efficient point. The crystal in its specially constructed holder acts as an extremely sharply tuned resonant circuit, which, when the crystal is cut carefully in a special way and is kept at a constant temperature, permits the circuit to oscillate at an almost unbelievably constant rate, never varying more than a few parts in a million. The frequencies of the other circuits may be changed easily by adjusting the capacitors or inductances and will drift slightly as the components change temperature. Sometimes this drift is minimized by special capacitors whose dielectric changes its characteristics to oppose the changes in the rest of the circuit.

The mechanical analogy of the electronic oscillator is the action of the balance wheel of a clock or watch. The hairspring in its state of tension, distended alternately in both directions from neutral, corresponds to the capacitor and its electrostatic stress.



Hartley Crystal Colpitts



Meissner Feedback oscillator

FIG. 16.3. Common oscillators used to generate radio frequencies.

The balance wheel, started rotating by the spring tension, is carried by its inertia and stored kinetic energy past the neutral point and tenses the hairspring in the opposite direction. And finally the pawls and escapement are timed in sequence with the movement to apply power from the mainspring potential-energy source at the proper instant to replace the friction (resistance) losses, or work, occurring during the cycle.

Although most oscillators are of the usual resonant-circuit type, there are two of a different kind that may have some use in industrial circuits. The first, used in low-frequency oscillators, is the so-called *resistance-capacitor* (*RC*) *type* (Fig. 16.4). It works on the principle that, if in a series circuit, a resistor and a capacitor are connected across a potential, the voltage drop across the resistance will be advanced in phase and the voltage drop across the capacitor will be retarded. If, then, a second *RC* series circuit is connected across this first capacitor potential, the relation of its capacitor potential to the original potential will be even more retarded. If this process is carried through a number of times, the final capacitor potential will be a full 180 deg away from the original potential, so that if the first potential is that of the anode of a tube and the resulting voltage is applied to the grid of the same tube we have the ideal condition for an oscillating circuit, the frequency of which is that at which the capacitor and the resistor have the proper ratios of impedance for the 180-deg shift. The frequency can be adjusted by changing either the capacity or the resistance of each element.

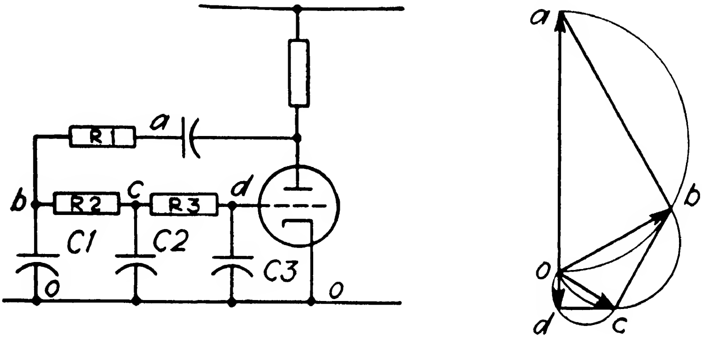


FIG. 16.4. A resistance-capacitance oscillator.

For example, if at a certain frequency the impedance of the capacitor is equal to the resistance of its adjacent resistor and the loading of succeeding stages may be neglected, the voltage across the capacitor will lag 45 deg behind the input. Four such stages will add up to 180 deg. Since the vector length decreases to 0.707 of the input each time, an initial amplification of at least four times is required for oscillation. On the other hand, if the impedance-resistance ratio is such that each phase lag is 60 deg, phase reversal, or 180 deg, will be reached in three stages but an amplification of eight is required. These are theoretical amplification minimums; the loading due to succeeding stages will always demand more.

The Parallel-T Oscillator. This oscillator makes use of degenerative feedback between two tubes for all frequencies except the one greatly attenuated by an *RC* network known as a parallel-T network, which is shown within the dotted line of Fig. 16.5. Like the *RC* oscillator above, it is useful for very low frequencies since it contains no inductive elements.

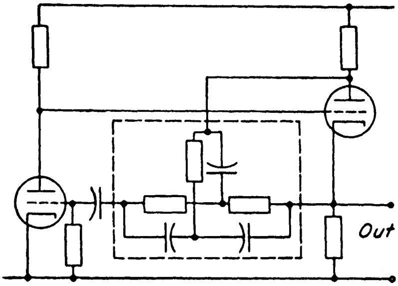


FIG. 16.5. The parallel-T oscillator. Low impedance from anode to grid for the desired frequency and from cathode to grid for other frequencies.

The Negative Transconductance Oscillator. This unusual type depends on a unique feature of a pentode tube (Fig. 16.6). The total electron current to be collected by both screen and anode is controlled by the first grid, so that if this grid potential is constant the total current is relatively constant. If the suppressor (No. 3) grid is used as the control grid, it will be noted that as it becomes *negative* the electrons are impeded in their flight to the anode and naturally flow to the screen, *increasing* the screen current. Thus, we have only to connect the screen as the output element and couple it by a capacitor to the suppressor grid in a suitable resonant circuit to fulfill the conditions of an oscillator. This is not an efficient oscillator, but it has interesting possibilities for some applications.

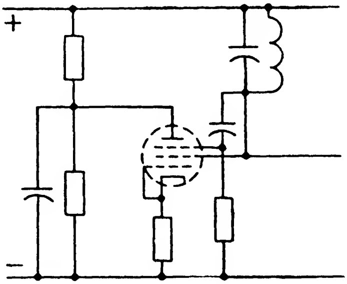


FIG. 16.6. The negative transconductance oscillator.

Thyratron Inverters. If the vacuum tubes in the multivibrator (Fig. 14.4) are replaced with thyratrons capable of carrying heavy currents more efficiently, we have the elements of the typical parallel inverter circuit for converting d-c to a-c. The anodes of the two tubes feed into the two ends of the center-tapped primary of the load transformer (Fig. 16.7). Since the thyratrons cannot be extinguished by driving the grids negative, it is necessary to force the anode potential below the arc potential and hold it there long enough for the tube to deionize. This is done by connecting a fairly large capacitor between the two anodes. The anode of the thyratron that is conducting will, of course, be at a lower potential than the anode of the nonconducting tube, and the capacitor charges up accordingly. Then, as the second thyratron is caused to conduct, the potential of its anode is lowered and, by its connection through the capacitor, forces the first anode negative while the capacitor discharges. While the anode is negative, the thyratron ceases to conduct and has a chance to deionize. The capacitor rapidly reverses its charge and is ready to repeat the operation on the second tube when the first is again fired. The primary current in the transformer primary, flowing alternately both ways to the middle, produces an alternating voltage in the secondary and permits an alternating current to flow in it. However, because the load current is reflected back into the primary, the load must be known fairly accurately for proper inverter design. There must always be sufficient capacitor effect (leading power factor) to permit commutation and deionization.

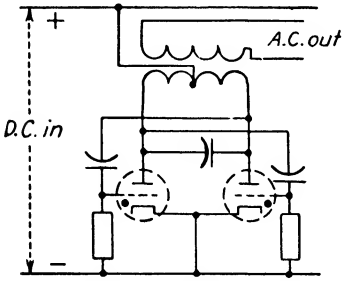


FIG. 16.7. A parallel-type thyratron inverter.

The timing of the grid firing, which determines the frequency of the a-c output, may be obtained from the tubes themselves as in the case of the multivibrator, or it may be obtained from an external circuit. Since the deionization time of a thyratron is comparatively long as expressed in microseconds, the output frequency of an inverter is limited to a few hundred cycles even with thyratrons designed for rapid deionization.

High-frequency Heating. Perhaps the most extensive use of high-frequency power in industry is for heating. It is very expensive for the actual amount of heat produced, since it has been estimated that 1 calorie of high-frequency heat costs as much as 1000 calories from coal. But high-frequency heat is unequaled in the accuracy with which the heat can be controlled as to intensity, timing, and area of application.

The field of high-frequency heating may be divided into two parts, the induction heating of metals or other conductors, and the dielectric heating of insulating materials. These are suggested in Fig. 16.8.

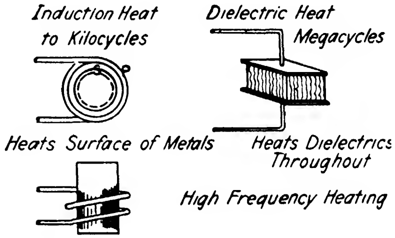


FIG. 16.8. High-frequency induction and dielectric heating. The material near the surface of the metal S acts as a transformer secondary coil for the primary coil P.

Induction Heating. For induction heating a coil carrying the high-frequency power is placed around the metal part to be treated so that the part lies in an intense alternating magnetic field. Eddy currents are set up in the elemental secondary loop within the metal surface by transformer action, and the RI^2 power loss appears as heat in the metal.

As the frequency increases, higher effective voltages and currents are induced near the metal surface so that at frequencies in the order of kilocycles the actual current necessary to balance the magnetic-field induction extends only a few thousandths of an inch below the surface. Thus, this form of heating, in which the surface can be brought to a high red heat quickly and quenched immediately, is ideal for operations such as surface-hardening shafts or gear teeth to produce a good wearing surface while permitting the interior to remain tough and flexible. A typical application and fixture is seen in Fig. 16.9.

Completely automatic operation may be obtained by a conveyor system to present the part within the coil, and timing and sequence control, often electronic, to apply the proper amount of heat and then to turn on the water from a spray ring surrounding the heating coil.

Other interesting uses of induction heating are heat applications for automatic soldering and brazing, and the flow brightening of electrolytic tinplating, in which the temperature of the dull tinned surface is raised above the melting point to flow to a bright, continuous surface.

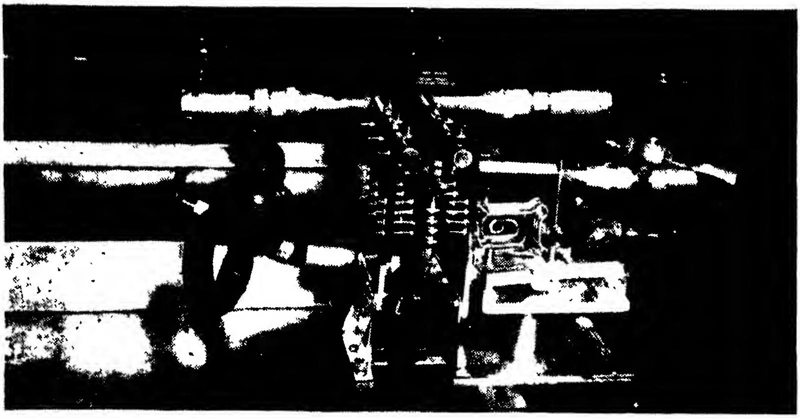


FIG. 16.9. An induction-heating application. The ax edge is heated and quenched to obtain the proper hardness.

For heating of large pieces with some heat penetration 60-cycle frequency is sometimes used, but frequencies of 1 to 10 kilocycles from rotating equipment or ignitron inverters are more common. For minimum penetration pliotron oscillators are employed. Frequencies of over a few hundred kilocycles are rarely used, however, because while higher frequencies would limit the heat production to a thinner layer, thermal conduction within the metal carries the heat inward so fast that there is little practical gain at the higher frequencies.

The high-frequency power is most often supplied by a Colpitts oscillator obtaining its d-c from an unfiltered one- or three-phase double-way rectifier.

Dielectric Heating. The heating of dielectric or insulating materials by high-frequency power depends on the heat due to the intermolecular friction within the material as it is subjected to the rapidly changing electrostatic field. So, in order to obtain the maximum heating with the minimum applied voltage, the highest economical frequency must be used, and dielectric heating frequencies are in the megacycle range. Multicavity magnetrons and klystrons are sometimes used.

As the heat in the dielectric material is due to the stresses set up within the material rather than to eddy currents at the surface, the heating is uniform throughout. This is something very difficult to accomplish by other means in which the heat is applied externally since most dielectrics are poor heat conductors.

For example, the preheating of plastic material before moulding (see Fig. 16.10) may be done in seconds by high frequency, whereas to bring the interior of the material to the same temperature in an oven would take much longer. Indeed, for some materials the surface might have been prematurely cured and unusable before the center reached the desired temperature.

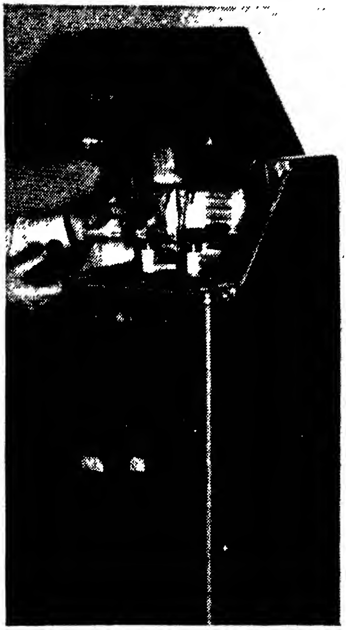


FIG. 16.10. Dielectric heating of plastic preforms.

Other popular applications are the setting of glue in furniture and plywood and the fast defrosting of frozen foods.

Questions

1. What is meant by degenerative coupling and what is its usual purpose?

2. Name and sketch three types of high-frequency electron-tube oscillators.

3. What is the principle of the *RC* oscillator?

4. What two fundamental laws must be met by any oscillator?

5. Draw a negative transconductance oscillator and explain its principle of operation.

6. What special precaution must be taken in the design of a thyratron inverter?

7. Name the two most useful types of high-frequency heating and give two applications of each type.

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Section IV

CLOSED-CYCLE CONTROL SYSTEMS

CHAPTER XVII

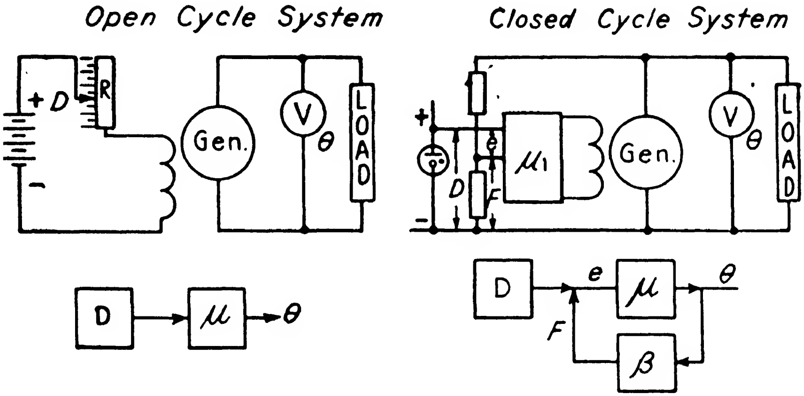
REGULATING OR CLOSED-CYCLE CONTROL SYSTEMS

Control systems may be divided into open- and closed-cycle systems. In both cases there is a controlling independent variable, usually designated by the letter "D," which is the system input. The output or controlled variable is usually represented by the Greek letter "θ." (These come from wartime gun-laying and radar-control practice where D was the director and θ the angle turned.)

Open-cycle System. In an open-cycle system there are control elements which amplify the power of the input D to control the major power elements to vary θ as desired. The over-all gain in amplification between D and θ is designated by μ (mu). This Greek letter was also used for the voltage amplification in a pliotron, but in this case μ is a comprehensive term including variations and lags which may occur throughout the system.

An example of an open-cycle system might be a generator with a field rheostat for voltage control. The position of the rheostat knob is the independent variable which the operator changes when he wishes to vary the dependent variable—that is, the output voltage. For a given knob position, the voltage may also vary because of changes in exciter voltage, generator speed, load current, and other factors. In an attempt to maintain a constant voltage, the operator must be eternally vigilant to note any changes in the voltmeter reading and to manipulate the knob to correct the error.

Closed-cycle System. In a closed-cycle system automatic means are used to replace the action of the operator. A signal F, indicative of the condition of the controlled variable, is returned to be compared with the D signal to find if the controlled variable has the desired value. The D signal now becomes a reference, and the input to be amplified by the control elements is the difference between D and F, known as the actuating, or error, signal and represented by e. The whole circuit path between θ and F is called β (beta). This, like μ, may be a variable containing time lags, although usually it is a fixed ratio, often unity. To take a voltage regulator as an example, the reference D may be a glow tube, the feedback voltage F taken directly from the output voltage by means of a simple β circuit consisting of a voltage divider.



Open Cycle System

Closed Cycle System

FIG. 17.1. Open- and closed-cycle systems.

Note that F must always be of the same form as D, in this case a voltage. Hence, for other systems in which θ might be position, speed, current, temperature, pressure, etc., if D is volts, the β circuit must translate the output into volts for comparison with D. If D had been a weight or a spring tension, F might be a magnetic pull or a hydraulic pressure on a bellows to be balanced against D.

Block diagrams of the open- and closed-cycle systems in Fig. 17.1 may make the difference clearer. Since electronic amplifiers and stabilizing circuits are playing an ever increasing part in the operation of high-performance regulating systems, a basic knowledge of their operation is very important to the industrial electronic engineer.

Equations of the Regulating, Closed-cycle System. Simple mathematics will help point out the important features of a regulator. From the relations described above, we know

$$D = e + F$$

$$\theta = \mu \times e$$

and

$$F = \beta \times \theta \quad \text{or} \quad \mu \times e \times \beta$$

so that

$$D = e + \mu e \beta$$

If we next divide θ by D, we have

$$\frac{\theta}{D} = \frac{\mu e}{e + \mu e \beta} \quad \text{or} \quad \frac{\mu}{1 + \mu\beta}$$

This means that the ratio of the controlled variable to the independent variable input is

$$\frac{\theta}{D} = \frac{\mu}{1 + \mu\beta}$$

With electronic amplification it is possible to make μ quite large so that we may replace $1 + \mu\beta$ by $\mu\beta$. Then

$$\frac{\theta}{D} = \frac{\mu}{\mu\beta} \quad \text{or} \quad \frac{1}{\beta}$$

This tells us two things. If μ is large, it may vary widely in value because of voltage and tube changes, generator field heating, speed, etc., without greatly affecting the θ/D ratio. On the other hand, any change in the β circuit is reflected immediately in the θ/D ratio. Note that this ratio is inversely proportional to β. If β is 2, θ will be one-half of D. If we wish to hold 250-volts generator output with a 150-volt glow-tube reference, β becomes 0.6.

Simple mathematics also shows us that the ratio of the change in output θ which will take place with a change of D in a closed-cycle or regulating system to that occurring in an open-cycle control system is $1/(1+\mu\beta)$. In return for this superior performance, we must provide a much larger value of μ in the closed-cycle system.

Limitations in Possible System Amplification. Since everything so far has indicated that a higher value of μ gives better performance, the question arises as to how high μ may be raised in a practical system. The answer is not a simple one and depends very much on the speed of response required from the system. No system can respond immediately to the director or error signal. There are always places where energy must be stored, such as in the inductances of magnetic fields, the inertia of rotating and moving parts, circuit capacitances, etc.

To consider the effect of this energy storage, let us return a moment to a circuit studied previously—the *RC* oscillator of page 195. There we found that the energy stored in a series of capacitors caused the signal to lag until, if there were three or more lag stages, the signal had lagged a full 180 deg before it returned to the input grid. Further, if the tube and network amplification, or $\mu\beta$, was sufficiently great so that the returned signal was equal to the initiating signal, the circuit became an oscillator.

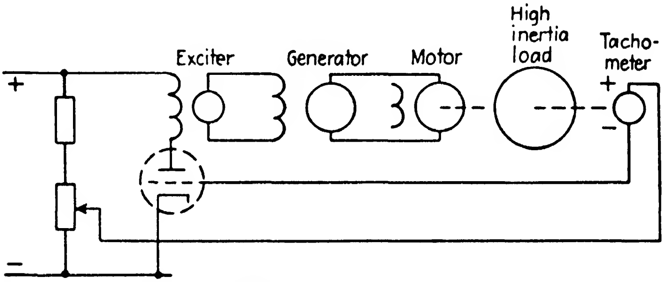


FIG. 17.2. An electronic speed-regulator system quite likely to oscillate because of lags in the exciter and generator field response and to the high inertia load.

The Closed-cycle System as an Oscillator. A glance at a closed-cycle regulating system having a high value of μ and a number of lags, such as Fig. 17.2, indicates that it is quite similar to the *RC* oscillator and under proper conditions will itself oscillate, or "hunt." This occurs if its feedback signal F becomes reversed in phase because of system lags and is equal in value to the input error signal e. Thus, while it is relatively easy to obtain a highly accurate output ratio of θ/D by increasing μ, to attain that accuracy and still have a system which is stable and does not tend to oscillate is an engineering problem of serious aspect. Obviously, the first step in attaining a stable system is to limit the value of μ to as low an amount as is consistent with the required results.

The Nyquist Approach to Stability Studies. In the 1930's Dr. H. Nyquist and his associates in the Bell Laboratories developed an approach to the study of system stability which is basically simple and straightforward and eliminated much of the tedious mathematics previously necessary. Previous methods had applied a sudden change to the independent variable D and, by advanced mathematics, determined the resulting change in the controlled variable θ. The change of any circuit constant required a complete new set of calculations.

In the Nyquist approach, instead of attempting an over-all solution immediately, the solution is split into a number of steps.

The Nyquist Diagram for Loop Gain. The first step was the opening of the loop at the D, F, e junction and treating the $\mu\beta$ circuit as an open-cycle system. An actuating signal e is applied which consists of a small sine-wave a-c voltage of constant amplitude and variable frequency (see Fig. 17.3). For each frequency the amplitude and phase angle of F in relation to e is determined. This may be done either analytically or physically. The magnitude of e is presumed small enough so that nonlinearities of the system are not appreciable. Values for a sufficient number of frequencies are taken so that a plot of the F-vector loci will be a smooth curve from very low to very high frequencies. A typical curve for F, called a Nyquist diagram or plot, is shown in Fig. 17.4. The relation between F and e, the complete story of a sine-wave signal through the $\mu\beta$ system to the controlled variable and back through the feedback path, is often called the "loop gain."

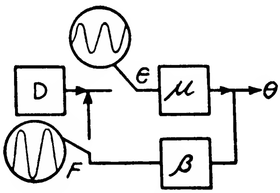


FIG. 17.3. The Nyquist approach. F is compared in phase and magnitude to e as the frequency is changed.

Closing the Loop. Having found the relation between F and e for any frequency for an open loop, the next step is to study the effect of this combination of components as the loop is closed into a closed-cycle system.

One of the fundamental equations of the closed-cycle system is

$$D = e + F$$

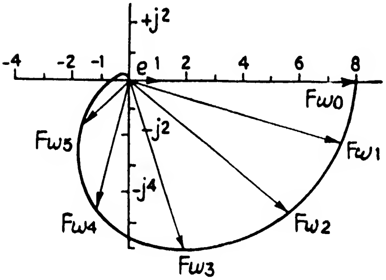


FIG. 17.4. A typical Nyquist plot.

If we limit ourselves to sinusoidal signals as Nyquist does, D becomes simply the sum of the two vectors e and F. For the Nyquist plot of F/e we assumed e to be a real positive-unit vector, and the length of F in the same units with its phase relation was plotted for a range of frequencies. To determine D, therefore, we have but to add the constant-unit vector e to F as plotted and draw the resultant D for any desired frequency. This can be done by placing the unit vector with the tail at -1 and the tip at the origin on the Nyquist plot. Values for F and D for two frequencies are seen in Fig. 17.5. The triangle thus formed is the key to the whole Nyquist approach. Its shape is fixed for a given system and frequency. Its size, assuming linearity, is known if we know the length of any vector. We began by considering e as a unit vector in the open loop, but more often in practice the known vector is the reference or independent variable D which sets the triangle size. Also, we are usually more interested in the relation between D and F, the independent variable and the feedback signal, which is usually closely associated with the condition of the controlled variable, than we are with the error signal.

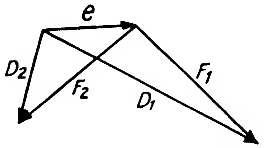


FIG. 17.5. The Nyquist triangle at two frequencies.

The Closed-cycle System as an Amplifier Element. Later we shall find that the closed-cycle system may itself become a series-amplifier element of a larger system. When this is the case the

F/D ratio and phase angle must be used as the transfer (or output/input) function through the closed-cycle element under consideration. See Fig. 18.15 for a typical example of such an over-all system.

Relation between F and θ. Once the triangle shape and size are known, the value and phase angle of *F* are known and from this θ may be found. However, in most stability studies, if the β circuit is assumed a fixed constant, the θ vector lies along the *F* vector but is of different length, so we find it most convenient to deal with the *F* vector directly.

Zero Frequency Response, Type 0 Systems. We shall call a Type 0 system one in which for zero frequency the *F* vector lies in the same direction as the *e* vector. Then *D* must also take this direction, as in Fig. 17.6. A study of this simple relation makes it plain that *F/D* can never be unity, that is, *F* can never follow *D* exactly, although as $\mu\beta$ is increased the discrepancy due to *e* may become very small.

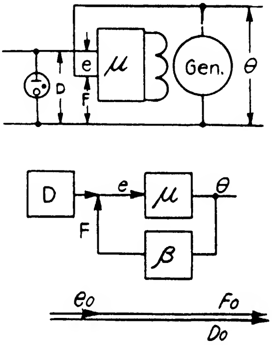


FIG. 17.6. A Type 0 system with zero frequency plot.

Zero Frequency Response, Type 1 Systems. In Type 1 systems the error signal is amplified to produce not θ directly but a change in θ. For example, in a position regulator such as the side-register control or a servomechanism, the signal due to position error is amplified to control the speed of a motor, which produces a change in position. The actual controlled position is due to the sum of all the motor actions over a given period of time. In calculus this is called the "integration" of a motor speed over time. When dealing with sine waves, the "integral" is found to be a negative cosine, or a vector lagging the sine vector by 90 deg. But as we approach zero frequency, the period over which we "integrate" becomes longer and longer, so that at zero frequency we have an *F* vector of unlimited length pointing straight down. The *D* vector must complete the triangle, so it will also be infinite in length. Thus, for zero frequency at least, *F* and *D* may be considered equal and for standstill conditions F will coincide with D. Figure 17.7 suggests this triangle shape.

In actual practice we know that if a position-error signal will cause a motor to operate to reduce this error, the motor will not stop turning until the error has been reduced to zero. However, if D is continuously changing so that the position must also change continuously, there must be an error signal to be amplified into motor velocity to change the position. Hence, although Type 1 systems have no static position error, they do have a velocity error.

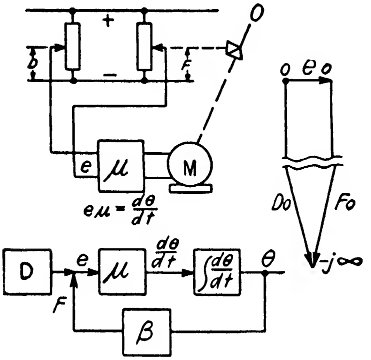


FIG. 17.7. A Type 1 system with zero frequency plot.

Zero Frequency, Type 2 Systems. In order to avoid velocity errors, systems have been devised in which the error in position produces an acceleration effect, that is, a change in the rate of change of position. This requires a double summation, or integration, between e and F. In sine-wave systems at zero frequency this means an F vector opposite in direction to e and of infinite length (see Fig. 17.8). We shall soon see that such a system is inherently unstable unless special precautions and difficult corrective measures are undertaken.

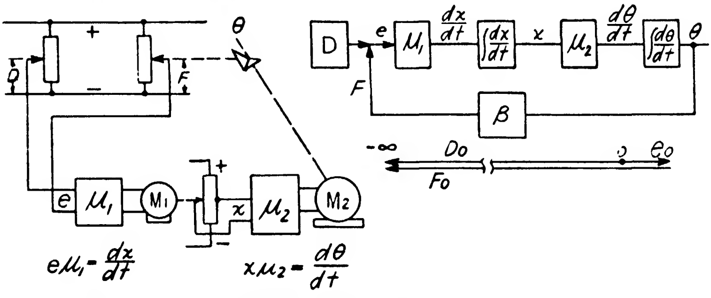


FIG. 17.8. A Type 2 system with zero frequency plot.

Type 3 and higher systems are so difficult to stabilize and so rarely used that they will not be considered here.

Overshooting and Hunting. It must be remembered that the 90-deg and 180-deg phase lags due to integration action in the Type 1 and 2 systems are characteristic of the systems and must be added to any inductive or inertia lags due to system components. The Nyquist F plot may have a different shape for each type, but once an F vector has been determined for a given frequency in any system, the formation of the D, e, and F triangles and the resulting knowledge is the same regardless of system type.

In Fig. 17.9 triangles are drawn for three typical F vectors. In (*a*) F is less than D, a condition previously discussed under zero frequency. In (*b*) the F vector has swung between 90 and 180 deg and is now seen to be slightly greater than D. In other words, if the independent variable D is varied sinusoidally, the feedback signal, and usually the output, θ, will swing over a greater range than it would for very low or zero frequency. A little "overshoot" of this nature usually is not harmful, and most systems can tolerate an F/D ratio of 1.3 to 1.5 without ill effects.

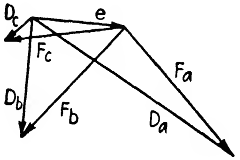


FIG. 17.9. Nyquist triangles for study of F and D relationship.

It has been found by experience that a sine overshoot of F/D ratio in the range of 1.3 to 1.5 corresponds rather closely to the maximum peak overshoot which will occur if a step function, or sudden change, is applied to the system. Also, the frequency at which the system will oscillate before settling down corresponds closely to the frequency point on the Nyquist plot at which the maximum F/D ratio occurs.

M Circles to Determine Maximum F/D Ratio. Because of the importance of the ratio F/D, it is often called M and curves for a constant M value may be superimposed on the Nyquist plot. Simple geometry shows that these constant M curves are circles, all of which surround the -1 point as shown in Fig. 17.10. By their aid it is easy to determine the maximum value of M and the frequency at which it will occur.

Inverse Nyquist Plots. Some workers find it more convenient to consider the F vector as the unit and to plot e/F rather than F/e. Then the length of the D vector becomes the inverse of F/D for, since F is unity, $F/D = 1/D$. The M circles all have their center at -1, but, since measuring the shortest D and taking the inverse is so simple, these M circles need rarely be drawn.

Regardless of whether the inverse function is used or not, it must be remembered that the shape of the eFD triangle for a given system and frequency is always the same and the ratio of its sides and their relative angles is likewise the same.

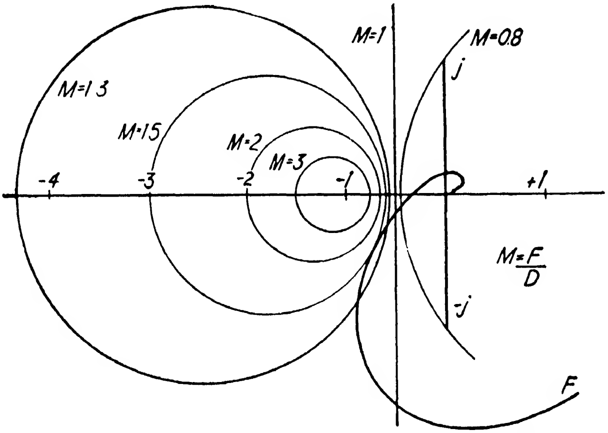


FIG. 17.10. M circles to indicate F/D ratio. The curve shown has a maximum value of $M = 1.5$.

High M Values. In *c* of Fig. 17.9 the F vector almost reaches the -1 point from which the D vector is drawn, so that the F/D ratio or M value is quite high. Such a system would have a bad overshoot. Quite likely slight disturbances would throw it into poorly damped oscillations, and while it would settle down eventually, it would be a generally undesirable system to operate.

Sustained Oscillations, or Hunting. As Fig. 17.11 indicates, the limiting case occurs when the F vector falls exactly along the e vector and the D vector becomes zero, making F/D or M equal to infinity. This means, in effect, that no independent variable signal is needed to keep the sine wave traversing the loop, which is thus capable of a self-sustained oscillation, or hunting.

Unstable Systems. Experience has shown that a system is unstable and hunting will occur not only if the Nyquist plot falls exactly on the -1 point but also if it crosses the negative axis beyond the -1 point and continues on to "surround" it. The mathematical proof for this statement is somewhat involved, and so we will say only that in practice this is about what happens: Assume D to be zero. A transient signal is applied to the system containing the frequency at which the F vector lies along the e vector reversed. Then, each time the signal traverses the loop, it is strengthened by the ratio F/e. After a few cycles, saturation of some part of the system is reached and the amplification $\mu\beta$ is reduced to unity. The oscillation continues then at that frequency and amplitude. The forcing action as the oscillation is building up usually tends to increase the frequency, and the final frequency at saturation may not be the original frequency at 180-deg lag. Also, saturation changes some of the system constants so that the constants for which the Nyquist plot was drawn are no longer accurate.

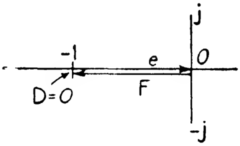


Fig. 17.11. The Nyquist triangle for $F/e = -1$ and $D = 0$.

Typical Nyquist plots for unstable systems are seen in Fig. 17.12.

Conditionally Stable Systems. These are systems in which the Nyquist plot crosses the negative real axis and then doubles back and recrosses it again at higher frequency so that it does not "surround" the -1 point. Fig. 17.13a shows a plot of this nature. Such a system is stable, for, as the forcing action increases the frequency, the F vector swings down clear of the -1 point so that sustained oscillations cannot occur.

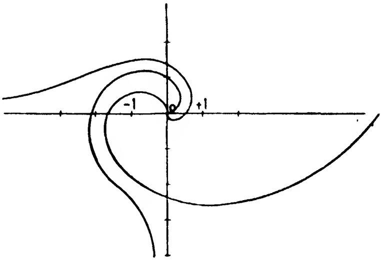


Fig. 17.12. Plots for unstable systems.

These systems are called conditionally stable because, if for any reason the loop gain should decrease sufficiently for the area beyond the negative axis to include the −1 point, as shown in Fig. 17.13*b*, the system will be unstable.

Unless such a system is very carefully engineered, it will have a high *M* value and give poor performance. Reference to Fig. 17.10 shows that the constant *M* circles each extend much further beyond the −1 point on the negative side, and so the Nyquist plot must swing well down below the negative axis in order to clear the required *M* circle.

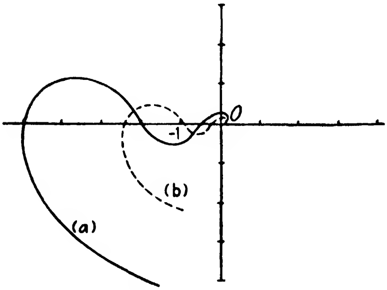


FIG. 17.13. (*a*) A conditionally stable system and (*b*) how it may become unstable if the amplification (vector length) decreases.

Summary. In the Nyquist approach we open the regulating-system loop, apply a constant-amplitude, variable-frequency sine-wave input *e*, and plot the length and relative phase angle of the feedback vector *F*. Since the independent variable *D* is the vectorial sum of *e* and *F*, we may form this vector triangle for any frequency and thus determine *D*. The maximum value of the ratio of F/D, called M_{max}, is important since it occurs at approximately the natural frequency of the system and is an indication of the peak overshoot for transient response. *M* values of 1.3 to 1.5 usually indicate acceptable systems.

Questions

1. What is the difference between an open-cycle and a closed-cycle control system? Describe one of each kind.
2. Explain the Nyquist approach to the study of a closed-cycle system.
3. What values must be known to make a Nyquist plot for system stability?
4. What is the criterion for system stability in a simple Nyquist plot?
5. What does a Nyquist triangle represent?
6. What is a "conditionally stable" system?

CHAPTER XVIII

BODE DIAGRAMS AND THEIR USE IN SYSTEM STABILIZATION

Thus far we have studied means to determine if a system is stable, and, just as important, we have learned something about the response of the controlled variable to changes in the independent variable. In order to present the over-all picture better, the details as to how the loop gain and the *F* vectors were determined have been omitted. Now we will proceed to take this up and to see how the system might be changed to reshape a Nyquist plot more nearly to that which we would like. To aid in this work, we will introduce a new tool which simplifies our calculations greatly. This is based on the work of Dr. H. W. Bode, an associate of Dr. Nyquist in the Bell Laboratories.

The Bode Diagrams. The Bode method may be considered a form of shorthand for the Nyquist approach. It is a method for finding the length and phase angle of the F/e vector. Here, a division of the work is made in that the length of the vector is plotted against frequency for one curve and the phase angle is plotted against the frequency for a second curve. We shall see that this has a number of advantages.

The most usual Bode method has certain limitations. It can deal only with systems which have lumped parameters and have constant coefficients, are linear, and are minimum-phase-shift networks. The first three requirements are self-explanatory, but perhaps a minimum-phase-shift network should be explained more fully. Another requirement is that the vector length shall not become greater than unity with increasing frequency, once it has become less than unity.

Minimum-phase-shift Networks. For any control or feedback element in which energy storage takes place, the output must decrease as the frequency increases. Also, as the frequency increases, the output vector lags more and more. However, in a minimum-phase-shift network this lag is least for a given decrease in output vector length. Most of our usual system elements, such as electronic amplifiers, variable voltage drives, hydraulic drives, motors with inertia loads, etc., are minimum-phase-shift networks. Excluded from this class are transportation lags, certain resonant and filter networks, and thermal systems and transmission lines having distributed constants.

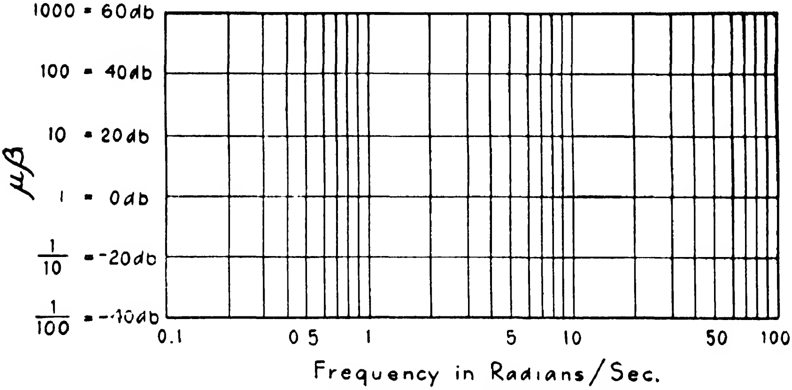
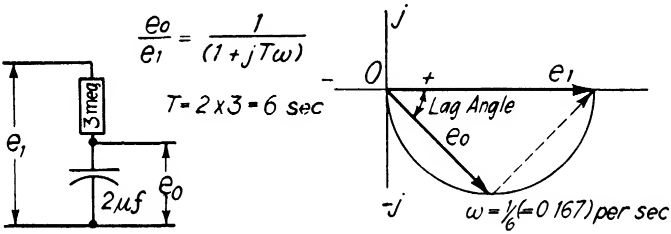


FIG. 18.1. The Bode attenuation diagram graduations.

The Bode Attenuation Diagram. The word "attenuate" is taken from telephone practice and means "to diminish." Hence the curve on the attenuation diagram is a plot of the decrease (or increase) in vector length with increasing frequency. In order to cover the widest range in both length and frequency, both the horizontal and vertical scales are logarithmic. The horizontal scale for frequency is usually obtained by logarithmic spacing. The unit may be cycles per second but is more often radians per second, expressed as ω (omega), where $\omega = 2\pi f$. For the vertical scale of vector length, the spacing is constant but represents the logarithm of the vector-length ratio. Since we assume e to be unity, this value becomes the F vector length. The unit is decibels, expressed as *db*, a term again taken from telephone practice and which simply means 20 × the logarithm to the base 10, 20 $\log_{10}$. For example, an F/e length of 10 is 20 db, 100 is 40 db, 1 is 0 db, and 1/10 is −20 db. The Bode diagram using this type of spacing is shown in Fig. 18.1.

The Attenuation Curve of a Single System Element. We will take the simple *RC* element of Fig. 18.2*a* with the Nyquist plot



(a) (b)

FIG. 18.2. The *RC* series network and its Nyquist plot.

of *b* and draw its attenuation curve of e_0/e_1. The Nyquist diagram for this simple circuit is the same as the vector semicircle of Fig. 15.3, page 175. In complex notation the equation for this circuit is

$$e_0/e_1 = \frac{1}{1 + j\omega RC}$$

Before plotting this curve let us observe both the circuit and the equation and draw a few conclusions. For very low frequencies (low values of ω) the capacitor charging has little effect on the output voltage, so e_0/e_1 is almost unity or 0 db. For $\omega = 1/6$ the capacitor and resistor voltages are equal, so the vector has a length of 0.707 or approximately −3 db. For high values of ω the resistor impedance is predominant, limiting the current to an almost constant value, so that the output voltage across the capacitor varies almost directly inversely with the frequency. With these key facts in mind, the attenuation curve can be plotted as in Fig. 18.3.

Note that this curve could be approximated quite well by the two straight broken lines, one a horizontal line along 0 db to $\omega = \frac{1}{6}$, the second a line intersecting the first at $\omega = \frac{1}{6}$ and sloping so that the vector length varies inversely with the frequency. The slope of this line may be expressed as $-1/f$, -20 db per decade, -6 db per octave, or simply as a minus one (-1) slope, since it is due to the lag of a single element. The value of ω at which the break, or corner, of the lines comes is that where $j\omega RC = j$, or where $\omega\ RC = 1$, so that $\omega = 1/RC$. Earlier we learned that for this circuit RC was the "time constant" (page 157), so that we can now see that this corner frequency in radians is the inverse of the time constant. This will be found true for other simple elements also.

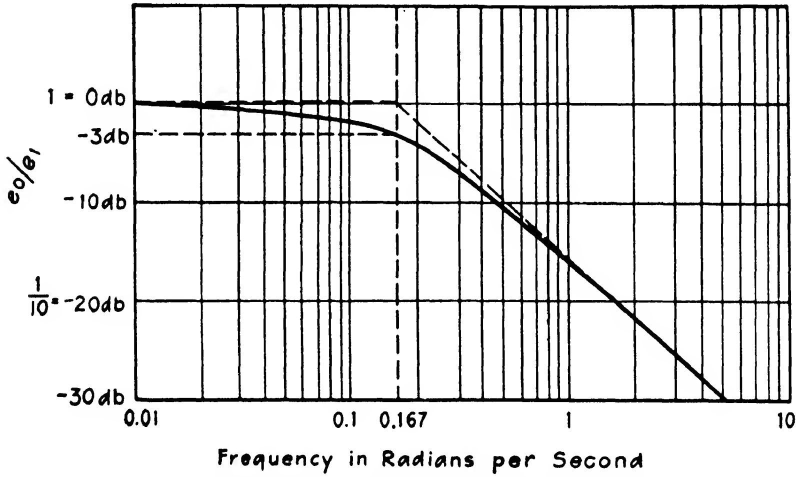


FIG. 18.3. Bode attenuation plots for RC series network of Fig. 18.2.

Construction of attenuation curves for system elements may be summed up briefly as follows: (1) Express the element "transfer function" (e_0/e_1) in complex form with the constants divided out so that the vector term has the form $K_1(1 + j\omega K_2)$. (2) The corner frequency in radians is $1/K_2$. (3) If the vector term is in the numerator at the corner frequency, the curve will turn upward by a unit slope; if in the denominator, the curve will break downward. (4) The vertical fix may be obtained by letting ω approach 0 or ∞, whichever is more convenient. (5) The exact curve is approximately 3 db inside the corner, 1 db inside an octave (1/2 or 2 × frequency) away from the corner, etc.

The Bode Phase-shift Curve. Referring again to the sample *RC* circuit of Fig. 18.2, it is seen that for every value of ω there is also a definite value of the phase-lag angle, between e_1 and e_0. This may be plotted on a linear vertical scale against frequency as in Fig. 18.4. The angle at the corner frequency, $\omega = 1/6$, is 45 deg and varies symmetrically above and below this frequency when a logarithmic frequency scale is used. It is important to note that in a minimum phase-shift network such as this, the vector length and the phase angle, having been both derived from the same semicircle Nyquist plot of Fig. 18.2*b*, have a very definite relation throughout and are both fixed on the frequency scale by the corner frequency.

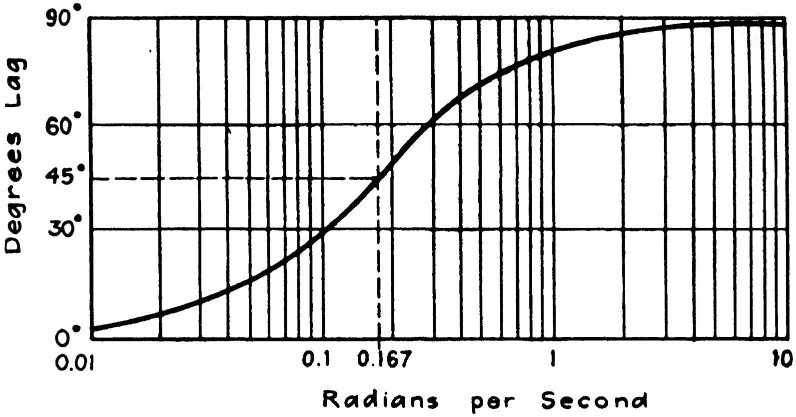
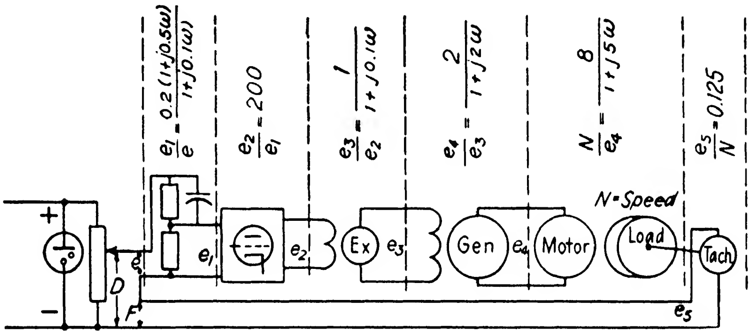


Fig. 18.4. Bode phase-shift plot corresponding to Fig. 18.3.

The Transfer Function of Elements in Series. The transfer function of the whole system loop, F/e, is the result of the action of a number of elements. For example, in Fig. 18.5 we have a speed-regulating system consisting of a glow-tube voltage reference *D* and an electronic amplifier energizing an exciter field, which in turn supplies power to the field of the generator of a variable voltage d-c drive. The motor drives a high inertia load. A d-c generator tachometer on the motor shaft feeds back a voltage proportional to speed. This is compared with the reference voltage to provide an error signal.

This system by itself would be unstable because of the phase lags occurring in the inductance of the two fields and the load inertia; so it is stabilized by a lead network shown ahead of the amplifier. (Networks for stabilization will be discussed later.)



$$\frac{F}{e} = \frac{e_5}{e} = \frac{0.2 \times 200 \times 1 \times 2 \times 8 \times 0.125\,(=80)\,(1+j0.5\omega)}{(1+j5\omega)(1+j2\omega)(1+j0.1\omega)}$$

FIG. 18.5. A system for obtaining a closely regulated motor speed. Transfer functions of elements and the over-all system are given.

The transfer function for each section is given and finally the whole transfer function F/e. For simplicity we have neglected some of the time constants, such as those in the amplifier and armature loop, and any back loading of succeeding elements. However, back loading on amplifier grids and machine fields is very slight.

The Multiplication of Vectors. Since each succeeding element acts on the output vector of the preceding element, increasing or decreasing its length and adding to its lagging or leading effect, we obtain the final vector as follows: (1) Multiply the length in turn by the amplification or attenuation of each element. (2) Add the angles, calling lagging positive and leading negative, contributed by all the elements.

On the Bode diagram multiplication of vectors becomes a matter of adding logarithms graphically. The angles may also

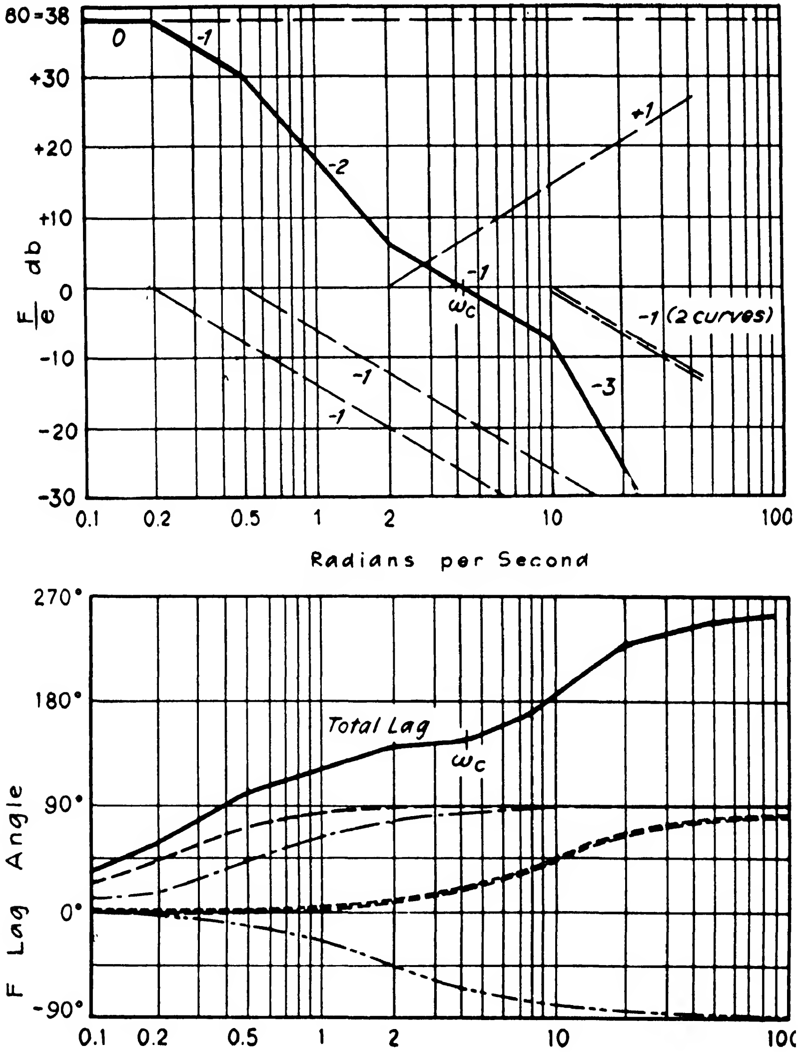


Fig. 18.6. How the combined Bode plots are made from those of the individual elements of Fig. 18.5. Element plots are shown as broken lines. Corner frequencies at $\omega = 0.2$, 0.5, 2, and two corner frequencies superimposed at 10.

be added graphically. In Fig. 18.6 we see how this is done for the transfer function of Fig. 18.5. The composite curve for the length of F/e starts at 38 db (which represents 80 times), the system amplification at a frequency so low that no lags are appreciable. As each corner frequency is reached, the curve breaks up or down, depending on whether the term is in the numerator or denominator.

The phase-angle curve is constructed as easily, by adding all lag angles for each frequency and subtracting the lead angle effect. It is interesting to note that at frequencies well above the corner frequency, the lag or lead angle due to that corner becomes almost 90 deg, so it can be assumed that for this transfer function at high frequencies the lead numerator term will cancel one of the denominator terms and the ultimate slope will be -3 (60 db per decade) and the ultimate phase lag 3×90 deg or 270 deg.

After some practice the relation between slope and lag angle becomes even more evident. For instance, if the slope continues as -2 for an extended distance, the angle approaches 180 deg; if the slope then breaks to a -1 slope, the angle drops toward 90 deg, only to rise again if the slope becomes steeper once more.

Stability Criteria. On the Nyquist plot a system was stable if the curve lay inside of the -1 point as it crossed the negative axis. On the Bode diagram we say the same thing by stating that when the curve crosses the 0 db line (unit gain) the phase angle shall not have lagged 180 deg. In the example given the curve crosses 0 db with a phase lag of 145 deg, and the system is stable. If the lead network had not been added, it definitely would not have been stable. This may be checked by leaving out the attenuation and angle curve for the lead network and redrawing the composite curve. The ease with which system elements may be added, removed, and modified on the Bode curves illustrates their usefulness in system design.

Type 1 and Type 2 Systems in Bode Diagrams. Type 1 and 2 systems, in which the F vector for very low frequencies on the Nyquist plot has almost 90- and 180-deg lag angles respectively, are as easy to draw on the Bode diagram as Type 0 systems.

Type 1 systems are drawn as if there were a corner at 0 frequency. This means that the attenuation starts with the -1 slope (hence called Type 1) and angle curve starts with a 90-deg lag angle. To establish the vertical position of the attenuation curve, a single point is plotted, usually at $\omega = 1$, and neglecting all system lags. (They are added later in the usual manner.) A study of the transfer function indicates that when lags are neglected and $\omega = 1$, the whole function becomes simply the constant K at this frequency.

Having established the position of the initial curve, the system lags are added to it at each corner frequency above and below $\omega = 1$ exactly as before (see Fig. 18.7).

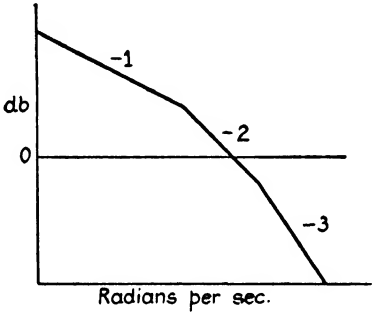


FIG. 18.7. Bode attenuation plot for a Type 1 system.

For Type 2 systems the procedure is the same for establishing a point at $\omega = 1$, but this time the initial curve has a -2 slope (hence Type 2) and 180 deg are added to all system lag angles.

Solution of the Nyquist Triangle. As stated before, the Bode curves are only another easier means for determining the length and phase angle of the F/e vector. Having found these, there is still the Nyquist triangle to construct and the F/D or M to determine. This could be done by transferring the Bode information into Nyquist form, but to save time and effort, a chart has been made up which gives this information directly from the decibel value and phase angles (Fig. 18.8). Sometimes the phase angle is expressed as "phase margin," which is 180 deg minus the lag angle. For best accuracy one should use the exact decibel values, found by correcting the curve 3 db inside each break as discussed earlier. As in the Nyquist plot, the maximum M value is usually found at vector lengths slightly greater than 1 or just above 0 db, so this area should be explored carefully for the maximum M value.

Stabilization by Series Networks. Experienced designers have found that if the Bode curve is made to cross the 0 db line at −1 slope and this slope continues for about 2 octaves each side

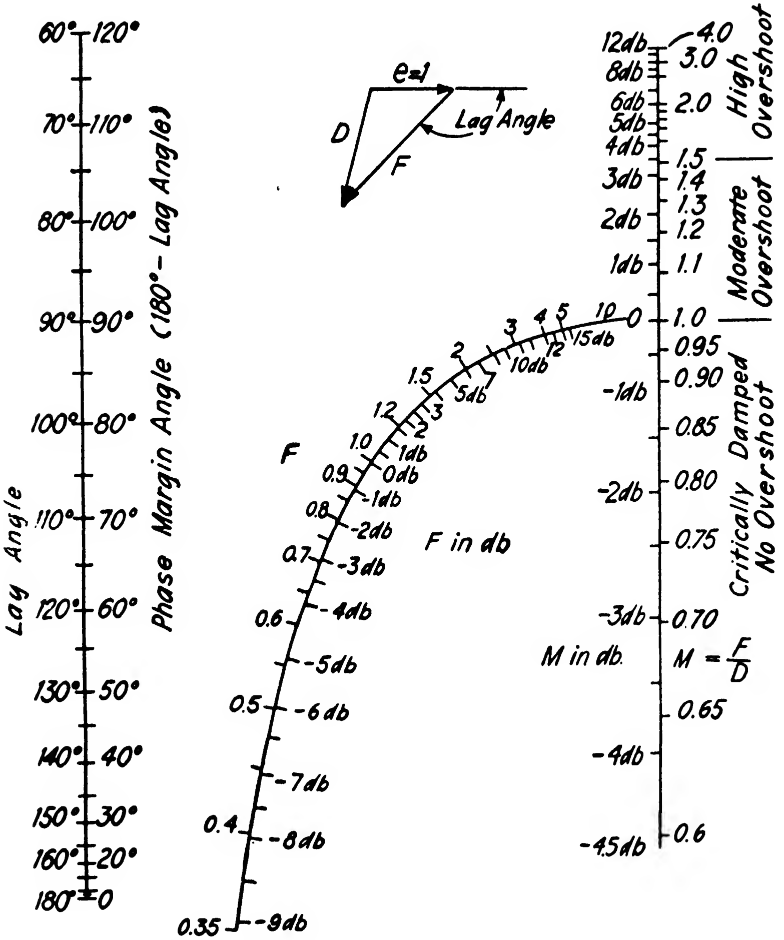


FIG. 18.8. Alignment chart for finding M or F/D. Place a straightedge to cut length of F and the lag angle. Read M.

of the crossing frequency (¼ to 4 times the crossing frequency), the M_{max} value will lie in the desirable range near 1.3. Often, so long a unit slope is not practical, but good judgment in the appraisal of cost against performance is the mark of a good engineer.

There are two means for stabilizing regulating systems; many systems use both. The first is the series network, a sample of which has been given. It is usually easiest to construct and apply but has a limited range. The second is the frequency-sensitive feedback.

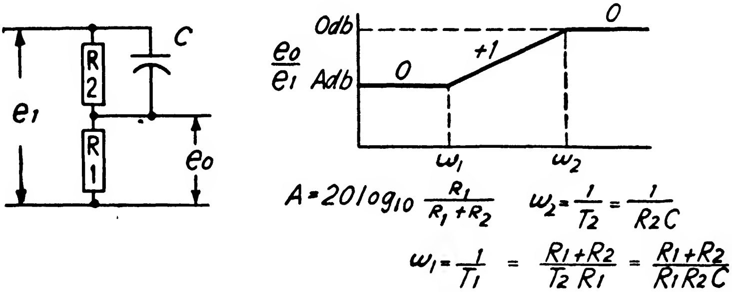


FIG. 18.9. *RC* lead network and Bode attenuation plot.

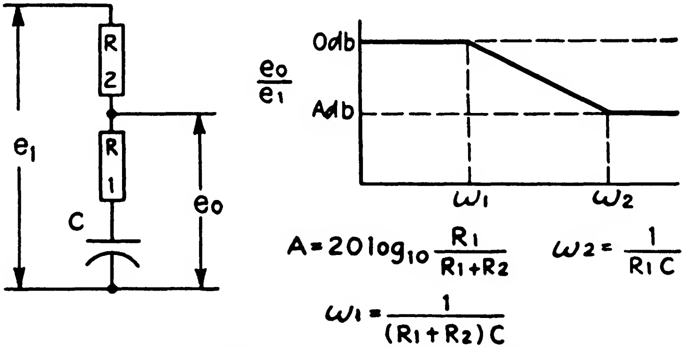


FIG. 18.10. *RC* lag network and Bode attenuation plot.

The Series Lead Network. This simple *RC* network is shown in Fig. 18.9. As its Bode curve indicates, there is a loss of gain at low frequencies which must be made up by additional amplification within the system. With electronic amplifiers this additional gain is usually easily obtainable. It is used, as in the example above, to cancel a lag slope in the 0 db region. Double networks are sometimes used to cancel two lag slopes, but their great sensitivity in the high-frequency range may accentuate parasite signals such as tachometer ripple and thus may not prove desirable for some systems. The lead network is sometimes called the "differentiating network."

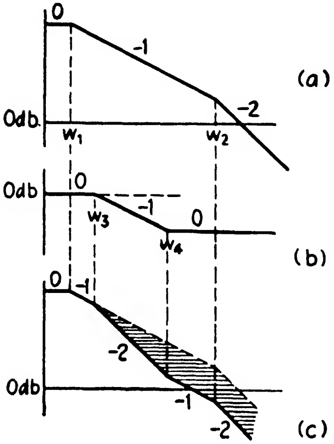


FIG. 18.11. Application of lag network of Fig. 18.10.

The Series Lag Network. This network, seen in Fig. 18.10, has a Bode curve about the opposite of the lead network. Its purpose is to attenuate the system gain more rapidly at lower frequencies so that 0 db will be reached before more than one system lag has become effective. Its effect is illustrated in Fig. 18.11. It will be noted that stability is obtained at a cost of speed of response, as represented by the shaded area. Other lag networks are sometimes not so obvious. In Fig. 18.12*a* a capacitor between the grid and anode of a triode permits full amplification at low frequencies but at high frequencies cancels the gain almost completely. A resistor in series with the capacitor in Fig. 18.12*b* permits some gain at high frequencies as a degenerated amplifier as described on page 192, Fig. 16.2. In Fig. 18.12*c* a capacitor between anode

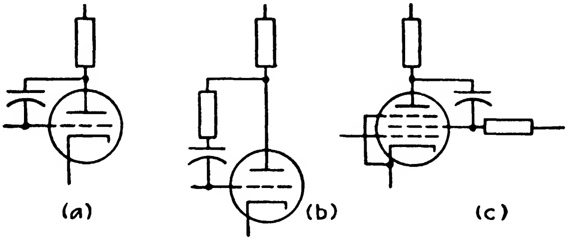


FIG. 18.12. Forms of lag networks used with electronic circuits.

and screen grid permits amplification as a pentode for low frequencies but only as a triode for high frequencies.

The lag network is sometimes called the "integrating network."

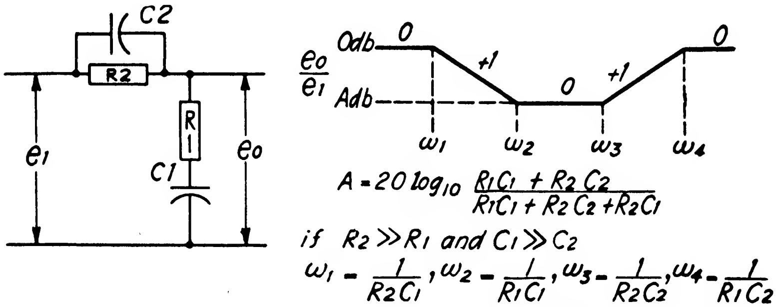


FIG. 18.13. The "notch," "lag-lead," or integral-differential network.

The Notch Network. This network, so called from its Bode curve in Fig. 18.13, is also known as the "lag-lead" and "integral-differential" network. It is seen to be a combination of a lag and a lead network, and because of the flexibility of its four time constants, it is very useful. Since it causes a loss of frequency response over only a narrow range, it can achieve stability with a minimum of response loss. This is indicated by the shaded area of Fig. 18.14.

Other Networks. There is a wide variety of networks which may be used for special cases. The reader is directed to the references at the end of the section for further information. However, unless the system constants are fairly accurately known, complicated networks may not work out nearly so well in practice as a theoretical design might indicate.

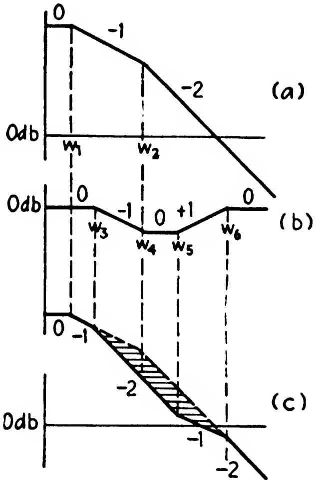


FIG. 18.14. Application of the notch network.

Stabilization by Frequency-sensitive Feedback. When deriving the fundamental relations in a closed-cycle regulating system, it was found that when the loop gain $\mu\beta$ was very large the relation between the output or controlled variable and the input or independent variable became very nearly $1/\beta$. So long as β remains constant, the output follows the change in input very closely—the objective of most regulating systems.

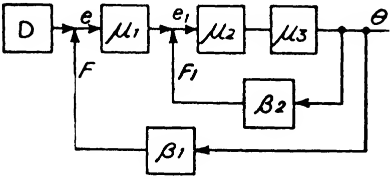


Fig. 18.15. Block diagram of internal-loop feedback.

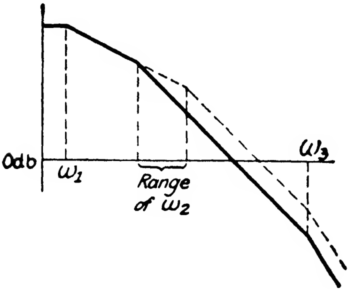


Fig. 18.16. System with a variable time constant.

However, there are times when we wish to have the relation between output and input vary with a change in frequency in order to assist in obtaining system stability. Sometimes this is done by making the principal β circuit frequency-sensitive at higher frequencies, although it remains essentially constant at the normal working frequencies. More often, though, only a part of the whole amplifier or μ circuit is by-passed by a frequency-sensitive β circuit to form an internal loop as in Fig. 18.15. In this manner the transfer function across the internal loop may be modified to eliminate a critical or variable time constant within it, such as the inertia of a roll of material that will change during a run, a motor with a variable field strength, etc. A second reason might be to set up a transfer function in a low-power control element to compensate and cancel an inverse transfer function appearing in an element using higher power. The stability obtained by the use of frequency-sensitive feedback is always had at a loss of frequency response.

Feedback Stabilization to Eliminate a Time Constant. Suppose that the Bode diagram of a transfer function of some of the elements in a μ circuit looks like Fig. 18.16. Since one of the time constants, T_2, may vary over the range indicated, stabilization by series networks might not be satisfactory and a frequency-sensitive feedback is indicated. This consists of a d-c generator tachometer with a series lead network as shown, with Bode diagram, in Fig. 18.17.

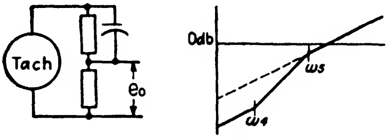


FIG. 18.17. Bode curve for tachometer generator with lead network.

The over-all response of these elements, including the feedback loop, may now be set up as follows: Where $\mu\beta$ is less than 1, we will assume the feedback to be ineffective and the over-all curve to be the initial μ curve (a) of Fig. 18.18. Where $\mu\beta$ is greater than 1, we assume the curve to be $1/\beta$ (the mirror image about 0 db of Fig. 18.17), as drawn in (b) of Fig. 18.18. Next we draw $\mu\beta$, which is $\frac{\mu}{1/\beta}$, or expressed in db, as the area between the curves μ and $1/\beta$, as shown at (c). This gives us the frequencies for transition between the μ curve, $1/\beta$, and back to the μ curve. The final over-all curve now looks like (d).

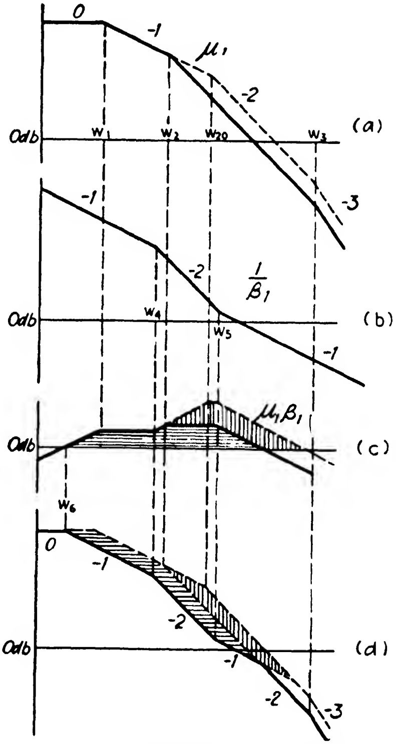


FIG. 18.18. Stabilization of system by means of tachometer feedback.

Remember that this is only an approximation which becomes more accurate as $\mu\beta$ becomes much greater or much less than 1. Therefore, to assure ourselves that no unusual curve changes occur because of resonance or similar effects at frequencies near where $\mu\beta = 1$, it is best to check at least one point, usually the upper transition frequency, by direct vectorial methods to note the general behavior in this region. If this plotted point lies much above the approximate curve, other points nearby should be taken to assure that the curve does not rise above the 0-db line to cause oscillation or hunting.

Another consideration is that the additional feedback makes this element a small regulating system within itself, having a loop gain as shown in Fig. 18.18c, and hence must be stable within itself. In this case the -1 slope at 0 db indicates that there is ample stability.

A glance at the solid and broken lines indicating the shift of time constant, T_2, shows that in this form of stabilization the shift in corner frequency has little effect on stability, since in this frequency range it is the $1/\beta$ and not the μ curve which governs the transfer function.

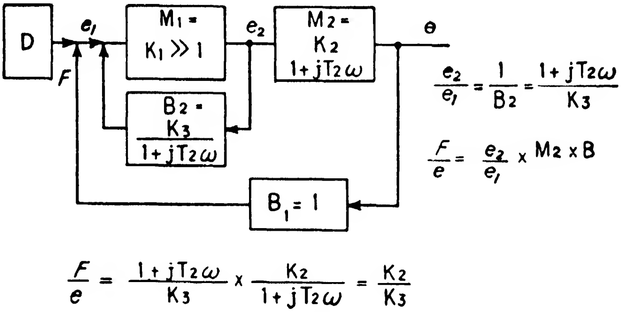


FIG. 18.19. Block diagram showing a lag-compensation feedback.

Feedback to Compensate for a Subsequent Lag. The use of feedback to compensate for a lag in a later power element is best shown by the block diagram of Fig. 18.19. Here the feedback around the first element, perhaps an electronic amplifier with no appreciable time lags, contains a delay vector closely matched to that of the second power element. So over the effective range e_2/e_1 becomes $1/\beta$, or $(1 + jT_2\omega)/K_3$, and the over-all transfer function becomes

$$\frac{e_3}{e_1} = \frac{1 + jT_{2}\omega}{K_3} \times \frac{K_2}{1 + jT_{2}\omega} = \frac{K_2}{K_3}$$

This indicates that the lag of the power element is effectively canceled out by applying the proper compensating signal to the input of the element. Note that K_1 does not appear. Its loss is the price paid for this form of stabilization.

Solution of Multiple Feedback Loops. Some systems, such as that shown in Fig. 18.20, have multiple or interlocking feedback loops, and their transfer function becomes quite complex. Each network requires its own attack and solution, although a few general suggestions may speed the work. Often the inverse function, e/F, will be found to be simpler in form than the forward relation, F/e. The number of terms in the inverse function will be the number of possible paths between output and input. For inverse functions the β elements will appear in the numerator and the μ elements in the denominator. However, watch out for internal loops which are found in the β circuit. It is usually best to solve these separately and then carry the solution as a β term.

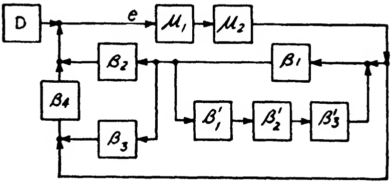


FIG. 18.20. A complex system having multiple feedback paths.

Intermittent Action and Neutral Zones. Two "brute-force" means much used in mechanical regulators and successful also in electronic regulators where only slow speed of response is required are the *intermittent-action* and *neutral-zone* types. These are required when the signal is intermittent and are necessarily slow in their action. The intermittent-signal action permits no sustained oscillation for the obvious reason that the input circuit is disconnected or rendered inoperative before the signal has had time to progress completely through the system.

In the other type a zone of no correction, or neutral zone, is provided as a range of tolerance surrounding the correct value in which the input signal is heavily damped or killed entirely. This satisfies the condition of less than unity amplification at all frequencies, provided that amplification is not great enough to permit oscillation surges to bridge completely across the neutral zone.

Stabilizing Transformers. A theoretically excellent method of phase advance utilizes a transformer to feed back a signal in the correct phase by proper loading of the secondary. This has the great advantage of taking a signal of comparatively high power from a point near the circuit output and stepping up its potential by transformer action, and then inserting it where desired near the input without regard to the potential difference of the two locations (Fig. 18.21). However, transformers capable of handling the low frequencies are bulky and expensive, and the secondary loading to obtain both the proper voltage and phase is not too easy.

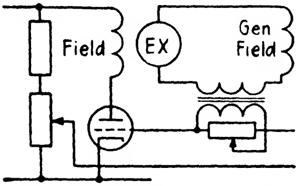


FIG. 18.21 Stabilizing transformer in circuit of FIG. 17.2.

In Conclusion. The use of closed-cycle regulating systems is expanding rapidly. Since electronic amplifier elements play such an important part, a basic knowledge of regulating systems is necessary to the industrial electronic worker. It is hoped that these chapters have given some insight into the system fundamentals. If the reader's work requires considerable familiarity with the regulating systems and their stabilization, it is suggested that a close study be made of the reference material given and the many excellent texts which are appearing in this vital and very active field.

Questions

1. What are the abscissa and ordinate quantities in a Bode attenuation diagram?
2. Translate these ratios into decibels: (*a*) 80, (*b*) 1500, (*c*) 1, (*d*) 0.005.
3. What ratios are represented by the following decibel values: (*a*) 0 db, (*b*) 45 db, (*c*) 6 db, (*d*) -30 db?
4. What is meant by the "corner" frequency in a Bode diagram? What is the phase shift due to a given element at its corner frequency?
5. What is the effect of (*a*) lead network, (*b*) lag network, (*c*) notch network?
6. Sketch a typical Bode attenuation curve for a Type I system.
7. Sketch a typical Bode attenuation curve which you know to be stable. Why is it stable?
8. On what principle is based stabilization by the use of a frequency-sensitive feedback network?
9. Plot the attenuation diagram and phase-shift diagram for Fig. 18.5 without the initial lead network. What indicates that the system is unstable?

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Section V

INDUSTRIAL ELECTRONIC CIRCUITS

CHAPTER XIX

ELEMENTARY DIAGRAMS

An understanding of the fundamental tube actions and the operation of basic circuits is necessary for a knowledge of industrial electron circuits. The basic circuits that have just been studied do not by any means exhaust the possibilities. The variety of circuits is endless. But there is a good chance that, when analyzed, a large part of any industrial electron circuit will be found to consist of a combination of the basic circuits or of variations of them.

Unless a circuit is very simple, it is difficult to study it as it is found in the wiring on the control panel or chassis. The first step usually consists in revising the circuit diagram to the elementary form. Further to simplify matters the tube-heater circuits are omitted (unless a tube is operated emission limited and the heater or filament circuit is part of the control circuit).

Start with a sheet of paper about twice the size you think you will need. Crowding a drawing encourages errors. Some engineers prefer to draw an elementary diagram so that the sequence may be followed in a vertical direction. In such cases the most negative potentials are placed at the right of the drawing, and the potentials rise progressively to the most positive potentials at the extreme left. If a component, such as a resistor, can reverse its potential or normally carries no current (for example, a grid protective resistor), draw it parallel to the power busses. In this arrangement the tube symbols should be drawn sideways, with the anode to the left of the cathode. Here the power or output circuit is drawn at the top and the input control circuit is at the bottom.

Others prefer to follow the control sequence horizontally from left to right, the potentials increasing from negative at the bottom of the drawing to positive at the top. This permits the tubes to be shown in an upright position. Use whichever system seems more natural to you. An engineer used to the other system need only turn your diagram at right angles to view it in the manner to which he is accustomed.

Layout. If each lead is numbered to agree with that on the panel diagram, it will assist materially in cross reference between diagram and elementary. Start at the top or right-hand side by showing the incoming power leads, the switches, and circuit protection such as fuses and cathode-heating timer. If magnetic-control devices such as push-button control, reversing contactors, or interlocking relays are employed, draw them in here or, if they are extensive, use a separate drawing for them.

Next come the cathode-heater-circuit transformer primaries (if desired) and the anode transformer primaries. If the circuit is to be operated by d-c obtained from a rectifier, the rectifier circuit is next added, with the positive and negative busses extended out to enclose the control circuits. Transformer primaries may be marked P (as $T1P$) and the secondaries S (as $T1S$). Polarity marks, or *start, finish* marks (S, F), may be used.

If the circuit operates from the a-c source without rectification, there is, of course, no positive or negative bus; but it is logical to place at the bottom or right-hand side that line or transformer lead which is negative when the principal power tube is conducting (that is, the lead connected to the cathode of the principal power tube), or the line side containing the most tube cathodes, or the grounded side. A tube that conducts on the negative half cycle may be drawn upside-down to indicate this.

Circuit Sequence. The sequence of circuits should be drawn in an orderly manner, beginning at the bottom or left with the input signal (phototube, tachometer, etc.) and adding each circuit in turn as the control signal is amplified or converted. Plenty of room between circuits and between components should be allowed. It is easy to misjudge the space required for the logical spacing of circuit elements.

If the circuit is at all extensive, a second or even a third redrawing is necessary to make a reasonably clear elementary diagram for study. Manufacturers of electronic equipment are fast learning the desirability of a clear elementary diagram for most efficient servicing and maintenance and are including them in instruction books to a much greater extent than heretofore. However, even these drawings may often be made clearer by redrawing. If a clear, well-drawn elementary diagram is available, the job of understanding the circuit is half completed.

Component Values. The next step is the labeling of the components with their correct values. Resistances are expressed in ohms or megohms. (1000 ohms is often shown as K; for example, 5000 ohms is $5K$.) Capacities are given in microfarads or micromicrofarads (μf or $\mu\mu$f), inductances in henrys or millihenrys. The voltages of transformer secondary windings and rectifier outputs should be indicated if the values are available. Finally, the tube types should be shown. Some prefer to designate the parts as $R1$, $C1$, or $1R$, $1C$, etc., and add a table of values. However, if space permits, a clearer understanding of the circuit function can be obtained by marking the component values directly on the circuit as near as possible to the component.

It might be said here that, although all the above information is desirable, it is seldom all available. The operation of most circuits can be determined even though many details are missing.

Care should be taken that thyratrons, ignitrons, and phanotrons are properly marked with a dot, indicating a gas-filled tube.

Signal Tracing. We are now ready to break down the circuit into its basic elements and to follow its operation from beginning to end. If an instruction book or a description of operation is available, it should by all means be studied and used to assist in tracing through the circuit. If no description of operation is available, we usually have some idea of what the input signal will be and the results that we wish to obtain at the output.

The circuit tracing may start at either end. Usually it is best to start at the input and follow through. If the going becomes too difficult, stop at the last point at which the operation is clear and start at the output to work backward. Soon the unknown part of the circuit may be narrowed down until *application of the principle of cause and effect* will make the solution possible.

A handy way to trace potential increases or decreases is to draw small arrows near a tube element to indicate its potential change when the control grid varies as required. Start with the first control element, and indicate its variation in the expected direction. If it may vary in either direction, assume that it becomes more positive (arrow points up). If the basic circuit uses a-c power, assume, as a starting point, that the cathode of the first tube is negative.

It may be necessary to draw vectors to determine the thyratron-grid phase shift, but normally the phase-shift circuit will follow one of the basic forms described previously (Chap. XV) closely enough to be immediately evident. As a final resort, a point-to-point curve of the voltages and currents through a complete a-c cycle or operation may be attempted.

Magnetic-contactor Circuits. If magnetic-contactor elementary circuits are to be drawn, they will follow the general pattern used in the electronic diagrams. However, since the controlled, or contact, circuit on the contactor may be insulated from the operating coil, unlike the electron tube where the grid-cathode and anode-cathode circuits are common, somewhat more freedom is permitted in the placing of the different parts of a single contactor at widely separated points in the circuit to allow the individual circuits to be drawn as directly and as simply as possible. Of course, the parts must be appropriately labeled with a common symbol to indicate their relation.

It is considered the best practice to connect all coils to the ground, or negative, line insofar as is practical and to do all switching in the positive, or hot, side of the line. In this way "sneak" circuits and false operations are best avoided.

"Wireless" Diagrams. A practice which is becoming increasingly popular in drawing wiring diagrams is to leave out the actual lines representing wires but, instead, to indicate at each termination whence the wire came. Each device has a designation as usual, and each terminal has a number. For example, if a wire goes from the No. 7 terminal on the socket for tube 2V to terminal No. 2 of the filament transformer secondary *S3T*, the designation at the filament terminal is written 7-*S3T*-2 and at the transformer 2-2V-7, or in some similar fashion.

The "wireless" diagram does have a neater appearance without the criss-crossing of wire lines on the sheet, particularly if there are many devices on the panel. It is claimed that, once familiarity has been gained, the time of both draftsman and wireman is saved. On the other hand, it becomes very important that the greatly increased amount of lettering be done very carefully and clearly since misreading a reduced-size print under poor lighting conditions can easily lead to serious error.

Cabled Wiring. Another factory practice which produces a neat-appearing panel (see Fig. 20.15) is that of running the wiring in laced cables. In quantity production, cabling is also less expensive since the operator makes up the wiring beforehand on a pegboard as a "harness" which is then transferred to the panel and connected up as a unit.

However, cabling makes it almost impossible for a serviceman to trace connections when trouble shooting, so a wiring diagram of the panel is almost essential for intelligent servicing of a cabled panel.

Also, because of the relatively high capacity between wires of widely different potentials in a cable, it is not wise to cable wires in high-impedance circuits, particularly if the panel wiring includes a high-gain amplifier. A practical suggestion is not to cable any wire having an impedance of more than one-half megohm to ground. At times even lower values may cause circuit instability and erratic circuit performance.

Questions

1. State four features of a good elementary diagram.
2. Why are both elementary and panel-wiring diagrams needed?
3. Give an advantage and a disadvantage of the "wireless" diagram.
4. Name a disadvantage of cabled wiring.

CHAPTER XX

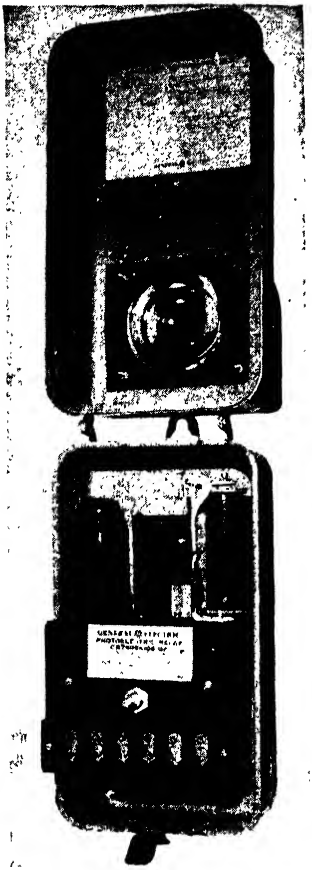
DIRECT-CURRENT PHOTOELECTRIC CIRCUITS AND MOTOR CONTROL

DIRECT-CURRENT PHOTOELECTRIC CIRCUITS

Commercial Electronic Control Circuits. In presenting the following electronic control circuits, which are taken from standard commercial devices, an attempt has been made to select a representative cross section of industrial electronic practice today. Most of the circuits are patented and are shown here with the manufacturer's permission. Because of the rapid advances in electronics, these circuits do not necessarily represent the latest or best of a particular manufacturer's products. Some circuits cannot be shown because of military restrictions. However, it is felt that through study of these typical circuits a more confident approach and a more rapid understanding of any industrial electronic circuit will result.

The GE CR7505K108 Photoelectric Circuit. This is a commercial photoelectric relay unit that is simple enough to illustrate well the first principles in circuit analysis. Figure 20.3 shows the actual panel wiring. Figure 20.4 shows the elementary diagram. Since the elementary diagram has been drawn according to the suggestions outlined above, the circuit is almost self-evident. Starting at the top there is a half-wave rectifier, with a small protective resistor in the anode lead and a resistive π filter to supply d-c for the unit. Below this is the voltage divider to furnish the proper cathode and screen potentials for the pentode tube used as an amplifier. The lower end of the divider is a rheostat to provide a variable grid bias. In series with the pentode anode is the contactor coil CR. The contactor contacts (single pole, double throw) are shown outside the electron circuit. The phototube and its series resistor *R*1 are at the bottom of the diagram.

Circuit Refinements. Circuit refinements are as follows: The phototube protective resistor *R*2 protects the phototube against overcurrent drawn via the amplifier cathode-grid circuit in the case of an extreme amount of light on the phototube. A capacitor *C*1 protects against very short transient light or electrical surges that might cause false operation or chattering of the contactor. Capacitor *C*4 permits more reliable operation on ungrounded lines. Since the relay is operated directly from the 117-volt line, it is not possible to ground the circuit directly to



FIGS. 20.1. and 20.2.—General Electric photoelectric relay CR7505K108. The phototube is behind the light mask at the center. The shaft for bias adjustment is below the name plate. (*Courtesy of General Electric Company*)

the case, although this is desirable in any photoelectric or other high-impedance circuit to prevent false operation due to the capacity effects of changing potential between the case and circuit components.

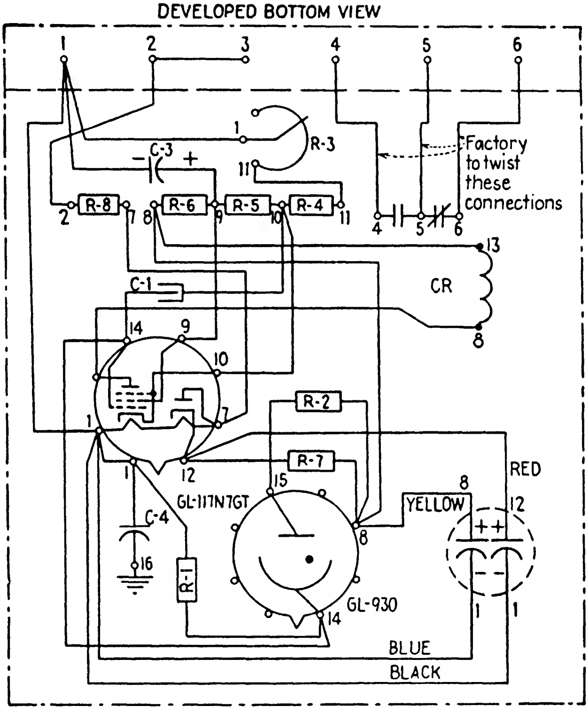


FIG. 20.3. Panel wiring diagram for GE CR7505K108 photoelectric relay

Operation. In operation, with no light on the phototube, there will be no current and thus no potential across $R1$. Hence, the grid of the amplifier tube will be at the negative bus potential. $R3$ is adjusted to produce a cathode bias such that insufficient current for operation will flow through the contactor coil. When light shines on the phototube, the electron flow through it and $R1$ will raise the potential of the amplifier grid, permitting sufficient current to flow to operate the contactor. The setting of $R3$ and the cathode bias determines the phototube current and the voltage drop across $R1$ necessary to raise the amplifier grid potential sufficiently to cause contactor operation.

The type 117P7 (or 117N7) tube used contains the rectifier

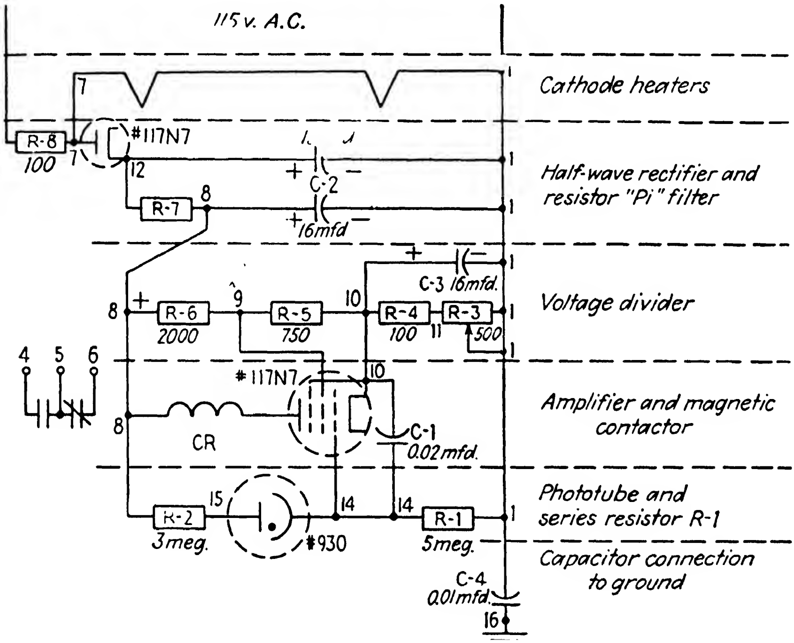


FIG. 20.4. The circuit of Fig. 20.3 redrawn in the elementary form.

and pentode within a single envelope. The designation 117- indicates that the cathode heater can be operated directly from the 117-volt a-c line.

Electronic Control Corp. Smoke Detector M-343. This form of photoelectric relay (Fig. 20.5) uses two phototubes in series with the grid of the amplifier tube connected to the mid-point. Light from a common source is directed on both phototubes equally when no smoke is present. When even a light haze decreases the light from one beam, the phototube current balance is upset and the amplifier grid is thrown more negative. This drops out relay *B* and sounds the alarm, or stops the ventilation blower.

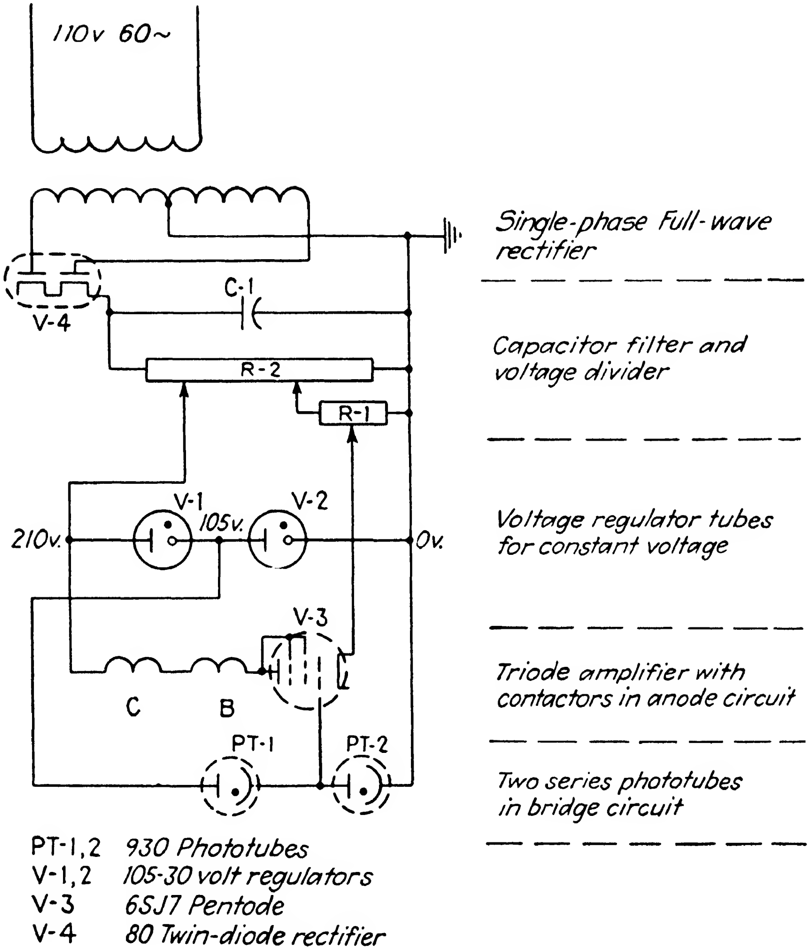


FIG. 20.5. Elementary diagram of the balanced phototube circuit used in the Electronic Control Corp. M-343 photoelectric smoke detector.

The electron circuit in elementary form is seen to be quite simple. The single-phase full-wave rectifier uses a single capacitor *C*1 across the voltage divider *R*2 as a filter. From a tap near the positive end of the divider resistor to the negative end are connected two VR105-30 regulator tubes, in series, to furnish a constant voltage of 210 volts for the amplifier circuit and 105 volts for the phototube circuits. The amplifier circuit is conventional, the cathode potential and bias being set by the position of the arm of the potentiometer *R*1. Since the light on the phototube *PT*2 remains constant, it may be considered as a nonlinear load resistor (actually a cathode resistor here) in series with the control phototube *PT*1. Thus, it performs the same function as the phototube resistor *R*1 in the photoelectric relay discussed previously. However, it has two advantages. By varying the light on *PT*2 its effective resistance can be varied over a wide range; and since the light source is common for both phototubes, minor changes in this light should not upset the balance appreciably.

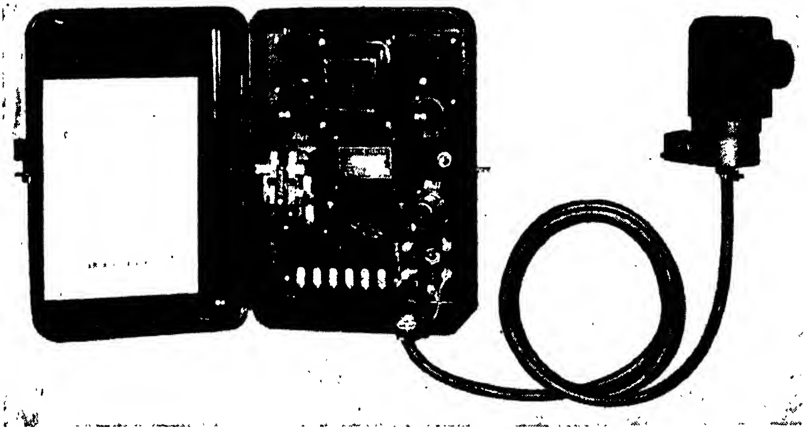


FIG. 20.6. The GE CR7505N110 photoelectric relay with extended phototube holder. (*Courtesy of General Electric Company*)

Refinements in this circuit consist in grounding the negative d-c bus; a series relay *C* warns of excessive amplifier current; and a relay in series with the light-source lamp warns of a lamp burnout.

The GE CR7505N110 Photoelectric Relay. This is a more advanced form of photoelectric relay; it employs a number of unusual circuits and deserves careful study (Fig. 20.7). It will be noticed immediately that there are two separate rectifiers, one for the output tube (at the top) and one for the voltage-amplifier tube. These are the two insulated halves of the 25Z6 rectifier.

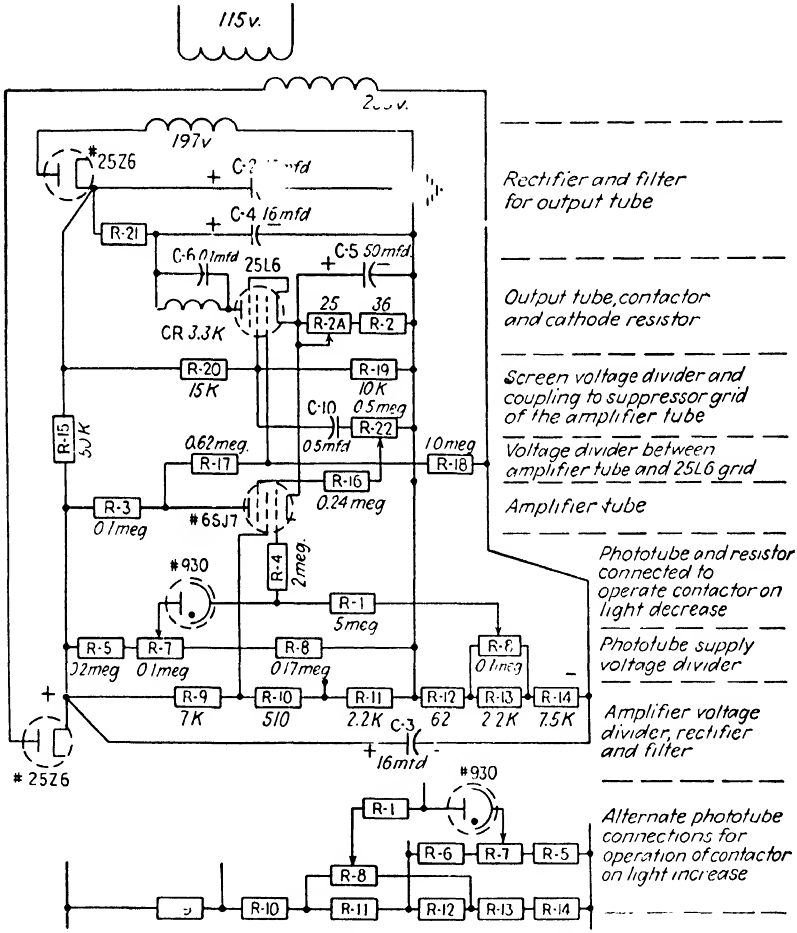


FIG. 20.7. Elementary diagram of the photoelectric relay of Fig. 20.6.

The top rectifier circuit includes a resistor π filter. The bottom rectifier uses a single large capacitor for a filter across the fairly high-resistance voltage divider. Since by changing terminal connections and throwing a switch on the panel the action of the phototube can be reversed, an alternate diagram of part of the circuit is drawn to show the other connection. Normally, of course, the circuit need be drawn only for the desired phototube connection.

Since the maximum permissible voltage across the gas-filled phototube is 90 volts, the dual-control potentiometers $R7$, $R8$ are used to obtain this voltage across the phototube and series resistor $R1$ throughout the range of adjustment of $R8$. This adjustment provides a bias on the amplifier tube equal to the potential drop due to the controlling phototube current through $R1$.

Initial Operation Conditions. The operation may be traced as follows: Assume sufficient light on the phototube to make the grid of the amplifier tube 6SJ7 equal to the cathode potential. This means that its anode is drawn down near the cathode potential (with maximum current flowing through the anode resistor $R3$) and the grid of the output tube 25L6 at the junction of the voltage-divider resistors $R17$ and $R18$ is well negative of the ground bus and tube cathodes. Hence, the 25L6 is definitely not conducting. The anode current of the 6SJ7 tube is flowing through the cathode resistors $R2$ and $R2A$ but the current and the resistance are so low that the IR drop is small. The arm of potentiometer $R22$ is assumed at ground potential.

Operation on Light Decrease. As the light on the phototube decreases, the phototube current and the drop across $R1$ decrease until, as the 6SJ7 grid goes sufficiently negative, the current in the anode resistor $R3$ decreases and the anode potential rises. This increases the potential across the divider $R17$ and $R18$, bringing the 25L6 output-tube grid more positive until a point is reached where the output tube begins to pass current. As soon as the output current becomes appreciable, its flow through the common cathode resistor $R2$ and $R2A$ raises the potentials of both the 6SJ7 and 25L6 cathodes. But the 6SJ7 stage has much the higher amplification so that the cathode rising with respect to the grid will permit its anode current to decrease rapidly. This draws the divider and 25L6 grid positive more rapidly, increasing the 25L6 current through the cathode resistor. Thus a "suicide," or snap, action takes place, permitting the 25L6 to pass full current through the contactor coil in its anode circuit. (See Fig. 14.11 for the basic circuit.)

When light on the phototube again increases, a point is reached where the grid of the 6SJ7 rises enough to start anode current flowing in that tube sufficiently to decrease the voltage across the divider *R*17 and *R*18. This drives the 25L6 grid negative and causes its anode current to decrease. When this occurs, a reverse snap action takes place and the contactor is immediately dropped out. Thus positive action of the contactor is ensured even though the change of light on the phototube is quite slow. The adjustment on *R2A* determines the amount of snap action and the range between pickup and drop-out.

The Pulse-lengthening Circuit. In the foregoing discussion we have assumed that the arm of the potentiometer *R*22 has been turned to the grounded end so that the suppressor grid of the 6SJ7 has remained at this potential throughout. Next let us consider this arm moved to the other extreme so that it is connected directly to *C*10. The other side of *C*10 is connected to the screen grid of the 25L6, on the voltage divider *R*19 and *R*20. The resistance of this voltage divider is fairly high so that the screen-grid current of the 25L6, when it snaps to full current, is sufficient to pull the screen considerably less positive than it was in the no-current condition.

This reduction of potential is transmitted through *C*10 to the suppressor grid of the 6SJ7 to drive it considerably negative. This definitely cuts off the anode current of the 6SJ7 until such time as *C*10 can recharge to the new condition—no matter what the potential of the No. 1 grid of the 6SJ7. Thus, when the arm of the potentiometer *R*1 is in this position, the potential of the No. 1 grid from the phototube need drop below the critical potential for only a brief time, less than 0.001 sec, to start current flow in the 25L6. After this the suppressor grid is driven negative, and a momentary locking action takes place that—in this extreme potentiometer position—will last for ½ sec or more. Intermediate positions of the potentiometer arm will give a shorter lock-in time before *C*10 discharges and the suppressor grid returns to ground potential.

Circuit Refinements. Circuit refinements consist in the switch for reversing the sense of phototube operation, as mentioned previously (page 255), and terminal connections directly to the No. 1 grid of the 25L6 tube so that, by external interlocking means, the grid may be connected to ground to hold the relay energized or to the negative bus to hold it deenergized in spite of the phototube action. By connecting the grid to ground through a normally open contact on the contactor, it is possible to hold in the contactor permanently after it has once been picked up momentarily by the pulse-lengthening circuit. Also, terminals are provided for capacity coupling between phototube and amplifier tube to permit operation only on rapid light changes.

An interesting detail is resistor *R*15, connected between the positive points of the two rectifiers. Since the power tube is off when the amplifier tube is drawing its maximum current, the power-tube rectifier has a higher potential than the amplifier rectifier and permits enough extra current to be drawn by *R*15 to balance the anode current of the amplifier tube, thus holding the potential across the amplifier-rectifier divider and the phototube practically constant.

A study of this circuit is especially helpful in acquiring an appreciation of the relative values of the currents and potentials that appear across different resistors. Note particularly the values of *R*2, *R*2*A*, and *R*15 in relation to the relative values of the other resistors in the neighboring circuits.

DIRECT-CURRENT MOTOR CONTROL

The Westinghouse DT3 Speed Control. This type of motor-speed control (Fig. 20.9) is capable of controlling some of the largest motors, since it operates on the field of an exciter, supplying the control field of the generator in a Ward-Leonard generator-motor combination. The indication of speed is taken from a d-c tachometer (or pilot generator) driven by the motor.

The circuit is quite simple. The exciter field is energized by a three-phase half-wave rectifier through three thyratrons with cathodes at a common potential. The grids of the thyratrons are controlled by the typical d-c and quadrature-phase-shift circuit. The quadrature phase is obtained by proper phasing of the grid transformers in relation to the anode windings.

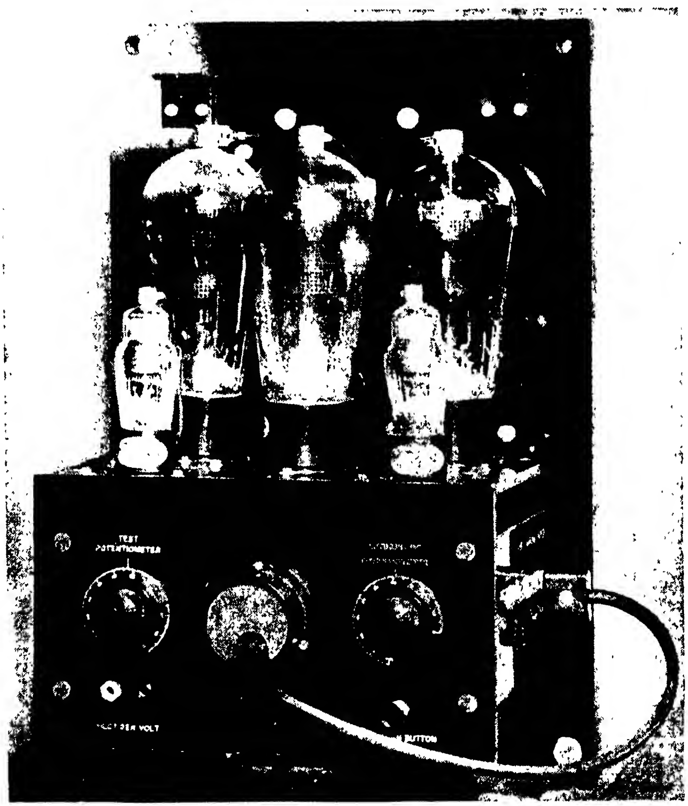


FIG. 20.8. Control panel of the Westinghouse DT3 motor-speed regulator. Note the test voltmeter with plug and jacks built into the panel. (*Courtesy of Westinghouse Electric Corporation*)

The d-c control component is obtained from the RJ-571 amplifiers, two of which are paralleled for maximum reliability. Direct current for this stage comes from a three-phase copper oxide rectifier and is filtered by a 4-μf capacitor. The voltage divider consists of two 10,000-ohm fixed sections and a 1500-ohm variable bias section for the RJ-571 tetrodes. The KU-628 thyratron

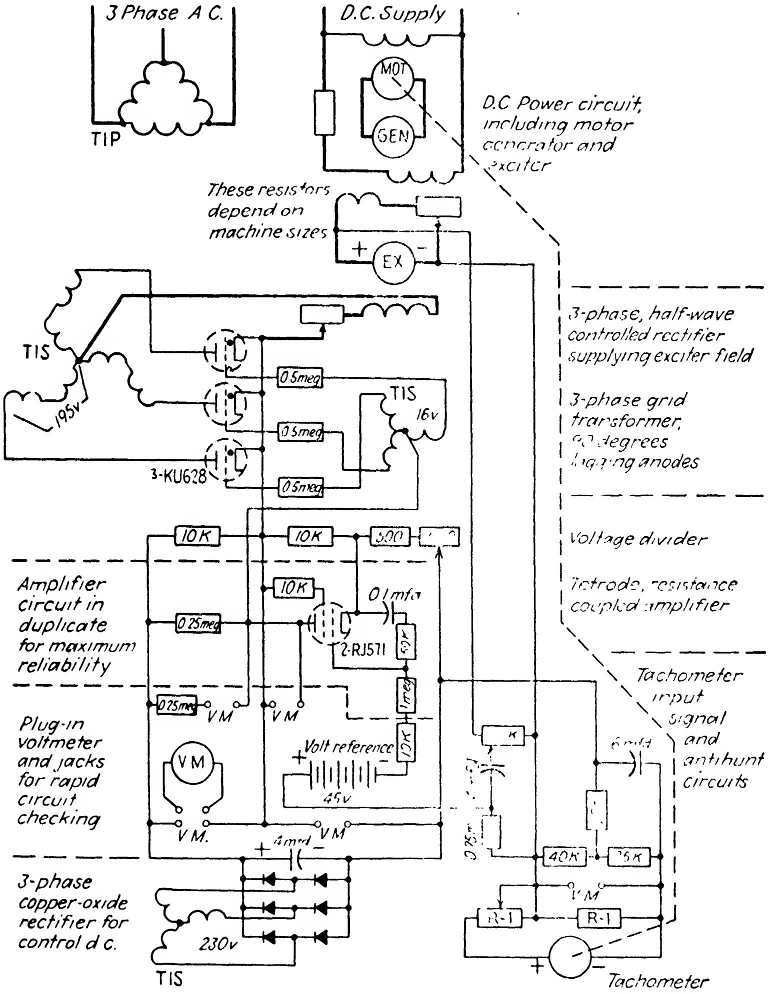


FIG. 20.9. Elementary diagram of the Westinghouse DT3 speed regulator.

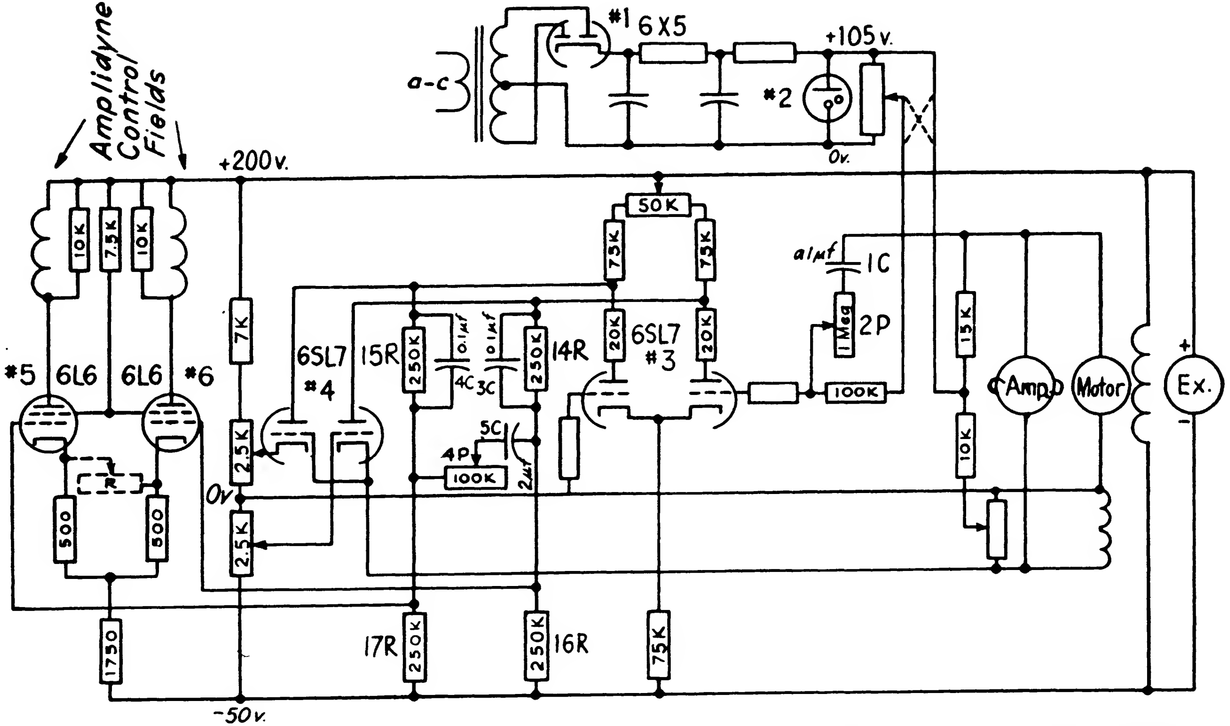


FIG. 20.10. Elementary diagram of the electronic amplidyne. Balanced voltage- and power-amplifier stages feed balanced amplidyne fields. Twin-triode tube 4 is the current limit takeover.

cathodes tap off at the mid-point of the fixed resistors, and the center point of the thyratron grid transformer is connected to the anodes of the RJ-571's and their common 0.25-megohm anode resistor.

A portion of the tachometer voltage, depending on the speed to be held, is matched against a 45-volt B battery as a reference standard, and the difference is applied to the control grids of the RJ-571's. This may not be immediately apparent because in this circuit the various antihunt circuits are placed. They may be recognized as follows: First we have a capacitor-resistor phase-advance circuit on the tachometer voltage itself. Next an adjustable resistor-capacitor lead network is taken from the exciter-armature voltage. Finally, a lag network is applied at the grids to form an effective notch network (Fig. 18.13).

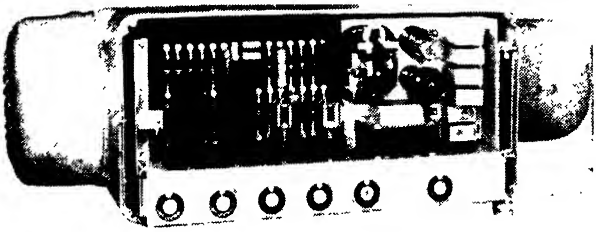


FIG. 20.11. The General Electric electronic amplidyne. *(Courtesy of General Electric Company)*

The desired speed is set by adjusting the portion of the tachometer voltage which is balanced against the fixed (battery) reference voltage by the use of the rheostat $R1$.

Refinements. Refinements consist in connecting, mechanically, a rheostat in the exciter-armature circuit to the speed control to hold the regulator in its midrange over the desired speed range and to assist in the prevention of hunting. The amplifier tubes are paralleled, as mentioned, for greatest reliability. A voltmeter is mounted on the panel, with a plug and jacks brought out from key points in the circuit for maximum convenience in circuit checking.

The General Electric Electronic Amplidyne. In this versatile d-c power unit the smooth, quickly reversible d-c power of the amplidyne generator is combined with the flexibility of the electron-tube input to produce an amplifier element of interesting possibilities. The assembly of Fig. 20.11 consists of an a-c motor driving a 1500-watt, 250-volt amplidyne generator and a small 150-watt, 250-volt exciter which supplies the amplifier anode power and also excites the field of a d-c motor up to 1½ hp when used with the amplidyne in a regulating or servo system.

As seen in Fig. 20.10, the electronic amplifier consists of a balanced long-tailed pair voltage-amplifier stage (tube 3) followed by a similar balanced power stage (tubes 5 and 6) which excites the two balanced control fields of the amplidyne. In this manner the circuit is well protected from variation in anode voltage and filament heating even though the complete electronic-amplidyne amplification is several hundred times.

The twin triodes of tube 4 act as current-limit tubes. The *IR* drop across the amplidyne-compensating field and the motor series field is applied to the grid of one triode and to the cathode of the other to give the polarities of grid potential required to take over the control from the anode of the corresponding voltage-amplifier triode of tube 3. The potentiometers 5*P* and 6*P* permit separate current-limit adjustments in each direction.

The circuit amplification can be adjusted, with a compensating gain in forcing action, by the "shoestring" attenuator between the cathodes of the power tubes.

Stabilizing for most systems can be accomplished by the lead circuit 1*C* and 2*P*, the notch circuit 5*C* and 4*P*, and the divider bridge 3*C*, 4*C*, 14*R*, 15*R*, 16*R*, and 17*R*.

Another feature of the circuit is the insulated reference voltage maintained by the 105-volt regulator tube 2. In addition to the connection shown, the reference potential may be compared against an *IR* drop to maintain constant current (with voltage limit) or to supply anode voltage for a phototube input, etc.

THE RELIANCE VSC ELECTRONIC VARIABLE-VOLTAGE DRIVE

This circuit, a development of the Reliance Electric and Engineering Company, applies electronic excitation to both the field of the motor and to the field of the generator supplying the armature voltage. Figure 20.13 shows a somewhat simplified circuit. Both fields are excited from "freewheeling" half-wave shunted rectifier circuits, having thyratrons controlled by d-c and quadrature-phase-shift grid circuits. However, the circuits for constant-rate acceleration and deceleration and the circuits for transition from armature to field control are somewhat unusual.

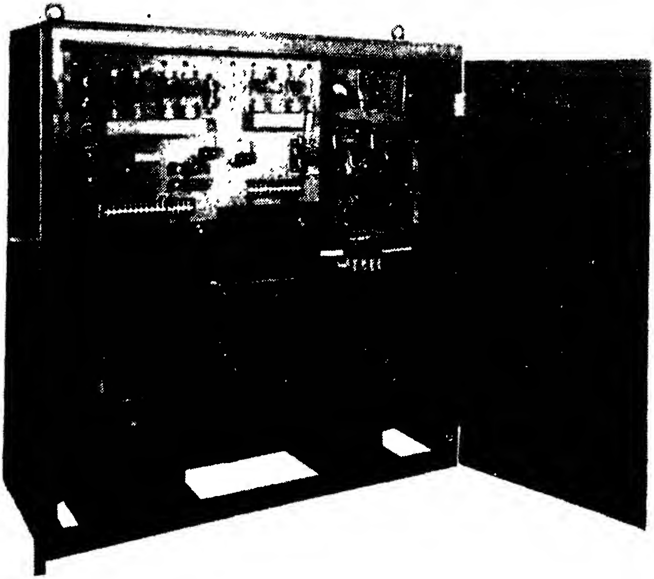


Fig. 20.12. The Reliance Electric and Engineering Company VSC Drive. (*Courtesy of Reliance Electric and Engineering Company*)

Constant-rate Acceleration. The circuit for constant-rate acceleration and deceleration is composed of the timing capacitor $C1$ and the 6SJ7, 6SN7, and two 6H6 tubes. It is, in effect, a combination of the pentode constant-rate charging circuit of

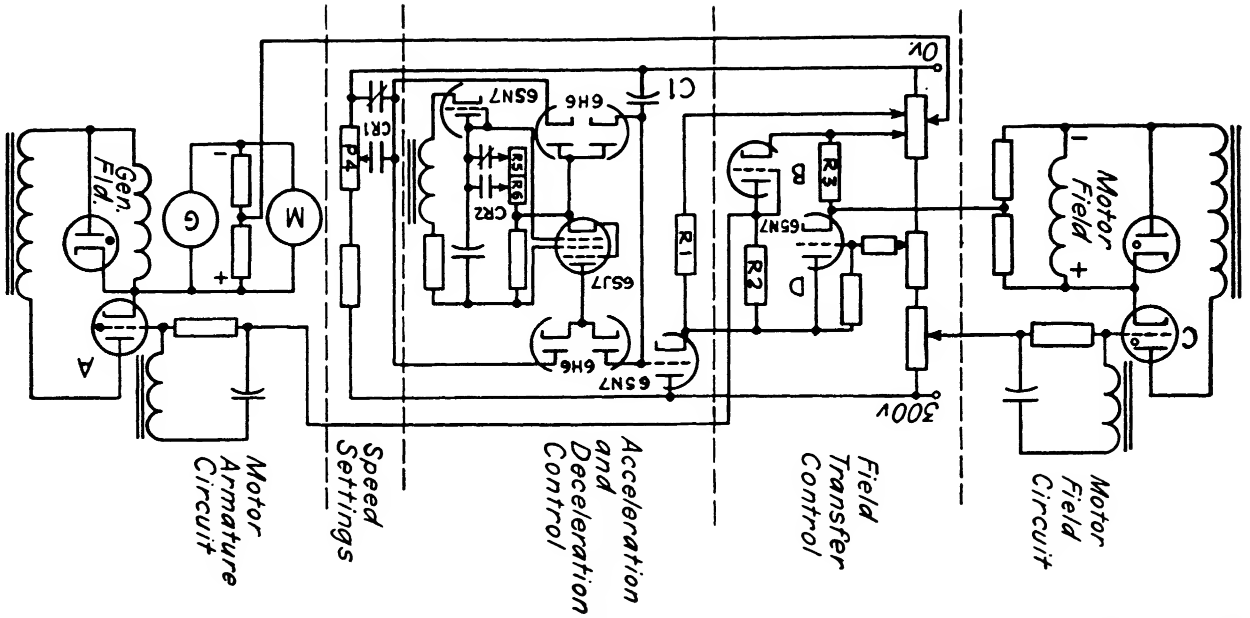


FIG. 20.13. Elementary diagram of the VSC drive. Adjustable voltage by "free-wheeling" rectifiers for both motor field and armature generator field.

Fig. 14.1 on page 157 and the bisected rectifier square of Fig. 15.4 on page 176, which permits the pentode to function as a constant-current element for both the charge and discharge of the capacitor *C*1, depending on the potentials established by the contactor *CR*1. One half of the 6SN7 twin triode acts as a rectifier for the screen and bias circuit of the 6SJ7 pentode and the other half as a cathode follower to transfer the timing-capacitor potential. By inserting different bias resistors *R*5 and *R*6, through contactor action different rates may be set for acceleration and deceleration.

Transfer between Armature and Field Ranges. When a d-c motor is to be operated above base speed in the weak field range, it is almost always desirable to accelerate to base speed with full field in order to obtain maximum torque and to weaken the field thereafter. Thus, it is desirable that, as the timing capacitor charges up, full thyratron conduction in the field rectifier continue as the armature rectifier is phased from off to full on, after which the field thyratron is phased back. Since both thyratrons have the quadrature-grid-phase circuit supplied through transformer windings and *RC* network, it is necessary only to change the relative d-c potentials between grid and cathode for control.

The generator-field-rectifier-thyratron grid voltage may be traced from the thyratron *A* cathode through a portion of the generated armature voltage to a point on the d-c voltage divider, and from the divider through the cathode follower resistor *R*1, *R*2, the anode resistor of tube *B*, and the quadrature-phase circuit to the grid of *A*. Therefore, as the timing capacitor *C*1 charges up, the generator-field thyratron starts conducting and the generator voltage starts to rise. Because part of the generator voltage is included in the grid circuit, a feedback action takes place so that the armature voltage builds up fairly linearly with the capacitor voltage. When the rising capacitor and *R*1 voltage reaches the cathode potential of tube *B* ($\frac{1}{2}$ of a 6SN7 connected as a diode), its rectification action snubs the grid voltage at that point and the armature voltage is held constant, the continuing rise in capacitor *C*1 potential being absorbed by the anode resistor *R*2. On deceleration, as the capacitor discharges, no decrease in armature voltage takes place until the capacitor *C*1 potential drops below tube *B* cathode potential.

Motor-field Weakening. The grid circuit for the motor-field thyratron *C* may be traced from its cathode through a voltage divider across the motor field to the cathode resistor *R*3 of tube *D*, to the supply d-c voltage divider, and from the divider to the quadrature circuit and grid. Because of the feedback action of the *IR* drop across part of the field voltage, which is opposed to that of the d-c-supply voltage divider, full field is maintained on the motor field so long as tube *D* is not conducting and there is no potential across the cathode resistor *R*3. (Note that the resistor *R*3 is connected to the divider at the same point as the cathode of tube *B*, which limits the armature voltage.) Hence, as the rising timing-capacitor potential rises past this point, tube *D* starts conducting; and its cathode potential, rising with the increasing *IR* drop of *R*3, raises the cathode potential of thyratron *C* with respect to its grid, decreasing the field voltage. The amount that the cathode of *D* can rise and the minimum field voltage are set by the point on the d-c voltage divider to which the voltage divider on the grid of *D* is connected. As the cathode of tube *D* rises to a potential where the grid becomes negative, the conduction through *D* becomes less and the increasing timing-capacitor potential will have little effect in raising the *D* cathode potential higher and further weakening the field.

In practice the grid action of *D* becomes a secondary safety-limiting action, since the actual limit to timing-capacitor potential rise will be set at some lower value by the speed-control potentiometer, *P*4.

Other Features. Reversing of the motor direction and dynamic braking are done by magnetic contactors in the usual manner. The constant-rate decelerating gives a controlled degenerative action. Multiple preset speeds may be set up on potentiometers and switched to control the timing-capacitor potential circuits as desired.

The General Electric Thymotrol GE CR7507G. This circuit (Fig. 20.16) permits control of the speed of a d-c motor over a wide speed range, including variation of both armature and field voltage and with provisions for limitation of current during acceleration. It also provides compensation for armature *IR* drop to obtain a more constant speed when the armature-terminal voltage is used as the speed reference.

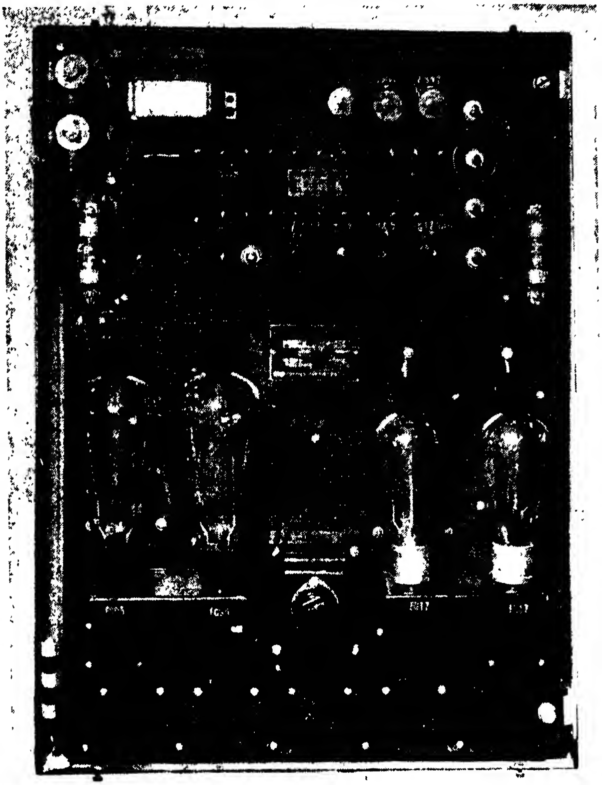


FIG. 20.14. The Thymotrol panel for complete motor control, GE CR7507G118. (*Courtesy of General Electric Company*)

In order to accomplish the various functions mentioned above it is natural that a number of tubes will be required. To conserve panel space and save wiring, general use is made of dual tubes in which two insulated triodes or a triode and twin diode are included in the same envelope. However, this should cause no confusion since the two halves may be separated in the elementary diagram.

The Power Circuits. Starting at the top of the elementary diagram (Fig. 20.16), we see first the power supply for the motor armature, a single-phase, full-wave rectifier using thyratrons as rectifiers. Next to it is a similar circuit for the motor field. Both sets of thyratrons are controlled by common center-tapped grid transformers, the phases of which are shifted by the resistor—saturable-reactor phase-shifting bridges (*SRA*, *SRF*) seen along the left-hand side of the circuit. These bridges are so connected that increased current in the d-c windings of the saturable reactors will cause the thyratrons to conduct earlier in the cycle and thus pass a larger average current. Hence, in considering the d-c control circuit below we need remember only that more direct current in the saturable reactor *SRA* will increase the armature

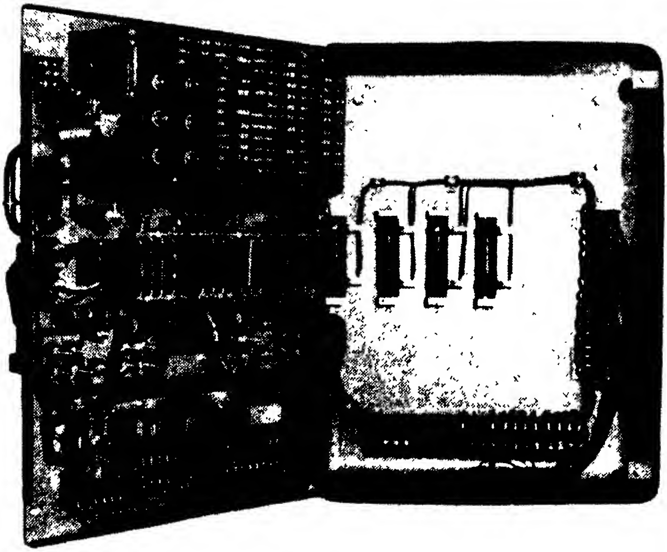


FIG. 20.15. Back view of a Thymotrol panel showing typical wiring and components of a compact electronic control panel. (*Courtesy of General Electric Company*)

input voltage and current, and increased current in the field saturable reactor *SRF* will increase the field current.

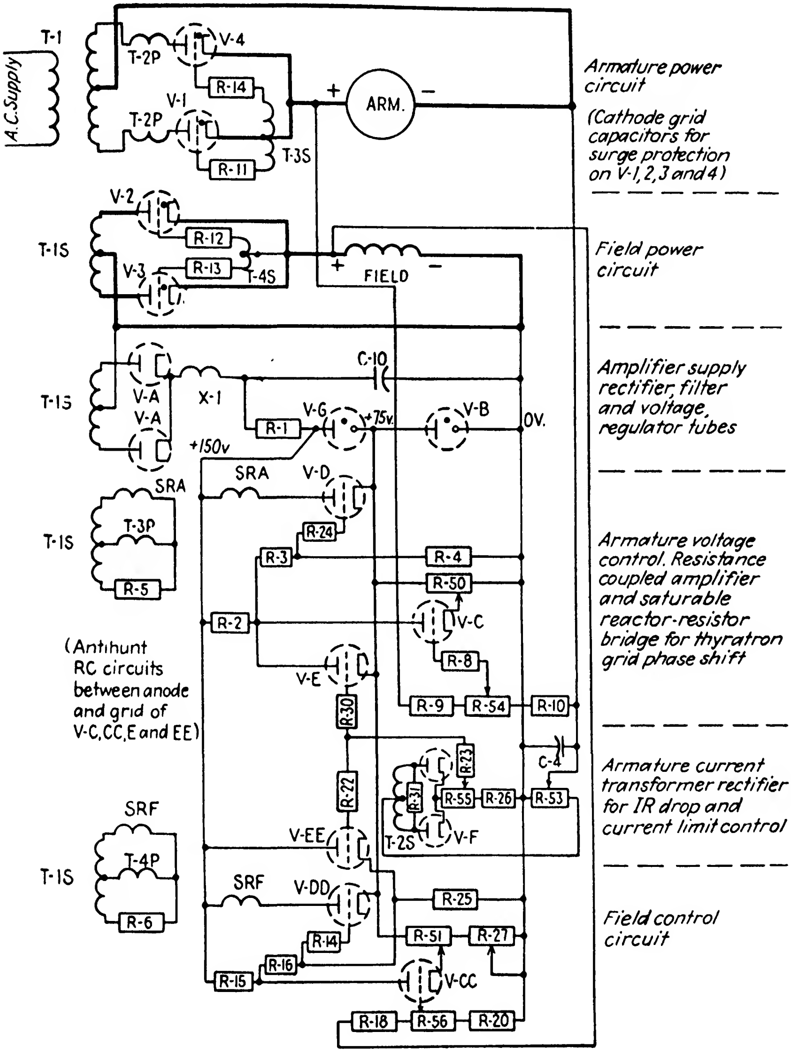


FIG. 20.16. Elementary electronic circuit of the Thymotrol.

The D-C Control Circuits. The control circuit operates from d-c supplied by the full-wave rectifier *VA* shown below the motor field. This d-c is filtered by an inverted L filter and regulated by two 75-volt voltage-regulator tubes, the more negative of which, *VB*, acts as the reference for speed voltage and field voltage.

The direct current for the armature saturable reactor *SRA* is controlled through tube *VD*, whose grid is fed by voltage divider *R*3, *R*4 from the resistor *R*2, which is the common anode resistor of tubes *VC* and *VE*. Assuming that the tube *VE* is nonconducting (its normal state, as we shall learn later on page 271), the armature control is exercised by tube *VC*. The cathode of this tube is at a potential preset on the voltage divider *R*50 across the 75-volt regulated supply, while its grid is connected to an adjustable point on a voltage divider *R*9, *R*54, *R*10, which is seen to be connected across the motor armature. Hence, if we assume for a moment that the arm of *R*50 is turned toward the negative bus, we note that the tube *VC* conducts more current and draws its anode voltage more negative. The same thing happens whenever the armature voltage rises high enough for the grid of *VC* to approach its cathode potential.

Thus the sequence of armature control from the speed as indicated by the armature voltage is as follows: Rising armature voltage permits the grid of *VC* to become more positive. *VC* passes more current, drawing its anode and the grid of *VD* more negative. *VD* passes less current through the d-c winding of *SRA*, the armature saturable reactor, the armature thyratrons are phased back, and the armature voltage is regulated at a point controlled by the grid bias of *VC*. The armature-voltage speed that will be held is determined by the setting of the arms on *R*50 and *R*54.

IR-drop Compensation. The armature voltage is not a true indication of speed. It includes also the voltage produced by the *IR* drop due to the current passing through the resistance of the armature winding. And for a given speed this *IR* drop will vary with change in load, so that if the armature terminal voltage were held constant the speed would vary with the load. In order to compensate for the *IR* drop we must create a signal proportional to the current and subtract it from the total armature voltage. This is done in the next lower circuit.

At the top of the circuit, in the armature power section, are seen two current-transformer primary windings *T2P* in the thyratron anode leads. These are on a common core with the mid-tapped secondary *T2S* and supply alternate half waves of primary excitation. *T2S* and rectifier tube *VF* feed the voltage divider *R*55, *R*26, and *R*53 in a full-wave circuit to produce a d-c voltage proportional to the armature current. For the moment we are concerned only with the drop across *R*53. It will now be seen that if the arm of this potentiometer is moved to include part of the potential in the circuit to the grid of *VC*, we have here just what was needed, a voltage proportional to the armature current, which is subtracted from the armature terminal voltage before this voltage is applied to the grid of *VC*. The portion of *R*53 used is, of course, adjusted to correspond to the resistance of the armature of the particular motor used.

Current Limit. Next to be considered is the remaining part of the voltage proportional to the armature current, that across *R*55 and *R*26. This is used as a current-limit control to prevent the flow of excessive armature current, which might damage thyratrons or motor. It will be noted that a preselected portion of this voltage is applied to the grid of *VE*. Under normal conditions the grid is well negative of the cathode and the tube is nonconducting, as mentioned above. However, should the current rise high enough to permit the grid to rise to cathode potential, *VE* does conduct and draws its anode—and the grid of *VD*—sufficiently negative to decrease the current in *SRA* and prevent further rise of armature voltage and current.

It should be stressed that this action takes place independent of anything that may be done by *VC* at the time. The current limit also overrides the field control through the action of *VEE*, as will be explained later (page 273).

Field Control. At the bottom of the diagram is the field control circuit. This is seen to be very similar to the armature control circuit. The d-c for the field saturable reactor is controlled by *VDD*, the grid of which is fed by the voltage divider *R*16 and *R*25 from the anode of *VCC*, which, similar to *VC*, has a cathode potential of a preset point on the voltage divider *R*51 and the grid of which is at a potential proportional to the voltage across the motor field. An increase in the motor-field current and voltage above the preset amount will raise the potential of the grid of *VCC*, increasing the current through this tube and drawing its anode and the grid of *VDD* more negative. This decreases the current in *VDD* and *SRF*, phasing back the field supply thyratrons to prevent further rise in field current.

In order to make it possible to preset the motor speed over the complete range of armature and field voltage permitted by the motor design, the control element is a dual potentiometer composed of both *R*50 and *R*51 mounted in tandem on a common shaft. The first half of the shaft motion moves the arm of *R*50 from the negative bus to the 75-volt bus to provide any preset armature voltage. During the second half of the control motion this arm rides over a low-resistance copper path so that the *VC* cathode remains at the 75-volt potential. On the other hand, the arm of the other potentiometer *R*51 rides over a copper path during the first half of the motion so that the cathode of *VCC* remains at its most positive point, 75 volts, to provide full field during the time that armature-voltage control is used. During the second half of the control shaft motion the arm of *R*51 is moved more negative to provide a weaker field for the speeds higher than base speed. The weakest field that may be used is set by *R*27 as determined by the motor characteristics.

It should be noted that the speed control is applied to the armature voltage and not to the field. The field setting determines roughly the speed necessary for the armature to turn to produce a counter emf necessary to match the 75 volts across *R*50 under the field weakened condition, but the close regulation of the speed is always done through small changes in the armature voltage.

Current Limit on Field Control. Let us refer back to the action of *VEE*. It will be remembered that increased armature current increases the potential of its grid. At the preset current limit this grid becomes sufficiently positive to permit *VEE* to conduct, drawing its cathode—and with it the grid of *VDD*—more positive and increasing the current through *VDD* and *SRF* to the value necessary to increase the field current sufficiently to prevent further rise in armature current. In operating above base speed it is best first to limit the armature current by increasing the field strength before reducing the armature voltage. This means *VEE* should conduct at a lower value of armature current than *VE*. The cathode of *VEE* is connected to the grid of *VDD* and therefore, when the field is not at full strength, is negative with respect to the cathode of *VDD* and also that of *VE* (both on the 75-volt bus). Hence, the rising common potential of the grids of *VEE* and *VE* will permit *VEE* to conduct first, raising its cathode and the grid of *VDD* before *VE* is permitted to conduct.

In a similar manner, no matter where the dual-potentiometer speed control is set when the motor is started, the current-limit voltage will ensure that full field will be applied to the motor if necessary until the motor has accelerated past base speed. Above base speed the field will become weakened only when the accelerating current has dropped below the preset current limit.

The Complete Circuit. For the sake of simplicity discussion of the magnetic motor contactor, reversing contactors, dynamic braking resistors, field-failure relays, fuses, and other typical magnetic control not necessary to the understanding of the electronic circuit has been omitted. Also not shown are surge-protection capacitors between thyratron cathodes and grids, and resistance-capacitor lag networks for stabilizing (see Fig. 18.12) between the anode and grid of *VC*, *VCC*, *VE*, and *VEE*.

Tachometer Control. Although with the addition of the *IR*-drop compensation the motor speed can be held within 2 or 3 per cent of the initial setting over a wide range of speeds and loads, if the best accuracy is required a tachometer driven by the motor is used to supply the voltage proportional to the motor speed. Since the load on the tachometer is constant, the generated voltage is a more precise indication of its speed and accuracies of better than 1 per cent in speed control are possible.

Questions

1. Draw the elementary diagram for a simple photoelectric relay operating on d-c obtained from an a-c line without a transformer.

2. Why does a balanced series phototube circuit permit a highly sensitive circuit?

3. Describe the snap action of the GE CR7505N110 photoelectric relay. Why is this action desirable?

4. Indicate, by drawing superimposed sine waves, the phase relation between anode and grid voltages and the required range of grid-voltage swing on the thyratrons in the Westinghouse DT-3 speed regulator.

5. Describe the action of the GE Thymotrol CR7507G118 when starting up with a speed setting in the weak-field range.

6. Why is the GE electronic amplidyne quite insensitive to exciter-voltage fluctuations?

7. Describe the action of the Reliance VSC drive when starting up to a speed in the weak-field range.

CHAPTER XXI

ALTERNATING-CURRENT RELAY AND POWER CIRCUITS

ALTERNATING-CURRENT RELAY CIRCUITS

For general-purpose inexpensive devices such as electronic timers and photoelectric relays it is often desirable to use the fewest number of tubes and to operate the circuit directly on a-c power without rectification other than in the control tube itself. Some of these typical circuits will now be considered.

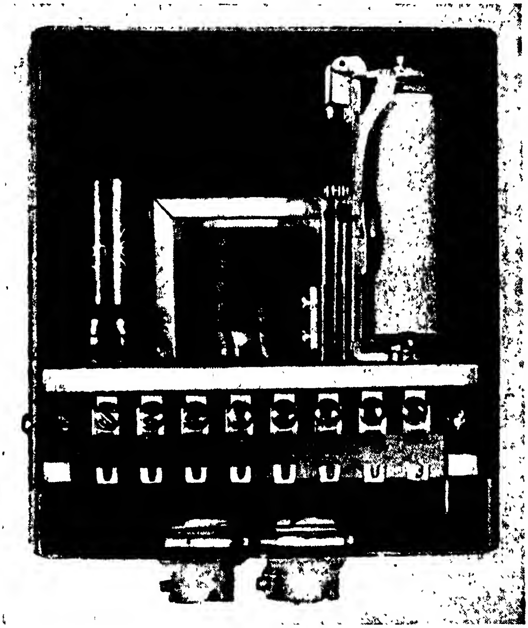


FIG. 21.1. The ES-15 electronic switch. (*Courtesy of Ripley Company*)

The Ripley Electronic Switch ES-15. This device (Fig. 21.2) uses a simple form of a-c circuit which substitutes transformer windings for the batteries or voltage divider of the d-c circuit. The anode circuit winding has sufficient voltage so that, when the grid of the 6J5 triode pliotron is at cathode potential, enough current will be passed through the tube during the positive half cycle to pick up the contactor and to store enough electrons in the parallel capacitor $C1$ to hold it in during the negative half cycle. However, the grid of the triode is normally held sufficiently negative by the opposite-phase bias winding to render the tube nonconducting. The grid is connected, not directly to the bias winding, but through a high-resistance $R1$.

It should be noted that on the inverse half cycle when the tube anode is negative the grid bias winding becomes positive and the grid draws a few microamperes until the grid-cathode drop and the IR drop in $R1$ add up to the instantaneous bias voltage. But since the anode is negative, there is no electron flow to the contactor even though the grid is positive.

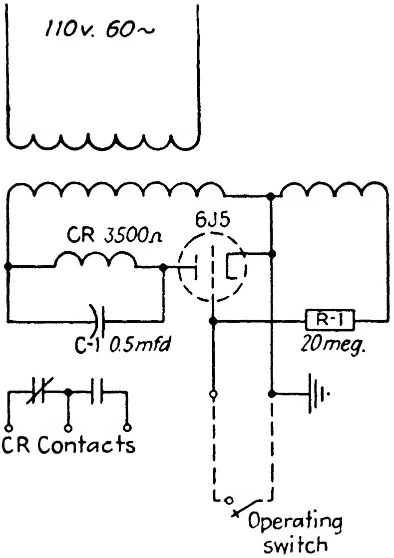


FIG. 21.2. The circuit of the ES-15 electronic switch.

To make the triode conducting and to pick up the contactor, the grid is connected directly to the grounded cathode. The bias voltage will appear across $R1$. The current passing through the initiating contact is only the current through this resistor, a few microamperes.

The contactor is provided with single-pole double-throw contacts to permit either making or breaking the controlled circuit when the grid-ground contact is made.

The General Electric Electronic Timer GE CR7504A1A. This form of timer (Fig. 21.4) is designed to delay the closing of the contactor for a preset time after the initiating switch is closed. This is done by precharging the grid-bias capacitor *C*1 through grid rectification action before the switch *SW* is closed. When the switch is open, it is seen that the cathode is connected through *R*2 to the same side of the line as the anode; so there can be no electron flow from cathode to anode. However, the grid is connected through *C*1 and *R*1 to a preset point on the divider *R*3, *P*1 between the a-c lines. Thus grid current will flow, charging up *C*1 to almost the full peak difference in potential between the preset point on *P*1 and the left-hand line. This is because the resistance of *R*2 is such a small percentage of *R*1 that the *IR* drop in *R*2 may be neglected.

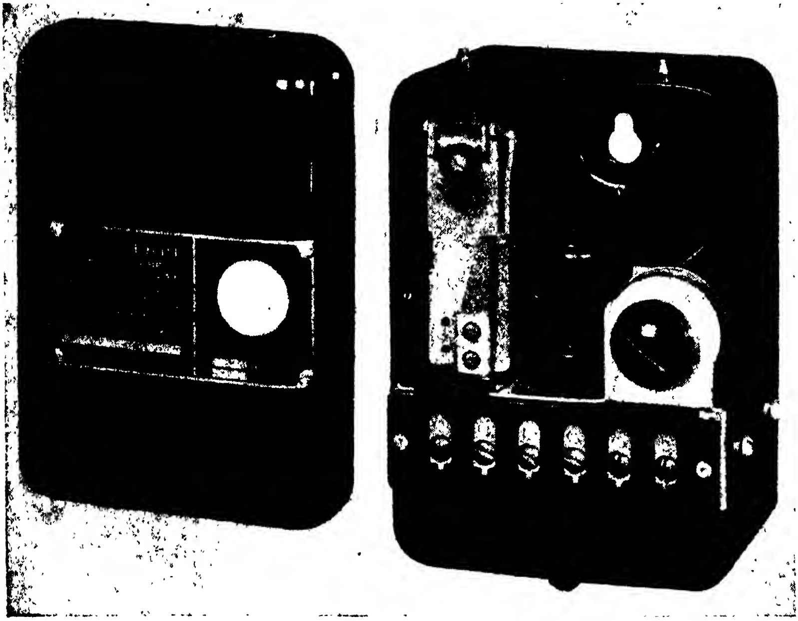
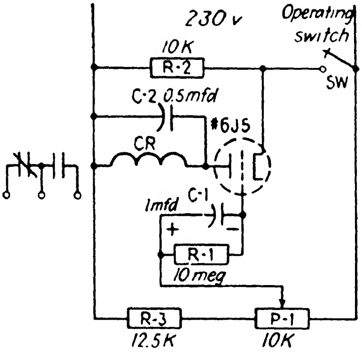


FIG. 21.3. The GE timer CR7504A1A with cover removed. (*Courtesy of General Electric Company*)

The Timing Operation. When the switch is closed, the tube cathode is connected to the right-hand line and the cathode-grid potential now consists of the negative d-c voltage stored in *C*1 superimposed on an inphase a-c voltage consisting of that portion of the voltage across *P*1 between the preset point and the right-hand line. The time delay is determined by the decay of the voltage across *C*1 as it discharges through *R*1. Since these components are of fixed value, the time constant is fixed and the time is determined by the point at which the grid circuit is connected to *P*1 (see Fig. 15.13 for typical timing action). As this point is moved farther to the right, the time is increased by two means: (1) The voltage to which *C*1 is charged is increased. (2) The inphase voltage, which tends to cause the tube to conduct, becomes smaller. Particularly at the shorter time settings the inphase voltage becomes a large fraction of the capacitor voltage, and so the grid is driven positive along a rather steep curve at a small fraction of the *R*1, *C*1 time constant to provide accurate timing in that portion of the range at which it is most necessary. Since the capacitor charge and the inphase voltage are both percentages of the line voltage, this circuit is partly self-compensating for reasonable variations in line voltage.



C-1 and R-1 depend on the timing range desired

Relay operates on 230v or on 115v from internal autotransformer

FIG. 21.4. Circuit of the GE CR7504A1A timer.

The contactor has single-pole double-throw contacts. It is held in during the negative half cycle by the charge stored in a parallel capacitor as in the case of that in the electronic switch described above.

The Ripley Timers, Type 52, etc. These timers (Fig. 21.6) adjust the time setting by varying the value of the resistance in the resistance-capacitor timing circuit. By simple changes in circuit connections it is possible to obtain a variety of timing actions as the initiating switch is closed and opened.

A **Circuit.** In the circuit combination *A* the contactor is normally picked up while the switch is open. When the switch is closed, the out-of-phase bias voltage is applied to the grid, dropping out the contactor and permitting the grid capacitor $C1$ to charge up by grid rectification to the peak value of the bias voltage. When the switch is again opened, the pickup of the contactor will be delayed until the grid capacitor has discharged sufficiently through resistor $R1$ to permit the tube to pass enough current again. $R2$ in series with the cathode prevents short-

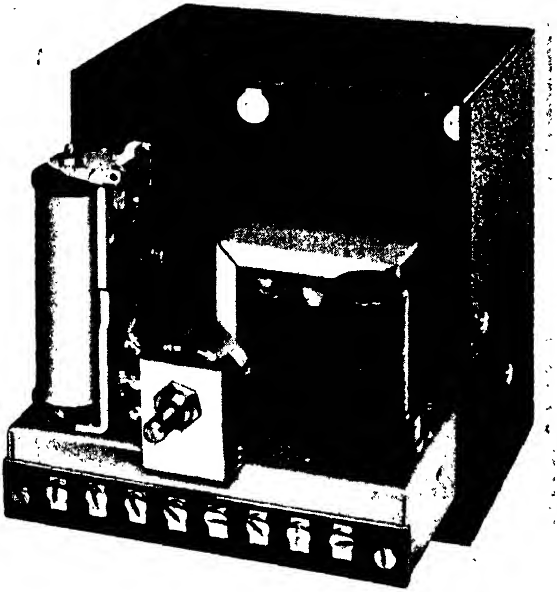
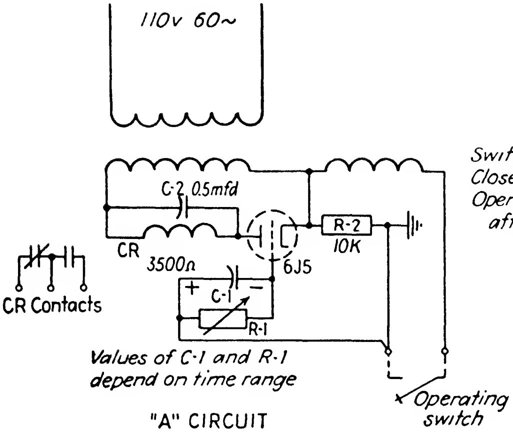


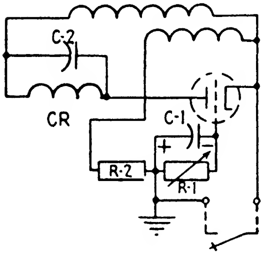
FIG. 21.5. The Ripley timer type 52 with cover off and chassis partly withdrawn. (*Courtesy of Ripley Company*)



Switch open - CR energized
Close switch - CR drops out
Open switch - CR energized
after time delay

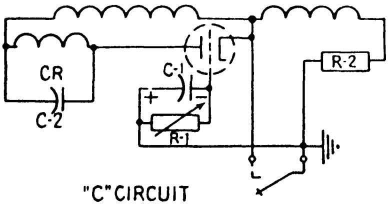
Values of C-1 and R-1
depend on time range

"A" CIRCUIT



Switch open - CR energized
Close switch - CR drops out
but is energized again
after time delay

"B" CIRCUIT



Switch open - CR is dropped out
Close switch - CR energized
after time delay

"C" CIRCUIT

Fig. 21.6. Alternate circuits for the Ripley timer type 52.

circuiting the bias winding when the switch is closed and provides the *IR* bias voltage.

B **Circuit.** Circuit combination *B* reverses the bias winding. While the initiating switch is open, the contactor will be picked up and the grid capacitor *C*1 will charge up to the peak bias voltage by grid rectification. When the switch is closed, the grid is immediately driven negative by the amount of the charge on the grid capacitor *C*1 and the contactor is dropped out to remain out until the grid capacitor *C*1 has discharged through the adjustable parallel resistor *R*1 and the grid has risen near enough to the cathode potential to permit sufficient electron current to flow.

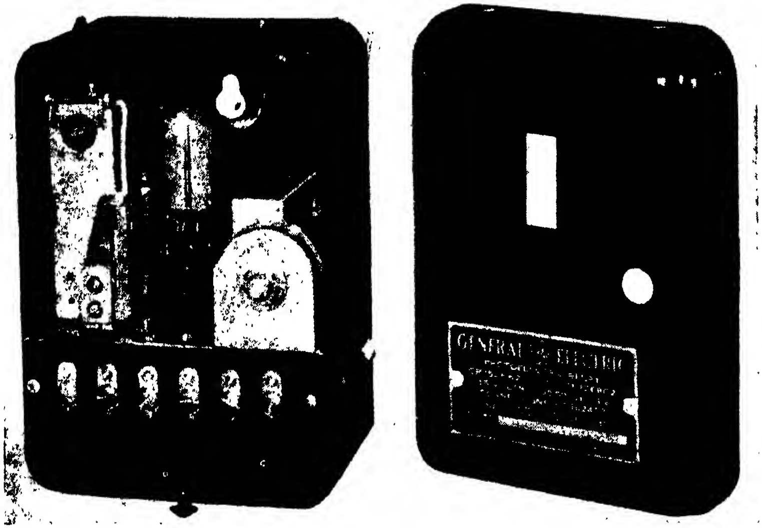


FIG. 21.7. Photoelectric relay GE CR7505K2. An extended phototube holder may be used. Left, cover removed; right, cover. (*Courtesy of General Electric Company*)

C **Circuit.** In circuit combination *C* the contactor is normally dropped out while the switch is open because the grid is held negative both by the out-of-phase bias voltage and the charge built up on the grid capacitor *C*1 through grid rectification on the negative half cycle. When the switch is closed, the effect of the bias winding is removed from the grid-cathode circuit but the grid is still held negative by the charge on the capacitor $C1$. But since the bias winding is no longer effective, the capacitor can no longer retain its charge and in the time determined by the adjusted value of $R1$ will discharge sufficiently to permit the tube to conduct and pick up the contactor.

A noteworthy feature of all the above circuits is the grounding of one side of the switch circuit. This often simplifies the wiring of the switching circuit.

An insulated single-pole double-throw contact arrangement is provided on the contactor to operate the controlled power circuit.

A Photoelectric Relay Operated from A-C (GE CR7505K2). This is a pliotron circuit very similar to those of the timers described above but having a phototube to supply the controlling signal (Fig. 21.8). The anode transformer winding and the contactor have been interchanged to permit easier wiring of the contactor and capacitor at ground potential; but since this is a series circuit, the operation is not affected. The phototube in series with a small capacitor $C1$ is connected across a 60-volt transformer winding. Across part of this winding is a potentiometer so that the pliotron cathode may be connected to the required point to obtain operation at the desired light level.

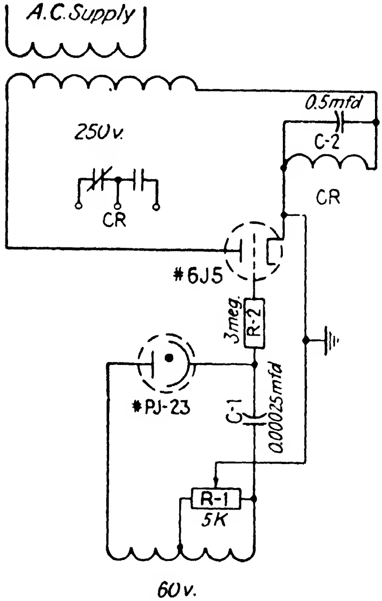
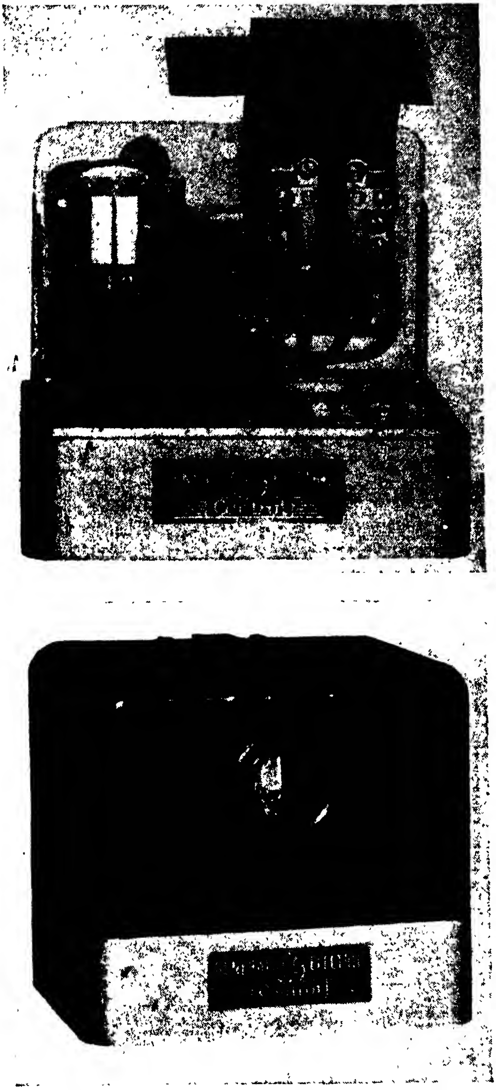


FIG. 21.8. Circuit of the photoelectric relay of FIG. 21.7.

The phototube and pliotron grid action can best be studied by noting the inphase relation of both the phototube and anode windings and the point on the phototube winding to which the cathode is connected. Assuming the phototube to be dark, the



FIGS. 21.9. and 21.10. A photoelectric relay using a thyratron, GE CR-7505K100. Views with cover off and cover on. A phototube-thyratron circuit is also used in the Westinghouse type RQ relay. (*Courtesy of General Electric Company*)

capacitor $C1$ is charged up by grid rectification on the negative half cycle just as in the case of the electronic timers. The voltage of the charge depends on the portion of the phototube winding below the cathode point. The combination of this out-of-phase voltage and the capacitor charge is more than sufficient to hold the pliotron nonconducting.

If a small amount of light shines on the phototube, the electron flow (which can take place only on the positive half cycle) will tend to discharge the capacitor but will not have sufficient effect to raise the pliotron grid enough to permit pliotron current to flow. However, as more light shines on the phototube, a phototube current is soon reached that is sufficient not only to discharge the charge on the capacitor due to the previous half-cycle grid rectification but to reverse that charge to balance the out-of-phase phototube bias winding component and to permit sufficient current to flow in the pliotron to pick up the contactor. The contactor will remain picked up only so long as there is sufficient phototube current to reverse the capacitor charge each cycle. The amount of charge to be reversed—and hence the intensity of light required—depends on the point at which the pliotron cathode is tied to the phototube winding. The grid resistor $R2$ protects the phototube against intense light, which would otherwise cause excessive current to be drawn through the phototube by way of the pliotron cathode and grid.

An A-C Photoelectric Relay Using a Thyratron (**GE CR7505-K100**).[1] All the a-c relays discussed previously have employed pliotrons. This device (Fig. 21.11) uses a shield-grid thyratron. It also has a *backward* circuit in which the contactor is dropped out as light on the phototube is increased, as contrasted to the *forward* circuit in which the contactor is picked up on light increase. However, this relay was designed for simple counting and limit switch operations in which the phototube is normally lighted. The thyratron and contactor, operating only when the phototube is dark, need remain energized only a small part of the time.

"Light-off" Condition. Although only a single, tapped winding is used, it will be noted that the phototube cathode is reversed

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[1] The Westinghouse RQ relay uses a similar circuit.

in relation to the thyratron cathode so that it conducts on the inverse half phase of the a-c supply. Assuming the phototube to be dark and no charge on $C1$, the potential of the thyratron grid will be approximately that of point b at the junction of $C2$ and $R3$. This combination $C2$ and $R3$ forms a fixed phase-shift bridge. Since the impedance of the capacitor at 60 cycles is

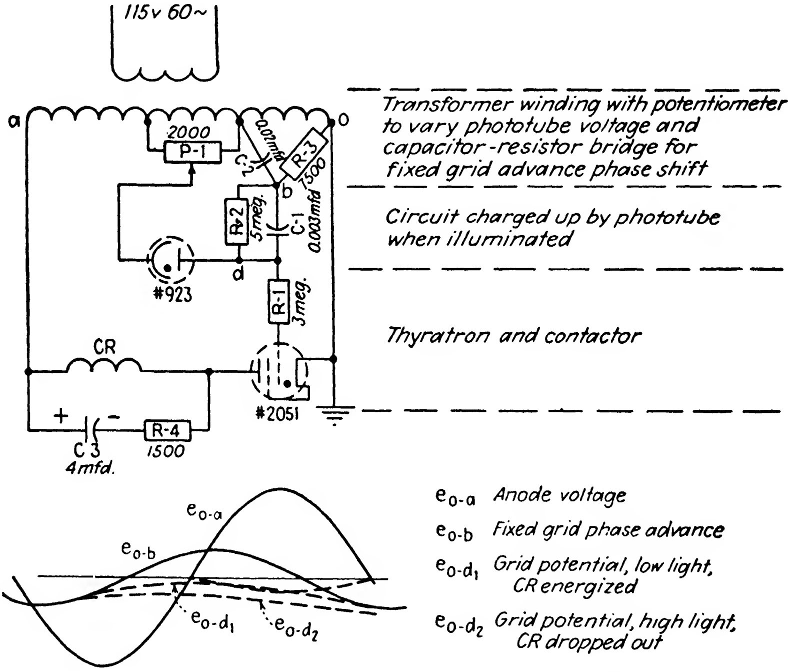


FIG. 21.11. Circuit and grid-voltage wave form of the relay in FIG. 21.9.

about 150,000 ohms and the resistor is only 7500 ohms and when it is remembered that the current to a capacitor leads the driving voltage, it follows that the IR drop in $R3$ produces a low grid voltage almost 90 electrical degrees ahead in phase of the thyratron anode voltage. This leading voltage on the grid ensures that the thyratron will be conducting for the full half cycle under the conditions as stated.

At this time, consideration may be given to the contactor in the thyratron anode circuit. Since the current capacity of the thyratron is much greater than that of the pliotrons previously considered, a larger contactor can be used. This is shunted by a large electrolytic capacitor to hold it in over the negative half cycle; and since the high charging surge might damage the thyratron and a reversal of charge would damage the electrolytic capacitor, a resistor *R*4 is placed in series with *C*3 to limit both the charging and discharging current.

"Light-on" Condition. Light shining on the phototube will permit it to conduct on the inverse half cycle, charging up *C*1 with, of course, the negative potential at the phototube anode (and thyratron grid). The time constant of the *R*2, *C*1 combination is $0.003 \times 5 = 0.015$ sec, or almost 1 cycle of a 60-cycle wave. So the phototube charges up the capacitor each inverse half cycle, and the capacitor discharges along the fairly steep curve during the half cycle in which the thyratron might be conducting.

The discharge curve is superimposed on the permanent advanced phase-shift curve as shown in Fig. 21.11. As the light on the phototube increases, the charge on *C*1 is increased and the whole grid-potential curve is drawn more negative to turn off the thyratron. But, because of the leading phase component, the grid potential will be most positive near the start of the positive anode cycle. Hence, the thyratron will conduct for almost the full half cycle if it conducts at all. The contactor cannot receive partial current and thus cannot chatter.

The potential applied to the phototube as determined by the position of the slider on the potentiometer *P*1 sets the light level at which the relay will operate. *R*1 is a protective resistor to prevent excessive grid and phototube currents.

ALTERNATING-CURRENT POWER CIRCUITS

Power Saturable Reactors, Electronically Excited (GE CR-7502). The series reactance of power saturable reactors of 32 kva and larger has been extensively used to control a-c resistive

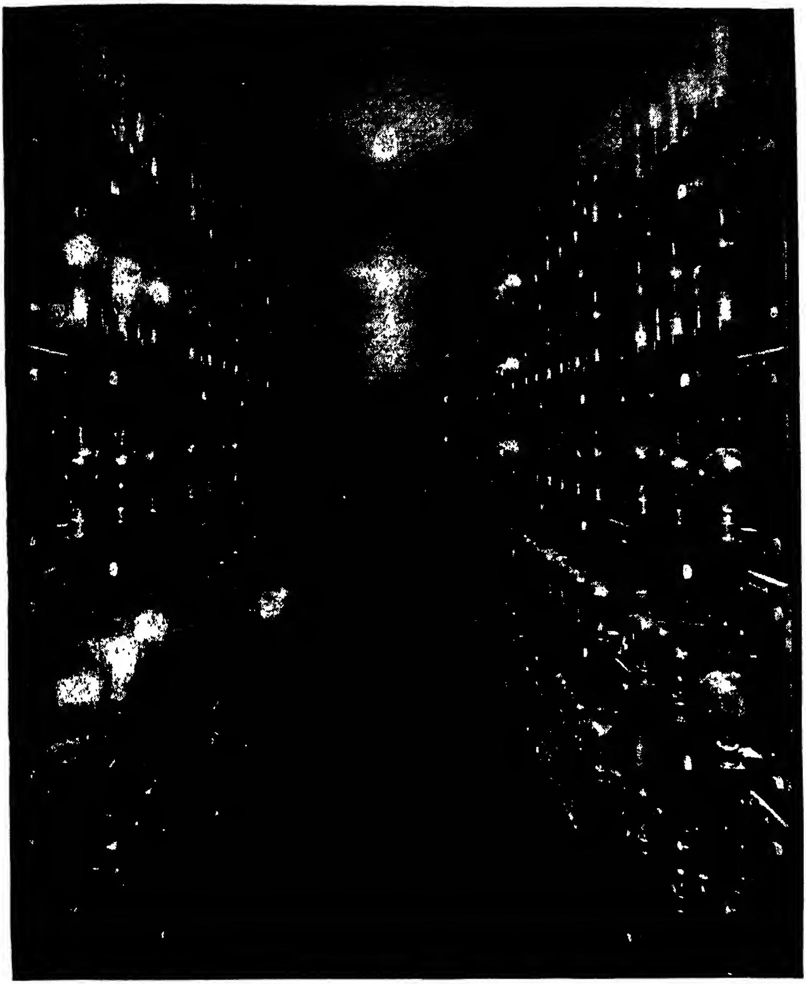
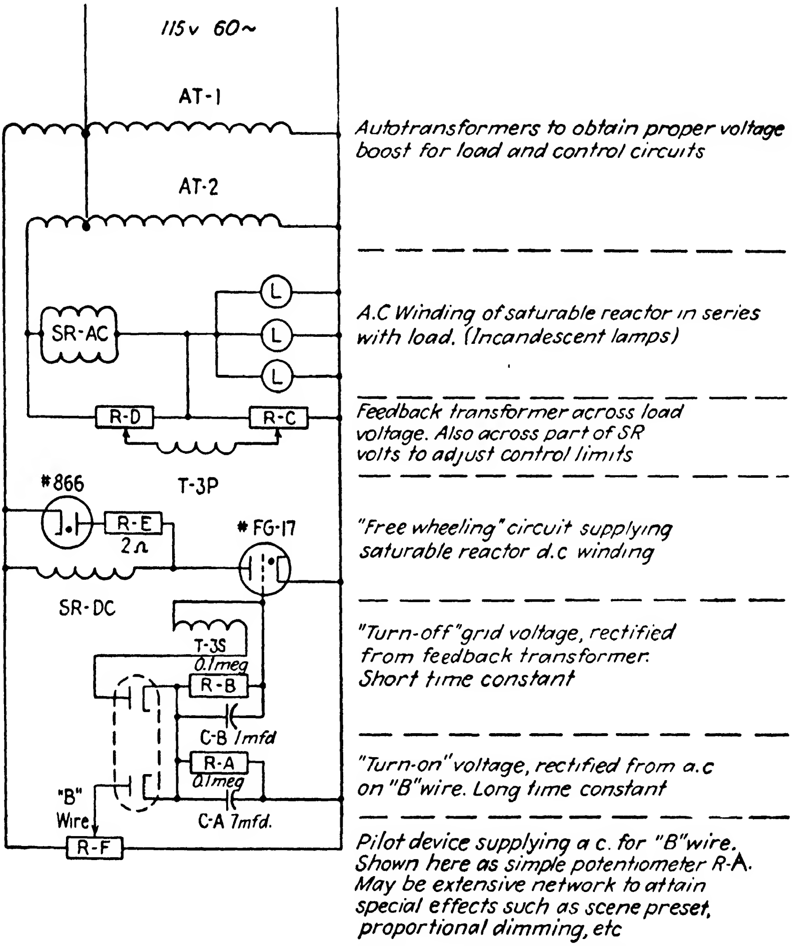


FIG. 21.12. A group of lighting-control panels using the basic circuit of Fig. 21.13. (*Courtesy of General Electric Company*)

loads such as theater lighting circuits and resistance electric furnaces. Because the large lamp filaments and resistor elements have a comparatively slow response, extreme speed in control is not required. The freewheeling circuit of Fig. 11.6 is usually employed because of the simplicity of control of its one thyratron (Fig. 21.13).

Since there is some voltage loss in the saturable reactor even when saturated, if standard 115-volt lamps or furnace resistors



Autotransformers to obtain proper voltage boost for load and control circuits

A.C Winding of saturable reactor in series with load. (Incandescent lamps)

Feedback transformer across load voltage. Also across part of SR volts to adjust control limits

"Free wheeling" circuit supplying saturable reactor d.c winding

"Turn-off" grid voltage, rectified from feedback transformer. Short time constant

"Turn-on" voltage, rectified from a.c on "B" wire. Long time constant

Pilot device supplying a c. for "B" wire. Shown here as simple potentiometer R-A. May be extensive network to attain special effects such as scene preset, proportional dimming, etc

FIG. 21.13. Circuit for the excitation of power-saturable reactors, GE CR7502B1A.

are to be used a small boost must be given to the line voltage by an autotransformer or other means to compensate for this loss.

The freewheeling circuit supplying d-c for the saturable reactor is seen to consist of the FG-17 (5557) thyratron and the GL-866 phanotron as an inverse shunting rectifier. Since the average d-c voltage on the winding of the saturable reactor from the half-wave 115-volt rectifier is about 30 volts d-c, the winding is designed for that voltage.

The control circuit for the thyratron grid consists of two parts, a *turn-on circuit* and a *turn-off circuit*. The turn-on circuit consists of an a-c voltage that may be supplied from any desired a-c control signal of any phase and comes into the tube panel by what has become commonly known as the B wire. The B wire voltage has been shown here as obtained from a potentiometer across the a-c line, as is the case in some of the lighting controls requiring only a few simple circuits. However, in complex circuits such as in the Radio City Music Hall or the Metropolitan Opera House in New York, the original voltage may have been initiated in a small induction regulator, switched, boosted, "dimmed," and passed through two or three master circuits before it finally arrives at the tube panel. Since the power required from this circuit is less than 1 ma at 50 to 100 volts maximum, the switching and dimming of a large number of circuits at a comparatively small, conveniently located control board become possible.

Turn-on and Feedback Voltages. The reason why the phase of the B wire signal is immaterial is that upon arrival at the tube panel the a-c voltage is immediately rectified by a half-wave rectifier in the twin diode GL-80 to charge the 7-μf 0.1 megohm combination, which has such a long time constant that a comparatively pure d-c results. The voltage across the capacitor is approximately equal to the peak of the B wire voltage.

The turnoff voltage is an a-c rectified by the other half of the GL-80; it is derived through a one-to-one insulating transformer from a potential across the load. (Although normally across the load, the two ends of the primary of the feedback transformer *T3P* may be positioned at will along potentiometers across the load voltage and across the saturable-reactor drop to vary the control curve and to set the maximum and minimum voltage limits.) When across the load, however, the feedback voltage rectified will balance out the rectified voltage from the B wire to place the grid of the FG-17 thyratron slightly below the cathode potential.

It should be carefully noted that the time constant of this turnoff d-c voltage is much shorter than that of the turn-on voltage so that if the feedback is properly phased with respect to the thyratron anode voltage the capacitor is charged on the inverse half cycle and the discharge begins on the thyratron positive half cycle. Thus, if the feedback voltage is just equal to the turn-on voltage, the thyratron grid will be at zero potential and the thyratron will tend to conduct for the full cycle. This would increase the load voltage and the turnoff voltage so that the next cycle the grid would begin at a voltage below the cathode potential and would rise more positive as the capacitor discharged, firing the thyratron sometime later in the cycle. If this is so late that insufficient saturating current is conducted, the feedback volts will fall and the new discharge curve will permit the thyratron to fire earlier next cycle. Actually, a bal-

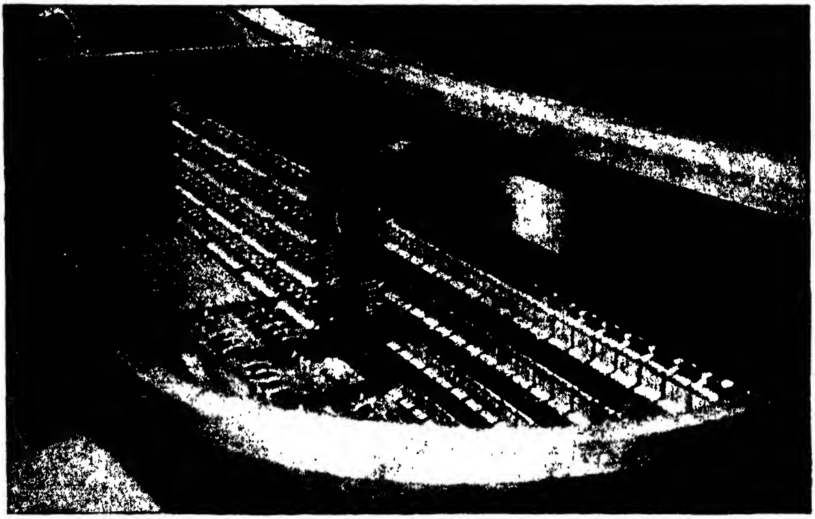
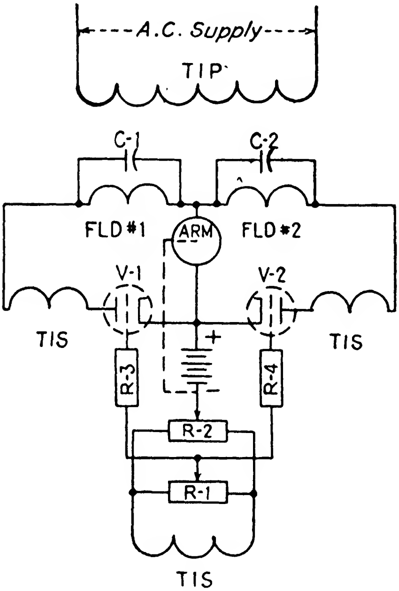


FIG. 21.14. Lighting control pit at Radio City Music Hall, New York. This elaborate board provides the proper switching and control of the B wire voltages required for the lighting circuit. (*Courtesy of General Electric Company*)

ance is held at which the load (and feedback) volts are very nearly equal to the turn-on volts as determined by the B wire voltage. If the feedback transformer is tapped across only a part of the load instead of the whole, then the load volts will be more than, but proportional to, the B wire voltage. If the feedback transformer primary volts include part of those across the saturable reactor, the B wire voltage must overbalance these before the thyratron will conduct at all and small undesired voltages induced or otherwise picked up on the B wire may be rendered ineffective.



Series a-c motor with split fields. Shunt capacitors C-1 and C-2 permit a more uniform current from the half-wave a.c.

V-1 and V-2 are power triodes (or pentodes connected as triodes) to control current to motor

Grid circuits combine fixed d.c. bias and reversible a.c. component from bridge R-1 and R-2

The potential on the arm of R-1 is varied by the primary signal. The potential on the arm of R-2 is changed by the operation of the motor to balance the bridge

FIG. 21.15. A follow-up or servo control using a reversible split-field motor.

Since this circuit tends to hold constant voltage across the load, rather than constant current, a change in the load, such as might occur if a lamp burned out, affects the voltage on the rest of the load only slightly. The load may be varied as much as 4 to 1 without appreciable voltage change.

Follow-up or Servo Control Utilizing Reversing Split-field Series A-C Motor. This circuit, shown in a simple form in Fig.

21.15, is typical of controls for small motors used in follow-up or servo mechanisms where the primary signal is too weak to operate the desired mechanism, which might consist of a valve, recording pen, etc.

The motor power circuit consists of two pliotrons with cathodes at common potential and with a split anode transformer supplying the motor through its individual fields in a full-wave rectifier circuit. Capacitors *C*1 and *C*2, sometimes used across the fields, permit more current to flow from the half-wave sources.

The control signal is taken from the resistance bridge composed of potentiometers *R*1 and *R*2. When the arms are at equal points on *R*1 and *R*2, no difference in potential exists; so the bias on the motor control tubes is the d-c bias only and thus equal on both. Hence, the motor stands still.

Control Operation. If the potential of the arm of *R*1 is varied with respect to that of the arm on *R*2, an a-c component is added to the d-c bias. This a-c is positive when one tube can conduct, thus increasing the current through that tube, but is negative on the other half cycle when the other tube can conduct, thus decreasing the current in that tube. This unbalances the motor-field current and permits the motor to rotate. Since the arm of potentiometer *R*2 is mechanically geared to the motor armature, it is moved by the motor rotation to balance the bridge once more, equalizing the position of the arms on *R*1 and *R*2.

The relative impedances of *R*1 and *R*2 are not important. So long as they are both linear or even have the same taper, the position of the arm of *R*2 will follow that of the arm of *R*1 accurately.

Many variations of this basic circuit are possible. The bridge output signal may be amplified before being applied to the power tubes. Four tubes may be used in two full-wave rectifiers with center-tapped grid transformers to supply a purer d-c to the motor. Thyratrons may replace the pliotrons to operate larger motors. This will require appropriate circuits such as that shown in Fig. 15.5 for grid phase shift. The basic circuit with an additional balanced amplifier stage is used in an Askania Regulator Co. electronic servo system. The output thyratrons control the

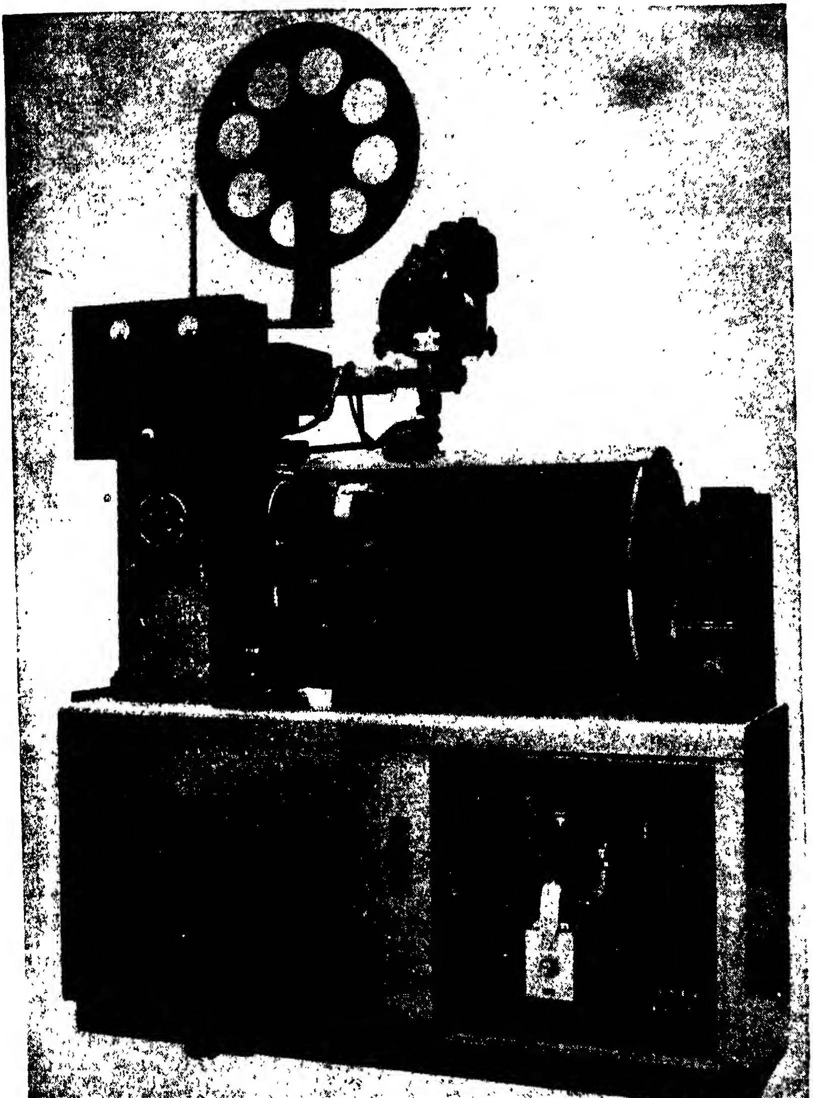


FIG. 21.16. An automatic arc welder using the circuit of FIG. 21.17 to control the rod-feed motor at the top of the machine. The tube panel is at the bottom on the extreme right. (*Courtesy of General Electric Company*)

two shading coils on a shaded-pole induction motor, however, rather than the series fields as described.

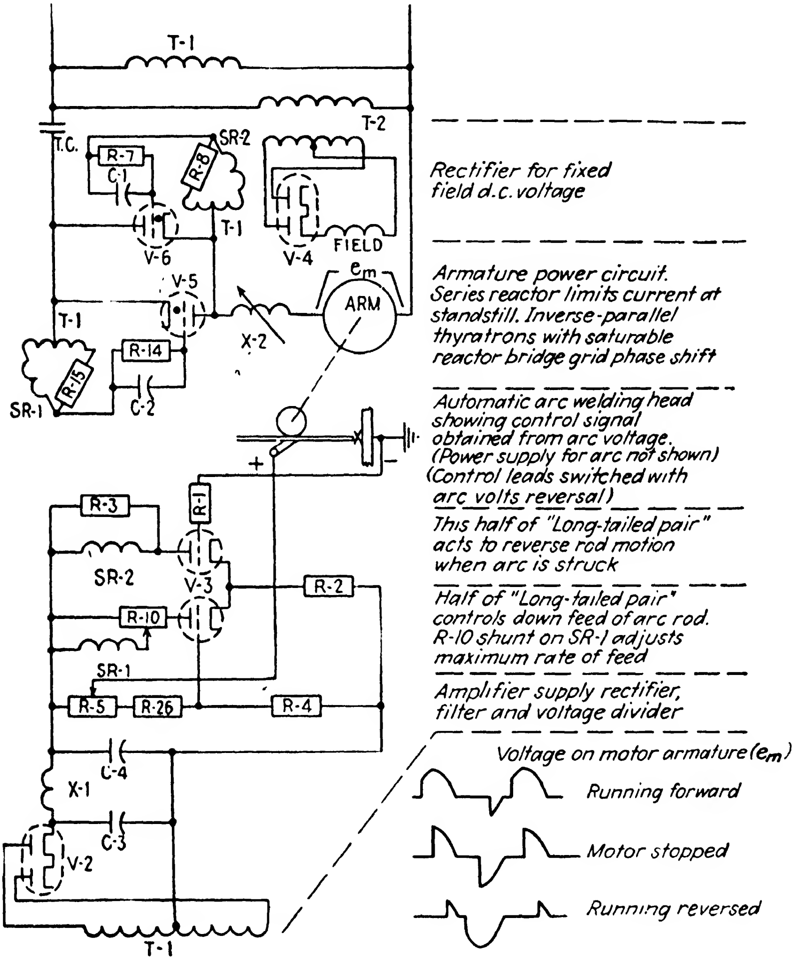
A similar circuit with Selsyn discriminator input has been used to excite balanced amplidyne control fields.

Thyratron Reversing Motor Control for Automatic Arc Welding (GE CR7507). This circuit (Fig. 21.17) is typical of reversing motor controls in which the motor speed can be changed from high speed in one direction, down to a creeping speed, to standstill, and through to high speed in the opposite direction, with plugging torque for rapid stopping or reversal if desired. A d-c shunt motor is used with constant field and the armature power applied as a half wave from the positive or negative half cycles of the a-c supply. To obtain the most sensitive response near standstill, equal fractional-cycle impulses are applied to the armature from both half cycles to keep the static friction broken and the shaft vibrating slightly.

The control circuit is based on the long-tailed pair and the saturable-reactor phase shift for the grids of two inverse-parallel thyratrons.

The Power Circuit. The circuit elementary is shown in Fig. 21.17. The motor field is excited by a full-wave rectifier. The inductance of the field itself is sufficient filtering, and so no other is used. The armature is supplied directly from the 230-volt a-c line through the inverse-parallel thyratrons and a series reactor to limit the armature current at standstill and under severe reversing service. The thyratron grid circuits include the phase-shift bridge, having a small saturable reactor as the variable element and, as a refinement, a shunt capacitor-resistor circuit, which, by means of a small grid-rectification action and a short time constant, lags the bridge signal slightly to allow for any phase difference between the line voltage used for the anode and that of the grid bridge winding. (If the proper-sized capacitors are added to the bridge circuit, the impedance of the capacitor-reactor combination at zero saturation may approach resonant conditions so that as the reactor is saturated the impedance will change even more sharply and a better phase-shift characteristic will be obtained than from the simple saturation action.)

The D-C Control Circuit. The d-c control circuit for saturation of the reactors is quite simple. The d-c is obtained from the



Rectifier for fixed field d.c. voltage

Armature power circuit. Series reactor limits current at standstill. Inverse-parallel thyratrons with saturable reactor bridge grid phase shift

Automatic arc welding head showing control signal obtained from arc voltage. (Power supply for arc not shown) (Control leads switched with arc volts reversal)

This half of "Long-tailed pair" acts to reverse rod motion when arc is struck

Half of "Long-tailed pair" controls down feed of arc rod. R-10 shunt on SR-1 adjusts maximum rate of feed

Amplifier supply rectifier, filter and voltage divider

Voltage on motor armature (e_m)

Running forward

Motor stopped

Running reversed

Fig. 21.17. Control for electronic reversing operation of a d-c motor on an a-c supply, GE CR7507A.

typical full-wave rectifier *T*1, *V*2 with pi filter *C*3, *X*1, *C*4 and voltage divider *R*5, *R*26, *R*4. The fixed grid for the long-tailed pair is tapped near the center of the divider, and the voltage to balance against the desired arc voltage is taken from a potentiometer $R5$, which is part of the divider. The d-c winding for the saturable reactor $SR1$ controlling the thyratron which feeds the electrode down to the work is in the anode circuit of that triode which has the fixed grid. The electrode-retracting motion is controlled by the other triode and $SR2$. It will be noted that the d-c winding of $SR1$ is connected in a form of potentiometer circuit to limit the maximum current which can flow in it. This is to limit the down speed of the electrode as desired in order that the most desirable arc-starting characteristic may be obtained. For other forms of reversing motor service, this arrangement might not be desirable.

Fig. 21.18. The control panel of the Westinghouse SC-2 register regulator. (*Courtesy of Westinghouse Electric Corporation*)

THE WESTINGHOUSE TYPE SC-2 REGISTER REGULATOR (FOR WINDER CONTROL)

The complete equipment is used to align the edge of a web, or a printed line on it, accurately as the web passes through a rewind or slitting machine. The edge of the web or line is scanned by a phototube shortly after it is unwound from the feed roll and, if not in the correct position, the roll is shifted by a motor to correct the alignment.

The scanning head includes a lens disk driven by a synchronous motor so placed that the rotating lens sweeps the image of a lamp filament across the path of the web or line edge. A phototube records the instant that the reflected light changes due to the contrast between the web edge or line and the background. Since the lens disk is driven by a synchronous motor, the filament-image position, and so the phototube signal, has a very definite relation to the electrical voltage cycle.

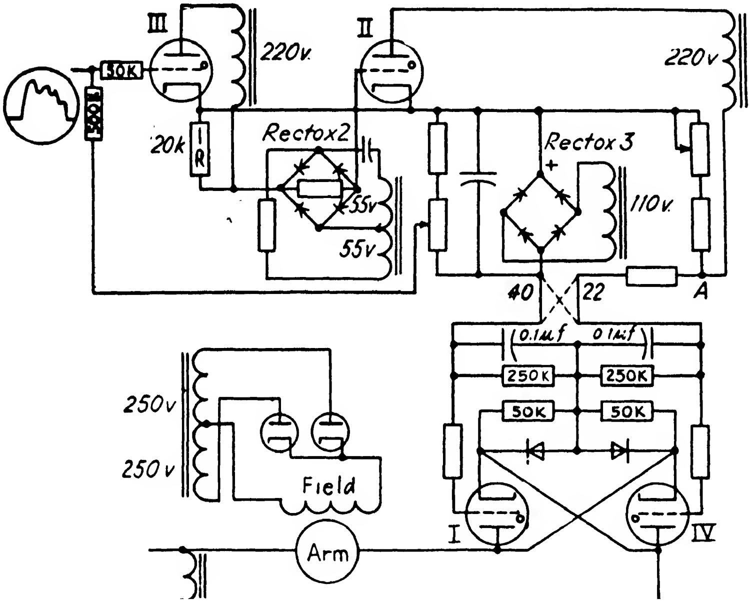


FIG. 21.19. Circuit of the Westinghouse SC-2 register regulator. The steep wave front of the amplified phototube signal fires thyratron III, driving the grid of II negative to prevent II from firing if it has not already done so.

The phototube signal is amplified and phased so that a sharp positive voltage rise occurs at the instant of passing of the filament image across the web edge.

Figure 21.18 is the control panel.

The circuit of Fig. 21.19 shows the essential discriminator and output circuit. Its action is as follows: All tubes are thyratrons. Tube III is normally biased off by the d-c from Rectox (metallic rectifier) 3 but is fired by the positive pulse from the phototube.

The current through tube III flows through *1R* driving the grid of tube II far negative and preventing its firing. Since tube II will fire when the grid rises to cathode potential, it will fire whenever the unfiltered voltage from Rectox 2 drops to zero, provided tube III has not already fired. Since the voltage applied to Rectox 2 is derived from the *RC* bridge circuit which shifts the phase a quarter cycle, the zero grid voltage point occurs at the peak of the positive cycle.

The Discriminator Action. The discriminator action is this: If the phototube signal occurs before the peak of the cycle, tube III conducts and holds tube II off. However, if the phototube signal occurs after the cycle peak, tube II has already been fired by the zero voltage point of Rectox 2 and the bridge circuit and the firing of tube III is ineffective. In brief, if the signal occurs before the mid-point of the filament-image travel on the web, tube II remains nonconducting; if after the mid-point, tube II conducts. This conduction or nonconduction of tube II must next be transformed into a reversal of the direction of the correcting motor.

When tube II is not conducting, the d-c voltage from Rectox 3 causes point 22 to be positive with respect to point 40. This potential, through the rectifier tie (see Fig. 15.16) causes tube IV to conduct. In a similar manner when tube II conducts, the greater voltage of its anode winding reverses the potential between 22 and 40 to cause the firing of tube I.

Tubes I and IV are connected in inverse parallel in series with the armature of the separately excited d-c correcting motor and so can cause it to turn in either direction (see Fig. 21.16). To sum up, if the position of the web or line is such that the phototube signal arrives early, tube II is held nonconducting and the correcting motor runs one way; if late, tube II conducts and the motor is driven in the opposite direction.

WHEELCO ELECTRIC CONTROL (CAPACILOG)

The circuit of Fig. 21.20 is that used for a motor-driven follow-up or servo control such as found in a recording instrument or controller. For single point control tube 2 might operate a relay as shown by the dotted lines.

This controller employs a tuned-grid, tuned-anode oscillator, tube 1, and detunes the grid circuit by the insertion of a light aluminum vane *C* (moved by the small power of the primary element) into the field of the grid inductance *A* as seen in Fig. 21.21. The eddy currents induced in the vane alter the inductance so that the grid resonant circuit consisting of *A*, *C*1, and *C*2 is no longer tuned to the frequency of the anode circuit *L*, *C*3 and the exchange of energy through the tube and the amplitude of the oscillation becomes smaller. When the circuit is oscillating most strongly, considerable grid rectification takes place and a minimum average current is drawn from the power supply. However, as the oscillation is decreased because of the vane movement, the grid rectification becomes less and the average tube current rises. The capacitor *C*4 filters the radio-frequency oscillations, permitting only a slowing, changing current through *R*2.

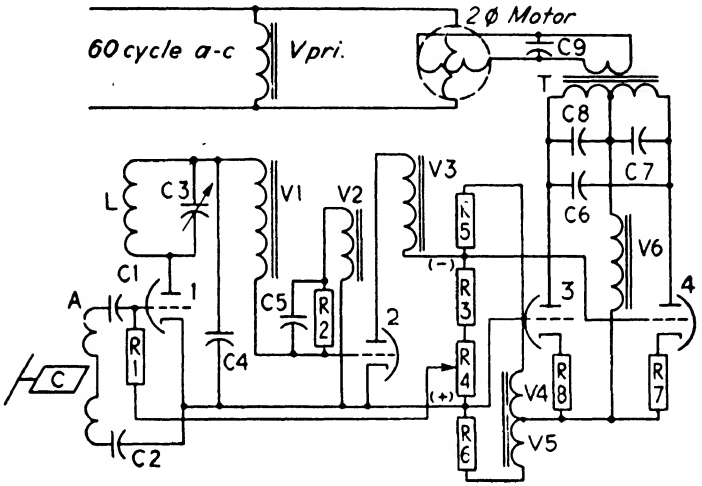


FIG. 21.20. The circuit of the Wheelco Capacilog control. The presence of the vane *C* in the field of the tuning inductance *A* changes the amplitude of oscillation. This causes a change in the *IR* drop of *R*2 which, amplified by tube 2, reverses the phase in the grids of tubes 3 and 4 and thus the direction of the two-phase motor.

The Power-frequency A-C Amplifier. The power supply consists of transformer windings excited from the usual 60-cycle supply, so low a frequency compared with the oscillating frequency that it might be considered almost as a slowly changing d-c. In this circuit all power is supplied by transformer secondaries, which are shown with polarities that occur during the same half wave of supply voltage.

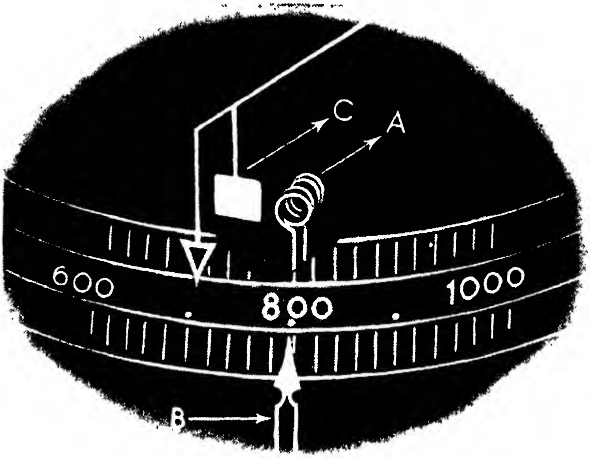


FIG. 21.21. A schematic view of the relative movement of the vane C and the oscillator grid inductance A. (*Courtesy of Wheelco Instruments Company*)

The anode voltage of $V1$ of the oscillator tube 1 and the bias voltage $V2$ of the amplifier tube 2 are so proportioned that the potential of the grid of tube 2 varies over the effective range because of the change in the IR drop across $R2$ and $C5$ as the oscillation amplitude changes.

The potential of the grid of tube 2 determines the flow of current in tube 2 and the IR drop in $R3$ and $R4$. A small amount of feedback bias from part of $R4$ to the grid of tube 1 assists in circuit stabilization. It should be noted that when current flows $R4$ is positive with respect to $R3$ and when tube 2 is not conducting $R3$ and $R4$ act simply as a passive resistor in the voltage divider of the grid circuit of tubes 3 and 4.

The Output Circuit. Let us next look at the output circuit, including tubes 3 and 4. They have a common anode supply $V6$, and their anodes feed the opposite halves of the primary of the output transformer T. So, if current flows in tube 3, a voltage will be induced in one phase in the secondary of T while, if current flows in tube 4, the voltage will be induced in the secondary in the reverse phase. The capacitors $C6$, $C7$, $C8$, and $C9$ assist in improving the wave form, which is somewhat distorted because of the half-wave rectification of tubes 3 and 4. Note that this is not a class B, or push-pull, amplifier since both tubes 3 and 4 can conduct only on the half wave in which $V6$ supplies a positive anode potential.

The output from T is applied to one phase of a small two-phase a-c motor, the second phase of which is supplied from a constant a-c source. As the phase of the tube-excited winding is reversed, the motor direction reverses. The motor operates the control, or recording, function and also changes the relation between the vane and oscillator coil to restore balance.

Since the direction of control movement depends on the relative current flow in tubes 3 and 4, let us trace their grid circuits to see how this can be changed. When there is no current in tube 2, the bias windings $V4$ and $V5$ place a negative voltage on the grid of tube 3 and a positive voltage on the grid of tube 4. Thus, when tube 2 is cut off, there will be full current in tube 4 and none in tube 3. But when tube 2 is conducting its maximum, sufficient voltage appears across the resistors $R3$ and $R4$ of opposite polarity to that of the bias windings $V4$ and $V5$ to reverse the polarity on the two grids and to cause tube 3 to conduct and 4 to shut off. An intermediate current and voltage through $R3$ and $R4$ will permit a balanced current through tubes 3 and 4, minimizing the voltage induced in T and stopping the motor. Under proper conditions the motor will respond to a change in relative vane and oscillator positions of between 0.004 and 0.006 in.

The tubes used are twin triodes, type 6N7. Two tubes are placed in parallel for 3 and 4 for greater reliability and better output at low-line voltages. A stop is placed to limit the vane

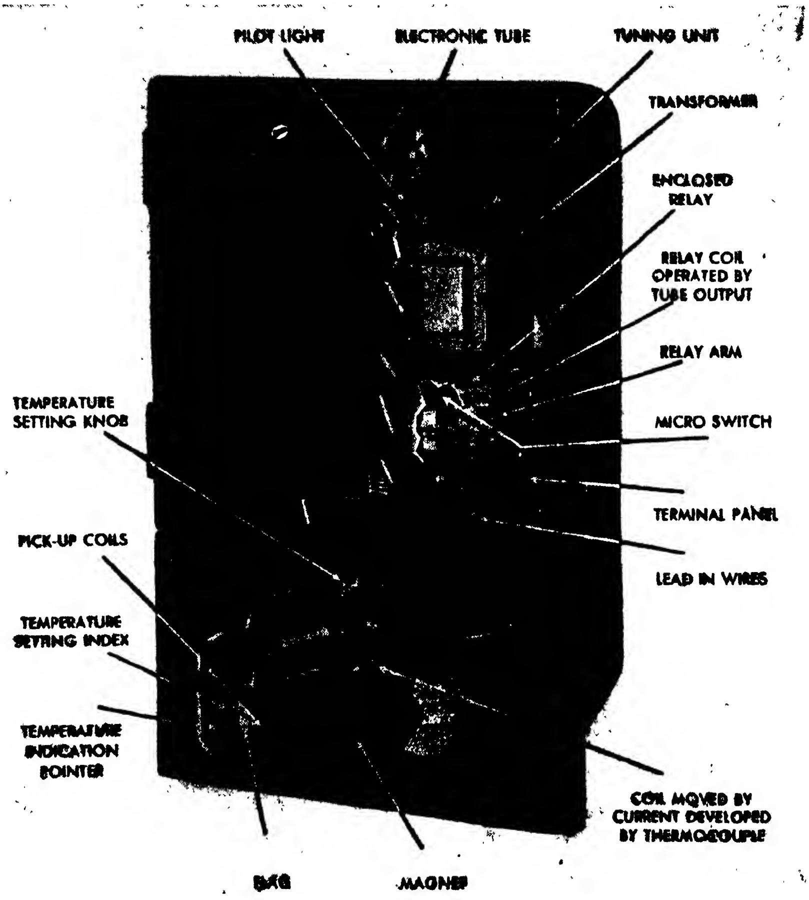


FIG. 21.22. A Wheelco temperature control using the principles described here. (*Courtesy of Wheelco Instruments Company*)

motion in order to prevent its overshooting the coil under unusual conditions. Figure 21.22 is a view of a temperature control in which a relay operated by tube 2 initiates the control action.

THE FOXBORO COMPANY ELECTRONIC BALANCING CONTROL UNIT (DYNALOG)

In the electronic balancing control used in the Foxboro Dynalog recording and control instruments, a Wheatstone bridge is used having a capacitor as the known variable to allow a really stepless operation. This device is also unusual in having a servo motor in the form of a balanced double solenoid, as seen in Fig. 21.23. The relation between the core length and the coils is such that the pull is dependent almost entirely on the coil current so that the direction of core travel depends only on the relative strength of the current in the two coils. A dashpot is

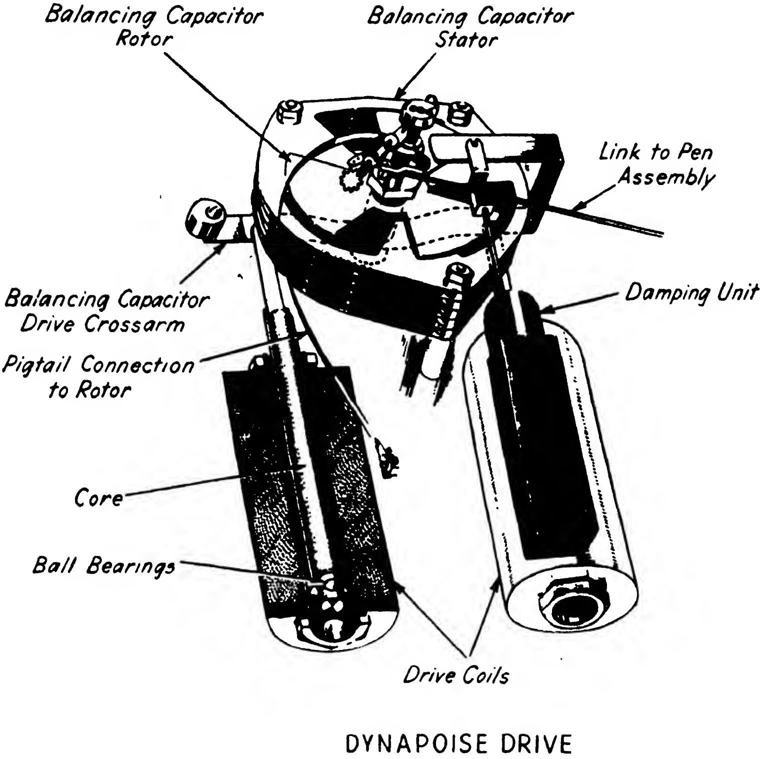


FIG. 21.23. The Foxboro Dynalog balancing capacitor and double solenoid servo motor. (*Courtesy of The Foxboro Company*)

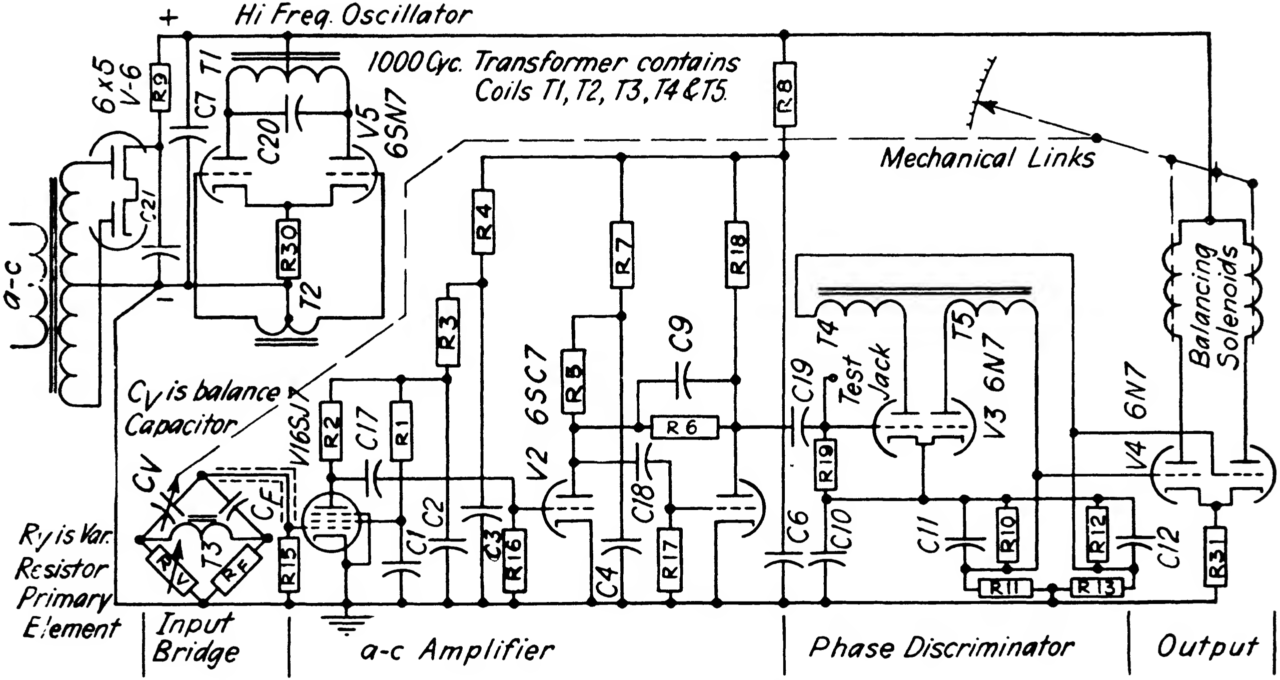


FIG. 21.24. Circuit of the Foxboro Dynalog. The oscillator V5 supplies 1000-cycle power for the measuring bridge and the discriminator V3. The greatly amplified bridge unbalance is converted by V3 to a difference in current in the servo solenoid coils.

used for mechanical stabilization. Movement of the core is transmitted both to the capacitor plates to rebalance the measuring bridge and to the pen to record the capacitor setting and hence the measured quantity.

The Oscillator. The circuit appears in Fig. 21.24. A typical full-wave rectifier supplies the d-c anode voltage. Next, a push-pull oscillator $V5$ (6N7) having a plate circuit tuned by $C20$ to 1000 cycles a second supplies the frequency to the measuring bridge and the discriminator circuit $V3$. Although shown separately for clarity, all windings $T1$, $T2$, $T3$, $T4$, and $T5$ are part of the same 1000-cycle transformer.

The Amplifier. The measuring bridge consists of the unknown resistance R_V (temperature element, strain gage, etc.), the fixed resistor R_F, the fixed capacitor C_F (which may be adjusted for calibration), and the variable balancing capacitor C_V moved by the output solenoid core. An unbalance of the bridge results in an a-c voltage between ground and the grid of the pentode $V1$ (6SJ7) which reverses in phase as the bridge passes through balance. This 1000-cycle a-c signal is amplified by the capacity-coupled amplifier $V1$ and both halves of the twin triode $V2$, a combination having a total gain of 100,000 times. Note that stability is secured by two decoupling filter stages $R3$, $C2$, and $R4$, $C6$ between the anode supply of the first and second stages and the lag network, or low pass filter $R6$ and $C9$, between the halves of $V2$. The amplified unbalance voltage is applied to both grids of the discriminator twin-triode tube $V3$.

The Discriminator. The anode supply for the triodes of $V3$ are windings of the 1000-cycle transformer of about 50 volts each and opposite in phase. Therefore, the grid voltage, for one condition of bridge unbalance, will be in phase with the anode voltage for one triode and out of phase for the other, producing a wide difference in current flow in the two halves of the tube. If the bridge should unbalance in the opposite direction, the difference of current in the two halves will be reversed.

The Output Circuit. The half-wave rectified current is filtered by $R10$ and $C11$ and by $R12$ and $C12$ to give a fairly smooth d-c voltage, which is then applied to the grid of the output tubes. It should be noted that the whole discriminator circuit of *V*3 with its insulated 1000-cycle anode supply is connected for d-c to the rest of the circuit only at the junction of *R*11 and *R*13 so that

FIG. 21.25. The Foxboro Dynalog unit, front and back views. (*Courtesy of The Foxboro Company*)

the average grid potential of the output-tube grids is that of the negative d-c bus and only the difference between the *IR* drop in the *V*3 anode resistors *R*10 and *R*12 is used to unbalance the output-tube grid potentials.

The output tube *V*4 (6N7) is another twin triode that acts as two simple d-c amplifiers having in their anode circuits the two coils of the servo solenoids. The unbalanced grid voltage received from *V*3 causes an unbalance in the solenoid currents, moving the cores to actuate the recording pen and the variable capacitor to restore the bridge balance. Full-scale travel may take place in less than a second without overshoot or hunting.

Questions

1. What is the advantage of an electronic switch? Suggest some appropriate applications of such a switch.

2. Draw a circuit for an electronic timer suitable for closing an output circuit a preset time after an initiating switch is closed.

3. Explain the recharging action of the timing capacitor in a typical a-c type electronic timer.

4. How does the grid control action take place in an a-c type photoelectric relay in which the phototube is in series with a capacitor?

5. Describe the action of the feedback potential transformer in maintaining load voltage in a saturable reactor lighting control.

6. Explain with wave-form sketches how reversing action takes place when a separately excited d-c motor is controlled by inverse-parallel, or "back-to-back," thyratrons connected in series with the armature.

7. In the Westinghouse SC-2 resistor regulator, how does the firing of thyratron 2 reverse the motor armature power?

8. Explain, with simple vector sketches, the motor direction reversal due to the grid-phase shift on the power tubes of the Wheelco Capacilog.

CHAPTER XXII

RESISTANCE-WELDER CONTROLS AND WELDER CURRENT REGULATING

RESISTANCE-WELDER CONTROLS

Electronic Resistance-welder Control for Spot, Seam, and Pulsation Welds (GE CR7503C110). This circuit (Fig. 22.2) will be seen to be an expansion of Figs. 15.14 and 15.21. The ignitron and thyratron firing circuits are the same, but circuits have been

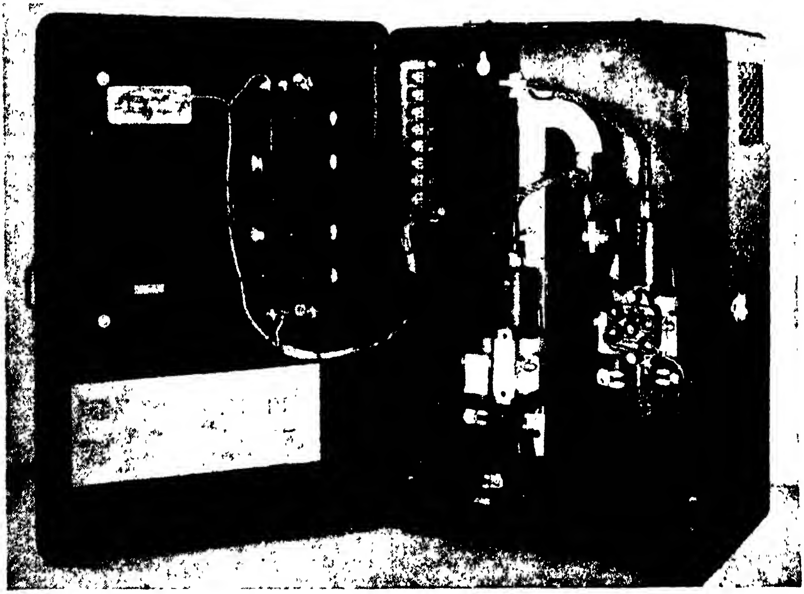
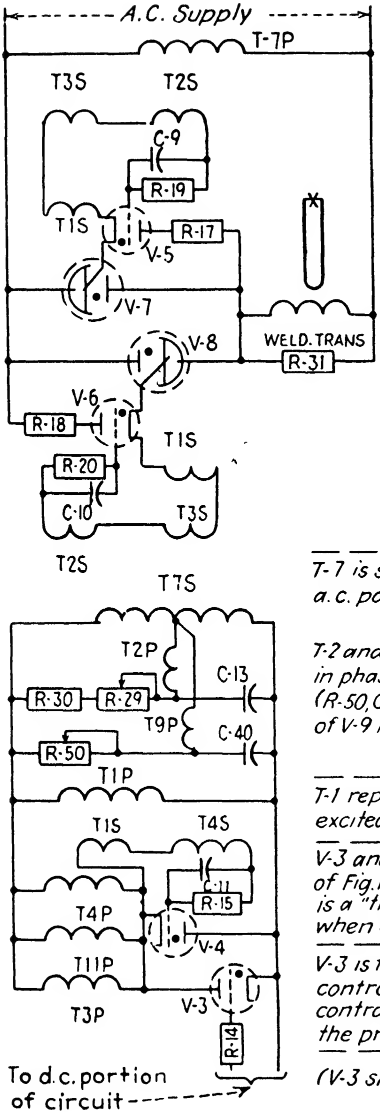


FIG. 22.1. Westinghouse ignitron contactor for resistance-welder control. In a basic panel such as this or in the extensive panel of Fig. 22.4, the ignitron conducts the power current while all other tubes are added to permit accurate timing and phasing. (*Courtesy of Westinghouse Electric Corporation*)



Welder power circuit. Ignitrons V-7 and V-8 and firing thyratrons V-5 and V-6. See Fig. 15.14 for an explanation of this part of the circuit

R-31 is thyrite surge protection across welder transformer primary

T-7 is step-down transformer energizing a.c. portion of the control circuit

T-2 and T-9 are peaking transformers shifted in phase by RC bridges (R-29, R-30, C-13) and (R-50, C-40). T-9 secondary is in grid circuit of V-9 in d.c portion of the circuit

T-1 represents all constantly excited control transformers

V-3 and V-4 replace the switch of T-2 of Fig. 15.14 to energize the welder. V-4 is a "trailing" tube, fired by T-4 when energized by V-3

V-3 is the leading or key tube. The d.c control circuit of Fig. 22.3 need only control the firing of this tube at the proper HEAT and COOL sequence

(V-3 shown again in Fig. 22.3)

FIG. 22.2. Resistance-welder control for spot, seam, or pulsation welds. GE CR7503C110, a-c portion of circuit.

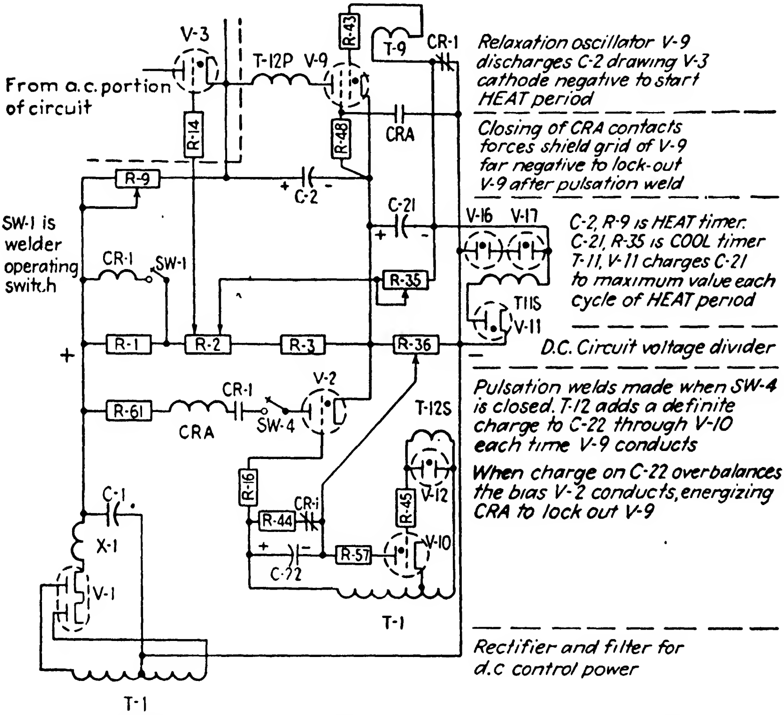
added to control the number of cycles in the heating period, the number of cycles for cooling between heat pulses, and the number of pulses. For *spot welds*, consisting of a single heat pulse, only a single "heat" sequence takes place and the control locks out. For *seam welds*, composed of a continuous series of heating and cooling pulses, the "heat" and "cooling" intervals are timed continuously until the initiating switch is released. For *pulsation welds* the heat pulses continue for a definite number of pulses before the control locks out. That is, the spot weld may be considered a pulsation weld with only one heat interval. The seam weld is a pulsation weld with an infinite number of intervals.

Studying the circuit itself more in detail we see that, aside from the ignitron and thyratron firing circuit, the control circuit is divided into an a-c and a d-c portion supplied by the familiar full-wave rectifier and filter capacitor.

The A-C Control Circuit. The a-c portion (Fig. 22.2) is fairly similar to that of Fig. 15.14. It consists of the peaking transformer *T*2, with the phase-shift network *R*29, *R*30, *C*13 to determine the phase angle of ignitron firing, the primary of the hold-off inverse phase bias, *T*1*P*, and the inphase firing transformer primary *T*3*P*, which, instead of being energized through a mechanical switch or contactor, is now energized through thyratrons *V*3 and *V*4 connected inverse parallel to pass a-c. Of these two tubes it should be noted that only *V*3 need be controlled. *V*4, which is normally held nonconducting by an out-of-phase bias from *T*1, is caused to conduct—or trail after—*V*3 by the inphase voltage from the secondary winding of *T*4, which is energized when *V*3 conducts. Thus each time *V*3 is fired the a-c control circuit and the ignitrons are energized for a full a-c cycle.

The D-C Control Circuit. The whole purpose of the d-c portion of the control circuit (Fig. 22.3), then, is to cause *V*3 to conduct or hold off for the desired heating sequence. The d-c voltage divider, from which all potentials are derived, is shown as *R*1, *R*2, *R*3, and *R*36. The initiating switch *SW*1 energizes *CR*1.

Let us first, however, consider the potentials as found before *CR*1 is energized, while its normally closed contacts are still closed and the normally open contacts are open. $C21$ is connected across $R36$ of the voltage divider and is thus charged up to that potential. Since this voltage is greater than the peak voltage from the peaking transformer $T9$ (which would otherwise fire $V9$ at a definite time in the inverse cycle), $V9$ is held nonconducting. Likewise, $C2$ will be found to be charged up to the difference of potential existing across $R1$, $R2$, and $R3$, carrying with it the cathode of $V3$ up to the potential of the positive d-c bus. Since the grid of $V3$ is at the preselected potential on $R2$, it will be negative with respect to its cathode, $V3$ will be nonconducting, and the welder will not be energized.



Relaxation oscillator V-9 discharges C-2 drawing V-3 cathode negative to start HEAT period

Closing of CRA contacts forces shield grid of V-9 far negative to lock-out V-9 after pulsation weld

C-2, R-9 is HEAT timer. C-21, R-35 is COOL timer T-11, V-11 charges C-21 to maximum value each cycle of HEAT period

D.C. Circuit voltage divider

Pulsation welds made when SW-4 is closed. T-12 adds a definite charge to C-22 through V-10 each time V-9 conducts

When charge on C-22 overbalances the bias V-2 conducts, energizing CRA to lock out V-9

Rectifier and filter for d.c control power

FIG. 22.3. Resistance-welder control, d-c portion of circuit.

To turn now to the pulse-counter circuit, the grid of the lockout tube $V2$ is tied through $CR1$ contacts to a preselected point on *R*36 and so is negative with respect to its cathode at the positive side of *R*36; therefore, *V*2 is held nonconducting. The grid capacitor *C*22 is effectively short-circuited through the low resistance *R*44 and the *CR*1 contacts.

The "Heat" Period. The initiating switch is energized. Let us assume first that the switch *S*4, closed for pulsation welding, has been left open for a seam weld so that the only action of *CR*1 is the opening of the *CR*1 contact connecting *C*21 to the negative bus. *C*21 immediately begins to discharge through *R*35, raising the potential of its negative end until the peaking voltage from *T*9 is sufficient to fire *V*9. *V*9, conducting, quickly discharges *C*2 connected across it and, through the inductive action of the primary of transformer *T*12 in its anode lead, has its anode driven sufficiently negative to permit deionization and its operation as a relaxation oscillator. When *C*2 is discharged the cathode of *V*3 is drawn well below its grid potential so that on its next positive half cycle it will conduct and start the welder heating cycle.

As the first half cycle of welding takes place, *C*21 is charged well negative by the action of transformer *T*11 (energized by *V*3 and *V*4) and the half-wave rectifier *V*11. Since *C*21 tends to discharge a little through *R*35 each cycle, a small charge from *T*11 and *V*11 will keep it fully charged to the voltage across *V*16 and *V*17 so long as *V*3 and *V*4 conduct.

However, while the heating cycle has been taking place, *C*2 has been gradually rebuilding its charge through *R*9; and after a preset number of cycles, as determined by the position of the *V*3 grid on *R*2 and the time constant of *C*2 and *R*9, the cathode of *V*3 again becomes more positive than its grid. Thus *V*3 is kept from conducting on the next cycle, and the heating period is over.

The "Cool" Period. Let us return, now, to the action of the grid of *V*9, which started the heating period. Since it was connected through the winding of the peaker *T*9 to the negative end of *C*21, it has now been carried well negative by the charging action of *T*11 and *V*11 and is held there so long as the heating continues. When the heating cycle is finished, *C*21 can discharge through *R*35 without interruption and it continues to

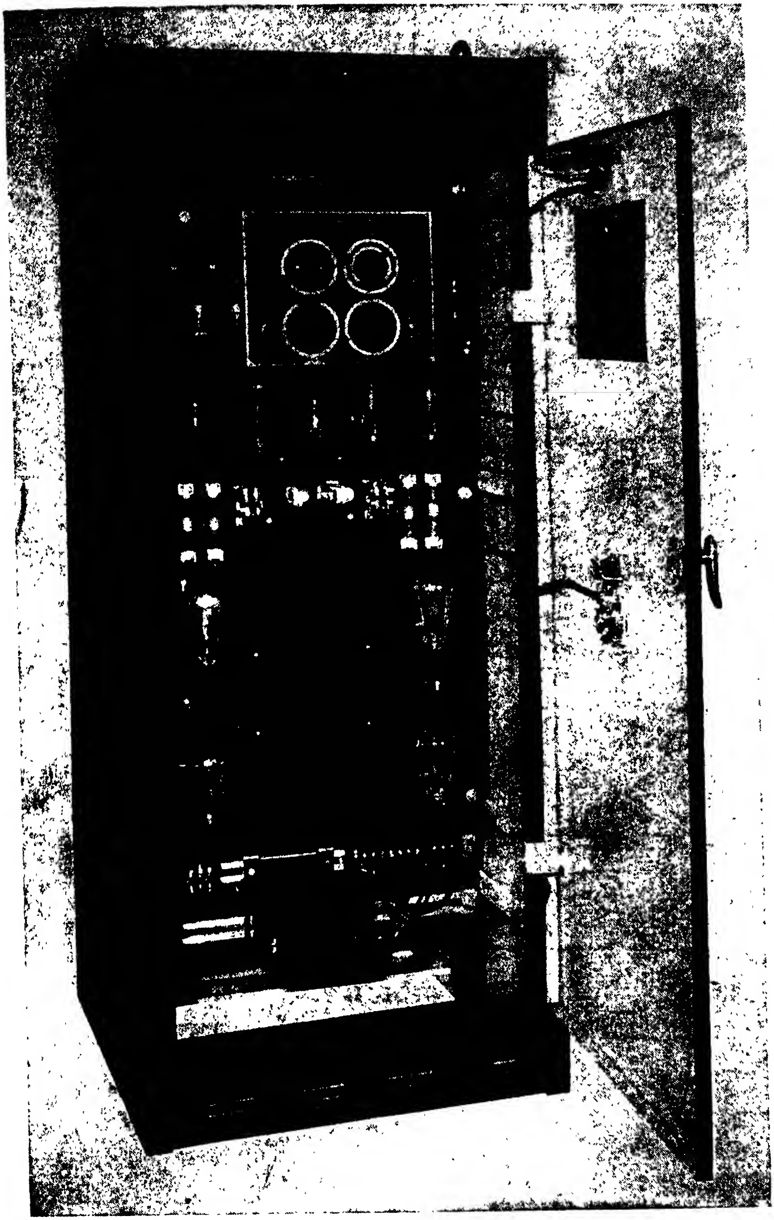


FIG. 22.4. Resistance-welder control, GE CR7503C110. Front view showing operator's panel and control tubes. (*Courtesy of General Electric Company*)

do so for a preset number of cycles, as determined by the point of connection of $R35$ to the voltage divider at $R2$ and the time constant of $C21$ and $R35$, until the grid of $V9$ again rises sufficiently near its cathode to permit the peaking voltage of $T9$ to

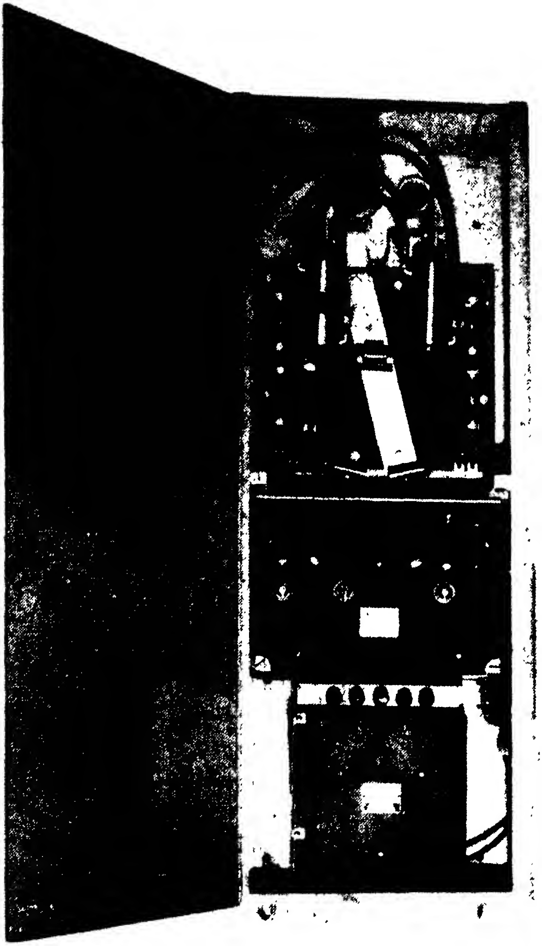


FIG. 22.5 The GE CR7503C121 resistance-welder control panel. (*Courtesy of General Electric Company*)

fire *V*9 again and start the heating period once more. This alternating heating and cooling cycle will continue as long as the initiating switch is closed.

Spot or Pulsation Welds. If a spot weld is desired, consisting of a single heating period, or a pulsation weld consisting of a definite number of spots, the switch *SW*4 is closed. This connects the anode of *V*2 into the circuit. The initiating contactor *CR*1 completes the circuit to the anode of *V*2 and removes the short circuit from the grid capacitor *C*22. But since the grid, through the uncharged capacitor, is connected to a preselected point on *R*36 negative with respect to its cathode, *V*2 cannot conduct.

However, each time *V*9 fires to start a heating period, the discharge current from *C*2 flows through the primary of transformer *T*12. The secondary of *T*12 is loaded across a voltage-regulating tube *V*12 to limit its output to a definite voltage, which overbalances the out-of-phase voltage holding *V*10 nonconducting and permits it to conduct for one half cycle, to pass through *R*57 a small increment of charge to *C*22 each time that *V*9 conducts to start a heating period. (It should be noted that *V*10 operates from the a-c supplied by a winding on *T*1, and not from the d-c supply.) After a definite number of charging pulses, as set by the position of the connection of *C*22 to *R*36, the accumulated charge placed on *C*22 will overbalance this bias and permit *V*2 to conduct.

In the anode circuit of *V*2 is the magnetic contactor *CRA*. Normally, when *V*2 is not conducting and *CRA* is dropped out, the shield grid of *V*9 is at approximately cathode potential. However, when *V*2 conducts, *CRA* is energized and closes its contacts, connecting the shield grid of *V*9 to the negative bus. Under this condition, *V*9 cannot conduct even if its No. 1 grid becomes positive. Thus the firing of *V*2 prevents further firing of *V*9 and locks out the control after the desired number of spots. Dropping out of the initiating contactor *CR*1 resets *V*2.

Two noteworthy features of this circuit are that only the steeper parts of the discharge curves of *C*2 and *C*21 are used for timing, thus ensuring definite action and greater accuracy, and that the heating and cooling times, determined by *C*2, *R*9 and *C*21, *R*35, respectively, are completely independent.

THE GENERAL ELECTRIC CR7503C121 THYRATRON CONTROL PANEL FOR A-C RESISTANCE WELDING

The modern resistance welding control is a very versatile instrument. One of its functions is the timing of the welder mechanical action. This may consist of opening the solenoid valve to apply air or hydraulic pressure to the work between the electrodes. This pressure is applied during the "squeeze" time. The weld heat is applied during the "heat" periods either continuously or in pulses. After the weld, pressure is held during the "hold" time to permit the weld to freeze, and finally in some sequences there is a time "off" after the pressure is released.

In the CR7503C121 panel the "squeeze," "hold," and "off" times are controlled by a CR7503F108 sequence panel. The more precise welding power-on and -off times are the duty of the CR7503B127 panel.

A further function of the B127 panel is the firing of the control ignitron at the desired phase angle to obtain the exact degrees conduction desired in each cycle.

The F108 Sequence Panel. The circuit for this panel is shown in simplified form in Fig. 22.6. It will be noted that this circuit uses both a-c and d-c anode supplies. A-C is used for the thyratrons 1, 5, and 6 and the magnetic relays *1CR* and *QTD*. Thyratron 9 and rectifier 2*A* receive their a-c supply from the B127 panel for both anode power and rectified bias.

The 150-volt d-c from a full-wave rectifier supply, not shown, is used for the *RC* timing circuits of 11*C*, 51*C*, and 61*C*. For seam welds (continuous on-and-off heat cycles) the two switches marked *S*4 are open. For spot and pulsation welds (a definite number of spots) they are closed.

Spot Welds. The initiating switch picks up 1*CR* which seals in and energizes the solenoid valve to apply weld electrode pressure. It also disconnects 11*C*, the "squeeze"-timing capacitor, from the negative d-c bus. 11*C* discharges through 11*R*, which is adjusted for the desired "squeeze" time, making the grid of thyratron 1 more positive until 1 fires, energizing *ACR* and 1*TD*. 1*TD* connects points 28 and 28*A* in the B127 panel to

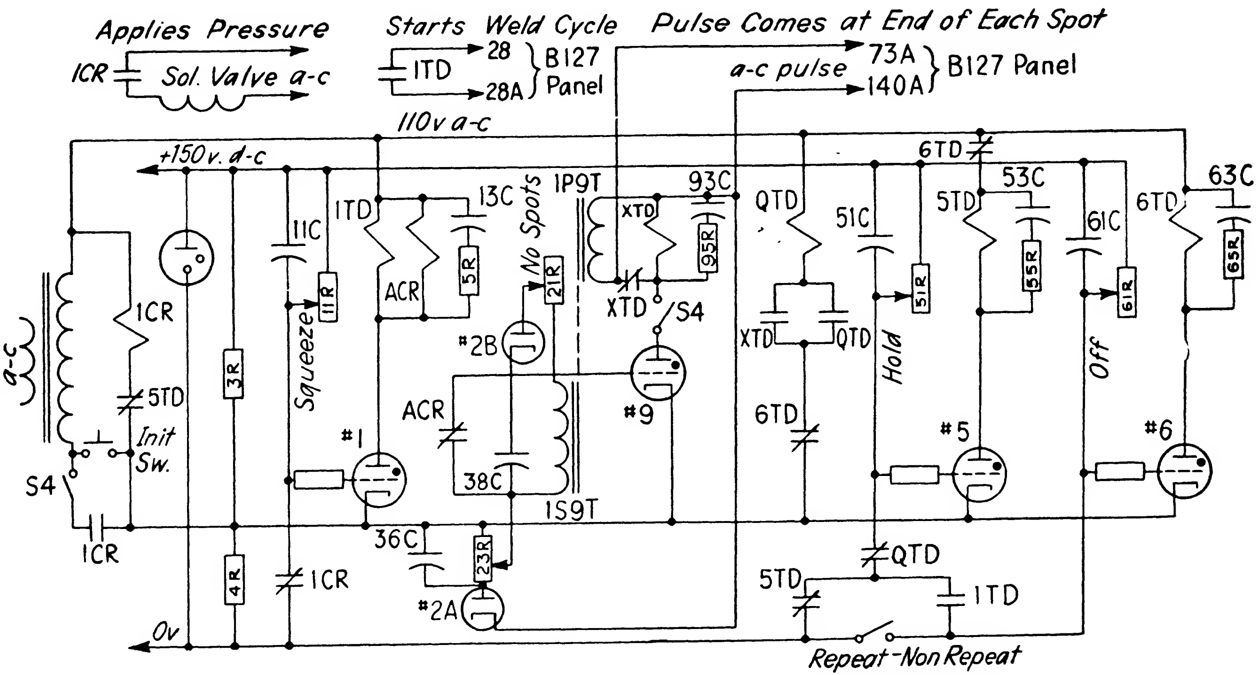


FIG. 22.6. The C121 sequence panel circuit, F108 section. 1*CR* starts operation. *Squeeze* timed by 11*C*, and 11*R*. Number of spots indicated by accumulated charge on 38*C*. *Hold* timed by 51*C* and 51*R*, *off* time by 61*C* and 61*R*.

start the weld heat period. $1TD$ also connects $61C$ to the negative bus, cutting off thyratron 6 and thus dropping out $6TD$. ACR removes the short circuit across $38C$ and permits it to start charging when there is voltage induced in $1S9T$.

At the end of the heat time a voltage pulse is received from the B127 panel on leads 107 and 108 to energize the transformer primary $1T9T$ and induce a voltage in its secondary $1S9T$. For a single spot $21R$ is set to a minimum resistance so that $38C$ charges quickly to a voltage sufficient to overcome the bias of $36C$ and $23R$ and to fire thyratron 9 and energize XTD. This picks up QTD which then seals in. QTD, in turn, releases the hold-timing capacitor $51C$ from the negative bus. $51C$, after discharging for the desired "hold" time as set by $51R$, raises the grid of thyratron 5 positive enough to fire it and energize $5TD$, which, in turn, drops out $1CR$, releasing the electrode pressure.

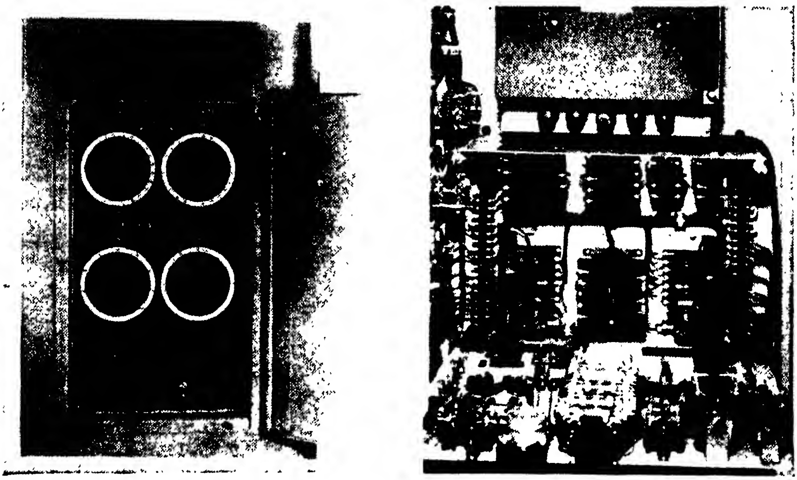


FIG. 22.7. At left is the C121 operator's control station. At right, B127 section swung down to permit access to the firing thyratron and circuit components. (*Courtesy of General Electric Company*)

If the "repeat-nonrepeat" switch is set to nonrepeat, the sequence stops here, but if it is set to repeat and the initiating switch is held closed, the drop-out of $1TD$ permits $61C$ to time out and "off" cycle and permits thyratron 6 to pick up $6TD$ which drops out QTD, cutting off 5 to drop out $5TD$ and thus permit $1CR$ to pick up again and start a new sequence.

Pulsation Welds. For pulsation welds having a definite number of spots, $21R$ is set to a higher value of resistance so that a definite number of pulses of power from the B127 panel are required to charge up $38C$ sufficiently to fire thyratron 9. Otherwise, this action is the same as that for a single spot. Note that after thyratron 9 has fired, XTD places a local voltage on $1P9T$ to assure that thyratron 9 remains energized throughout the sequence.

Seam Welds. For seam welds, continuous heat and cool cycles, $S4$ is open. $1CR$ cannot seal in, and QTD and $5TD$ cannot operate. Thus, all that the F108 panel does is to apply the squeeze time and maintain operation of the B127 panel through $1TD$ until the initiating switch is released.

The B127 Precision Synchronous Timing Panel with Heat Control. This panel provides the more precise timing required for turning the welding power on and off, or the heat and cool time. Its ultimate purpose is to reverse the phase on the bias transformer windings $S3T$ (Fig. 22.9) which normally prevents the firing thyratrons 12 and 13 from supplying ignitor power to the ignitron contactors 14 and 15. The action of the ignitron contactor was described on page 191. Also, a somewhat similar method of grid-phase control using an RC bridge such as $5C$ and $4R$ and $5R$ is taken up on page 175, so need not be repeated here. In the simplified circuit for the B127 panel of Fig. 22.8, tubes $7A$ and 10 are kenotrons, tubes 9 and 11 are pliotrons, tubes 1 and 8 are glow tube regulators, and the rest are thyratrons. Since some tubes operate on opposite "A" and "B" half cycles of the a-c supply, the transformer buses are shown twice, above the ground bus when they act as anode supply and below when they act as a negative bias. In this way it is hoped that the circuit operation will be clearer.

The circuit depends for part of its operation on "trailing-tube" action. For example, thyratrons 2, 3, and 4 have parallel inductances and resistances in their anode circuits. On page 119 we

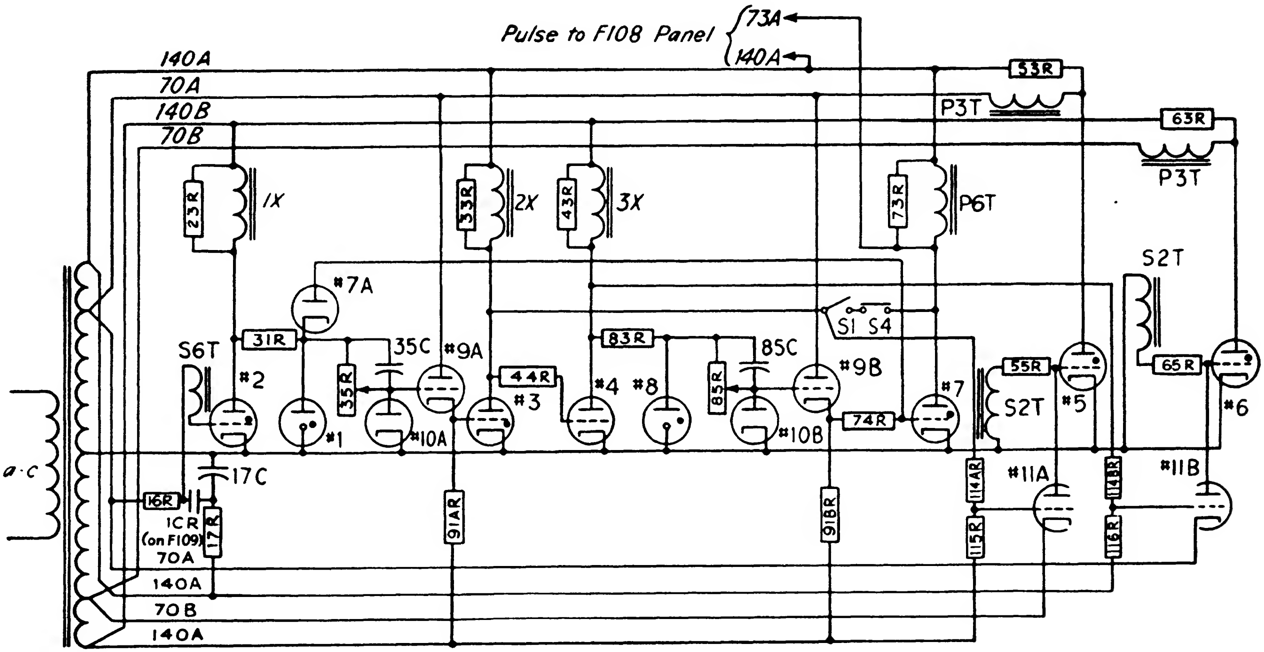


FIG. 22.8. The C131 circuit, B127 section. *Cool* period timed by 35*C* and 35*R*, *heat* period by 85*C* and 85*R*. Tube 3 trails 2 after *cool* time delay. Tube 4 trails 3. Tube 7 trails 4 after *heat* time delay. Tubes 5 and 6, when fired, reverse the phase of transformer *P3T* to fire the ignitrons.

found that this network tended to hold the anode positive after the start of a negative half cycle. Hence, if the anode is connected to the grid of a tube having its anode positive on the other half cycle, as is the case of tubes 3 and 4, when tube 3 fires it will cause 4 to fire on the next half cycle. Similar action occurs between 2 and 3 and between 4 and 7, but in this case timing circuits delay the action for a preset number of cycles.

Circuit Operation of B127 Panel. Thyratron 2 is normally held off by the negative grid bias from 70*A* since its anode is positive on the "B" half wave. However, closing of the 1*CR* contactor in the F108 panel shifts the grid phase through 17*C*, 17*R* network and fires tube 2. When tube 2 was off, the timing capacitor 35*C* became charged through 10*A* to the limit of 105 volts set by tube 1. So when thyratron 2 conducts, the negative side of 35*C* is driven negative 105 volts minus the drop in 2 and is held down by the anode of 2 so long as 2 conducts. Then 35*C* cannot recharge and so discharges through 35*R* which is calibrated in the number of cycles required to reach the critical voltage needed to fire thyratron 3.

To prevent undue loading of the capacitor circuit and obtain precise timing, a cathode follower tube 9*A* is interposed to fire the grid of thyratron 3. Since it will be seen later that the firing of tube 3 causes the ignitron contactor to conduct also, it appears that the delay between the firing of 2 and 3 is the off or cool time.

The Heat Time Action. We noted above that 3 fired 4 as a trailing tube, but now let us follow another action of 3. Through the voltage divider 114*AR* and 115*R*, its conduction supplies a negative cutoff bias to tube 11*A*. Normally, 11*A* conducts and applies a negative bias to thyratron 5 through the drop in 55*R* so that the action of *S*2*T* is ineffective. However, by the action of 3 in biasing off 11*A*, thyratron 5 is free to respond to the positive volt swings of *S*2*T*. *S*2*T*, it is seen, is the secondary of the heat-control phase-shift transformer *P*2*T* (Fig. 22.9), which sets the desired firing angle. So tube 5 fires at this preset phase angle.

In the anode circuit of tube 5 are 53*R* and *P*3*T*, half of the primary of the bias transformer which holds off the firing thyratrons 12 and 13. When tube 5 is off, *P3T* is excited from the voltage between 70*A* and 140*A* to supply holdoff bias to 12 and 13. But when tube 5 conducts, *P3T* is effectively placed across 70*A* and ground, reversed in phase from its previous excitation, and a positive voltage appears to cause *S3T* to fire thyratrons 12 and 13.

Also when tube 4 is fired by the trailing action of tube 3, it will be seen that 4 acts through 114*BR* and 116*R* on 11*B* as 3 did on 11*A* and so the action of tube 6 and the other half of *P3T* is exactly the same as that of 5 to complete the phase reversal on the firing thyratron bias and complete the excitation of the ignitron contactor to apply power to the weld.

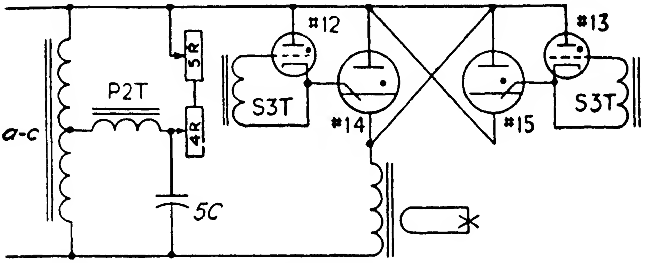


FIG. 22.9. C121 power- and phase-shift circuits. Compare this circuit with Figs. 15.21 and 15.14. Here firing occurs due to the reversal of phase of *S3T* rather than by the addition of voltage.

Returning again to tube 4, it is noted that it too controls the action of a timing circuit, composed of 85*C* and 85*R* and a cathode follower 9*B*, which, after a preset time delay, fires thyratron 7. This timing period, which takes place while 4 is conducting, is the "heat" time.

The Reset Action. Thyratron 7 energizes the primary *P6T* of a transformer whose secondary *S6T* in the grid circuit of tube 2 is phased to hold it off and permit 35*C* to recharge.

(In the description of the F108 panel, the voltage mentioned which appeared across 1*P9T* to permit charging of 38*C* is also that across *P6T* which appears when 7 fires for its resetting action.)

Since tube 3 fired in the same half cycle that 7 fired, the action of 3, firing 4 during the next half cycle, and 4, in turn, firing 7 on the second succeeding half cycle, cannot be prevented in the circuit described. Thus the minimum number of cycles that tube 2 can remain off—and hence the number of heating a-c cycles—is two.

The Single-cycle Heat Time. When only one cycle on is needed, it may be obtained in the following manner: *S*1 is closed, connecting the anode of tube 3 to that of tube 7. Now, on the very first "on" cycle, when 3 fires, *P*6*T* is energized and tube 2 is cut off. Thyratron 3 will fire 4 in the usual manner; but should 4 attempt to fire 7 on the next half cycle, it will be found that the failure of 2 to fire during the previous half cycle had allowed the energy in 9 to decrease and the anode of 2 to reach the 140*B* bus potential. This on the "A" half cycle draws the grid of 7 far negative because of the action of 7*A*. *P*6*T* is not energized, and 2 fires again after having been off for only one cycle, thus having permitted only one cycle of power to be delivered.

The Power and Phase-shift Circuit. In Fig. 22.9 we have the ignitron contactor and phase-shift bridge. The reversal of the phase of the bias transformer 3*T* by tubes 5 and 6 fires the thyratrons 12 and 13 and through them the ignitrons 14 and 15 to apply power to the welder.

WELDER CURRENT REGULATING

Electronic Current Regulator for Resistance Welding Control (GE CR7503D160). This circuit is designed to compensate for changes in line voltage, throat depth, and other factors affecting secondary reactance in order to hold a constant-rms welding current. Its fundamental principle of operation consists in energizing the filament cathode of an emission-limited kenotron from a current transformer measuring the welder current and then amplifying the drop in the kenotron anode resistor to shift the phase of the ignitrons in an attempt to hold the welder current—and the kenotron emission current—constant.

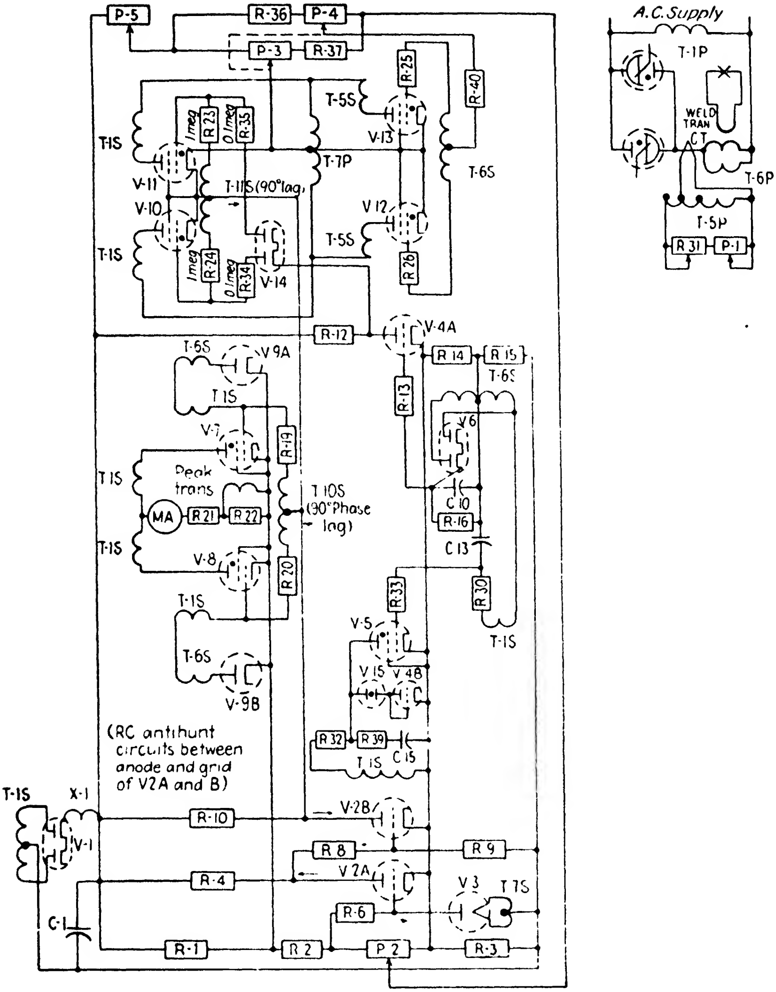


Fig. 22.10. A regulating panel to hold rms welding current constant, GE CR7503D160. Filament of $V3$ heated by rms value of welding current through action of transformers CT, $T5$, and $T7$. Emission current of $V3$ through $R6$ is amplified by $V2A$, B to vary grid phase on $V7$, 8, and phase of "shock-excited" peaking transformer which replaces $T2$ of circuit of Fig. 21.4. Between heat periods $V3$ is kept at proper average emission by power from $T1$ regulated through $V10$, 11 to $T7$. MA reading set by $P3$, 4 equal to average heat reading. During heat period $T1$, $V10$, 11 are cut off by $V4A$, and $V12$, 13 are fired by $T6$ to energize $T7$ from $T5$. $V5$ shunts neon lamp $V15$ except when current limit is reached. $V9A$, B limit forward-firing phase angle.

Since the cathode of the FP-400 kenotron used is a fine tungsten wire heated to a high temperature, its response is remarkably fast. Only one or two cycles are required for it to attain equilibrium. In order to hold the cathode at approximately the correct temperature between welds an auxiliary *stand-by*, or *off-time*, circuit is provided. When the weld begins, automatic electronic means transfer the cathode heater transformer over to operate from the welder current transformer. A signal circuit illuminating a neon light indicates when the circuit is functioning to supply full current to the welder and has reached the limit of its range.

This panel does not control the timing of the weld, that is, the number of cycles for heating and cooling. That is the function of the timing panel described above (Fig. 22.2 or Fig. 22.8) or similar panels. This panel only shifts the phase of the ignitron firing point to attempt to hold constant the rms welder current during the weld. In short, the whole purpose of this control is to vary the phase of the peaking transformer which replaces that of *T*1 of Fig. 15.14 or *T*2 of Fig. 22.2.

Circuit Simplifications. Although the individual circuits of this panel are not difficult to trace, because of the multiplicity of circuits it is necessary that the relative values of the components be known and their position in the circuit noted so that their relative importance may be understood. For example, on the panel, all thyratrons have small capacitors of 0.00005 μf between grid and cathode for the suppression of radio-frequency surges. Since their impedance at 60 cycles is extremely high, they do not affect the control action appreciably and may be omitted from the elementary. Almost all grids have series protective resistors of 1 megohm or so to limit grid current. If they perform no other function, they may be omitted from the functional elementary. Once the magnetic control part of the circuit, including the timer and contactor for cathode protection and continuously excited transformer primaries, has been traced, this part can be assumed and omitted from the elementary.

In this circuit, phase-shift bridges and the center-tapped secondary of the main control transformer *T*1 place a quadrature lagging phase on the primaries of transformers *T*10 and *T*11; so the bridge circuit may be omitted, and this fact may be noted near the secondaries of these transformers as they appear in the electronic circuit.

In the circuits of tubes *V*2*A* and *V*2*B* there are resistor-capacitor networks connected between anode and grid. From our study of basic circuits these are recognized as an antihunt circuit; so, unless hunting is the problem to be considered, these networks can be omitted, temporarily at least, from the circuit.

The Basic Circuit. In considering the circuit stripped to its bare essentials, perhaps the best starting point is at the welder itself. Two signals are given to the control by the welder. (1) The primary of transformer *T*6 shunted across the welder is energized by the welder primary voltage whenever the welder operates. (2) The weld current, through the current transformer, energizes the primary of transformer *T*5 whose output is adjustable both by taps and by loading on *P*1 and *R*31 to set the current to be held. These adjust the weld current required to energize the cathode of the emission-limited kenotron *V*3 to the required temperature.

The secondary of *T*5 is found to be split into two halves, which can be connected alternately by the thyratrons *V*12 and *V*13 to the two halves of the mid-tapped primary of the *V*3 cathode transformer *T*7. It is further seen that *T*7 might also be energized in a similar manner from the two halves of the secondary of the constantly excited transformer *T*1 through the thyratrons *V*10 and *V*11.

The D-C Control Circuit. In the d-c control circuit the full-wave rectifier including the twin-diode rectifier tube *V*1, the inverted L filter *X*1 and *C*1, and the voltage divider *R*1, *R*2, *P*2, and *R*3 are familiar. The emission-limited kenotron *V*3 and its anode resistor *R*6 are connected to the negative part of this divider. An auxiliary voltage divider is also tapped off the positive portion of the main divider. This consists of *P*5 and the parallel resistor circuits *P*3, *R*37 and *P*4, *R*36, whose common negative end is connected to the adjustable point on *P*2. *P*3 and *P*4 are two insulated potentiometers on a common shaft.

They are of the same resistance and have the same potential drop across them; but, because of the staggered positions of *R*36 and *R*37, the potentials are also staggered, with the result that as the common shaft is rotated the arms of the two potentiometers will always have a fixed difference of potential between them. The adjustments of *P*2 and *P*5 are preset to provide the desired range for *P*3 and *P*4.

Further inspection of the grid circuit of *V*12 and *V*13 shows that the difference of potential between the arms of *P*3 and *P*4 is a d-c bias on the two thyratrons, normally sufficient to hold them nonconducting. Therefore, under these conditions any excitation of the *V*3 cathode transformer *T*7 must come from *T*1 through *V*10 and *V*11.

Emission Control during "Off" Period. Let us assume that *V*10 and *V*11 are conducting and *T*7 is energized. The filament cathode of *V*3 is heated, and its emission current flows through *R*6, the *IR* drop drawing the anode of *V*3 and the grid of *V*2*A* more negative. As the grid of *V*2*A* is lowered below its cathode, the anode current of *V*2*A* decreases, raising the grid of *V*2*B* through the voltage divider *R*8, *R*9. The anode current of *V*2*B* is increased, drawing its anode more negative. But the anode of *V*2*B* is connected to the grids of thyratrons *V*10 and *V*11 through the quadrature-phase transformer *T*11, and the cathodes of the thyratrons are connected to the voltage divider at the arm of *P*3. This is a typical quadrature-phase d-c shift thyratron control circuit (page 179 and Fig. 15.8). Since the action for an increase in emission of *V*3 is to draw the anode of *V*2*B* more negative, this will tend to phase back the thyratrons, thus decreasing the excitation of *T*7 and preventing further increase in the cathode heating. So the emission of *V*3 tends to regulate itself at a value determined by the potential of the *V*10, *V*11 cathodes on the adjustable arm of *P*3.

Control during "Heat" Period. Let us assume that the welder has been energized. The shunt transformer *T*6 and the current transformer *T*5 are excited. The excitation of *T*6 has two immediate results. Its secondary in the grid circuits of *V*12 and *V*13 drives the grids positive in the correct phase relation to permit these tubes to conduct full current from *T*5 to energize *T*7. Also, the center-tapped secondary forming the full-wave rectifier with *V*6 charges up the capacitor-resistor network *C*10, *R*16 in a direction to overcome the normal cutoff bias (the drop across *R*14) on the grid of *V*4*A* and causes it to conduct full current, drawing its anode down; and with it, through the twin diode *V*14, the grids of *V*10, and *V*11 so far negative that *V*10 and *V*11 are definitely cut off. Note that, since *R*23 and *R*24 are 1 megohm and *R*34 and *R*35 are 0.1 megohm, the action on the grids of the potential of *T*11 is now not effective. The excitation of the *V*3 cathode transformer *T*7 has now been transferred from *T*1 to *T*5, whose potential is proportional to the welding current.

An increase in welding current will now cause an increase in emission in *V*3 that will be amplified in *V*2*A* and *V*2*B* as before, drawing the anode of *V*2*B* lower. This time we are most interested in the action on the grids of *V*7 and *V*8. These grids are also controlled through the varying d-c and mid-tapped quadrature transformer winding *T*10. The lowered anode voltage of *V*2*B* will cause *V*7 and *V*8 to fire later in the cycle. The anode circuit of these thyratrons is supplied from the continuously excited transformer *T*1, and the common load circuit includes a series milliammeter and a voltage divider *R*21 and *R*22 from which is tapped the primary of the peaking transformer controlling the firing thyratrons on the ignitron panel. The peaking transformer is *shock excited* by the steep current wave front twice each cycle when each thyratron fires and so can control both igniter thyratrons. Since *V*7 and *V*8 are phased back with increasing welder current and *V*3 emission, the welder current is kept from rising and a constant current regulation is secured.

When the weld is completed, *T*6 is deenergized, *V*12 and *V*13 cease to conduct, *C*10 discharges, and *V*4 ceases to conduct, permitting *T*1 through *V*10 and *V*11 to supply *T*7 again.

The "Off" Period Adjustment. The reason for the ammeter in the peaking-transformer circuit is as follows: A given firing angle for *V*7 and *V*8 means a definite average current in the milliammeter. When a job is set up and the desired welding heat is obtained, the milliampere reading is noted during a weld. Since this part of the control circuit operates all the time, the emission of *V*3 is set during the "off" period to match as nearly as possible the average emission of the "on" period by setting the double potentiometer *P*3, *P*4 at such a potential that the same milliammeter reading is obtained.

Control Limits. The twin diode *V*9*A* and *V*9*B* in the grid circuit of *V*7 and *V*8 serves to prevent the control from phasing forward beyond the natural phase angle of the welder (reference to page 97 and Fig. 9.5 will show the transients that occur if this is done). The continuously excited windings of *T*1 connected to the grids are of such a phase that the anodes of *V*9 are negative with respect to their cathodes during the positive half cycles for *V*7 and *V*8 and hence do not affect the normal operation of the circuit. The potentials of the windings of *T*6, however, oppose this voltage. If these potentials, proportional to the welder voltage, should become sufficiently large to overbalance the *T*1 voltages, the anodes of *V*9 will become positive with respect to the cathodes during the working half cycles for *V*7 and *V*8 and force the grids negative to limit the phase advance.

The Signal Light. A refinement of this circuit is the neon light, which indicates when the welder output has reached its maximum. The device consists of a neon light *V*15, limited to firing on positive half cycles by the rectifier *V*4*B* (triode used as a rectifier) and normally short-circuited by the thyratron *V*5. *V*5 is normally kept conducting and the neon lamp extinguished by the inphase continuously excited winding of *T*1, which overcomes the small d-c grid bias voltage across *R*14. However, as in the phase-limiting circuit described above, when the out-of-phase voltage across *T*6 becomes sufficient to overbalance *T*1, *V*5 ceases to conduct and the neon light is lit. Phase shifts in the anode circuit *C*15, *R*39, and *R*32 and in the grid circuit *C*13 and *R*30 assist in the effectiveness of the control.

Questions

1. Define "spot," "seam," and "pulsation" resistance welds, and explain how each is timed in the GE CR7503C110 welding control.

2. How does firing thyratron *V3* of Fig. 22.2 cause the welder to pass a full cycle of power at the proper phase angle?

3. In the weld current-regulating control of Fig. 22.10, what is the means for obtaining a controlling d-c voltage proportional to the weld current?

4. Why should the filament of kenotron *V3* of Fig. 22.10 be kept heated between welds, and how is this accomplished?

5. Describe the pulse-counting action during pulsation welding when using the GE CR7503C121 welder control.

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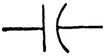
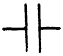
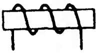
Electronics, May, 1943, p. 109; June, 1943, p. 128.

APPENDIX

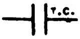
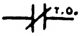
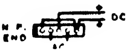
APPENDIX I

NOMENCLATURE

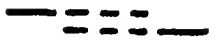
SYMBOLS

Standard industrial symbol	ASA No.	Device	Other symbols used for this device
	2.1	Battery	
	3.4	Capacitances (or condensers) (fixed)	 
	3.5	Capacitance (adjustable, variable)	 
 Air core  Iron core	5.1 5.2	Reactors or inductances (fixed) (a transformer may be shown by two or more of these symbols)	 
	5.8	Reactor or inductance (adjustable)	 
	7.1	Wire crossing, no connection	

SYMBOLS—(*Continued*)

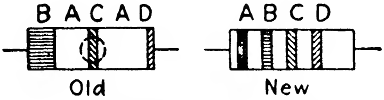
Standard industrial symbol	ASA No.	Device	Other symbols used for this device
	7.2	Wires connected	
	7.4	Ground	
	8.1	Contacts, normally closed when device is not energized	  
	8.2	Contacts, normally open when device is not energized	  
	8.3	N.O. contacts, time-delay closing	
	8.4	N.C. contacts, time-delay opening	
	8.8	Contactor, magnetic	 
	9.1	Fuse	
	10.2	Lamps; letter indicates color	
	15.1	Metallic rectifiers (copper oxide, etc.)	 

SYMBOLS—(*Continued*)

Standard industrial symbol	ASA No.	Device	Other symbols used for this device
	17.2	Resistor, fixed (may be marked to suit application)	
	17.3	Resistor, adjustable or potentiometer	
		Electron-tube elements:	
	. . . .	Cathode, directly heated filament	
	. . .	Cathode, unipotential, indirectly heated	
	. . .	Cathode, cold	
	. . .	Grids	
		Anode	
Ignitor 	. .	Ignitron	
Dot  (anywhere in envelope)	. . . .	Gas-filled tube	 Envelope area cross-hatched

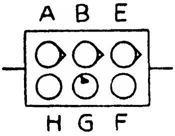
RMA Color Code for Resistors and Capacitors. The larger resistors and capacitors are usually marked with the rating on the body or support; but the resistors of 2-watt rating and below and the small mica capacitors, which are most often mounted on the panel where close inspection is difficult, are hard to identify. To make recognition easier they are marked with a color code to indicate the value of the resistance or capacity. Resistances are expressed in ohms, capacities in micromicrofarads.

Three or four colors are applied as shown below. Since most industrial electronic panels use components having a tolerance of 5 per cent or more, this method of marking is sufficiently accurate.



Note: In old form Color C was sometimes a dot.

RESISTORS



CAPACITORS

Resistors

A—Color for first significant figure.
B—Color for second significant figure.
C—Color for number of zeros after second significant figure.
D—Gold or silver to indicate tolerance (when applied).

Capacitors

A—Color for first significant figure.
B—Color for second significant figure.
E—Color for third significant figure.
F—Color for number of zeros after third significant figure.
G—Color for tolerance per cent.
H—Color for working voltage (in hundreds).

Examples:

Resistor: Green body, black end, yellow band—0.5 megohm. Blue band, red band, black band, silver band—62 ohms, 10 per cent tolerance.

Capacitor: Red, green, black, brown, red, blue. 2500 $\mu\mu$f or 0.0025 μf. 2 per cent tolerance, 600 working volts.

Color	Significant figure	Multiplying value
Black	0	×1
Brown	1	×10
Red	2	×100
Orange	3	×1000
Yellow	4	×10,000
Green	5	×100,000
Blue	6	×1,000,000
Violet	7	×10,000,000
Gray	8	×100,000,000
White	9	×1,000,000,000
Gold	5 per cent	Tolerance or 0.1
Silver	10 per cent	Tolerance or 0.01
No color (*D*)	20 per cent	Tolerance

Industrial-Tube-Type Cross Reference

Std. No.	Description	Equivalent types
5550	Ignitron, welder size A	GL-415, WL-681/686
5551	Ignitron, welder size B	FG-271, WL-652/657
5552	Ignitron, welder size C	FG-235A, WL-651/656
5553	Ignitron, welder size D	FG-258A, WL-655/658
5554	Ignitron, rectifier, 100 amp	FG-259B, WL-679
5555	Ignitron, rectifier, 200 amp	FG-238B, WL-653B
5556	Pliotron, triode, 8 mu	PJ-8
5557	Thyratron, merc. tri., 0.5 amp	FG-17, UE-967, WT-272
5558	Phanotron, merc., 2.5 amp	FG-32
5559	Thyratron, merc. tri., 2.5 amp	FG-57, WL-631
5560	Thyratron, merc. tetr., 2.5 amp	FG-95, WL-632A
5561	Phanotron, merc., 6.4 amp	FG-104
5620	Ballast tube, 6 volts, 0.25 amp	FB-50
5621	Ballast tube, 18 volts, 1.0 amp	B-6
5622	Ballast tube, 12 volts, 1.1 amp	B-25
5623	Ballast tube, 13 volts, 2.2 amp	B-47
5624	Ballast tube, 13 volts, 3.0 amp	B-46
5625	High-voltage kenotron, 1 amp peak	KC-4
5739	Pliotron, ionization gage	FP-62
5740	Pliotron, electrometer tube	FP-54
5742	Pliotron, triode, 30 mu	PJ-7

APPENDIX II

OHMIC VALUES OF RESISTANCE AND REACTANCE

Introduction. Since the tolerance on the values of the resistors, capacitors, and reactors used in industrial electron circuits is usually ±5 per cent, there is little need to find the ohmic values more exactly than to two digits or 1 per cent. Hence, a graphical determination of values is sufficiently accurate; furthermore, it provides a means for a rapid survey of the effect of changes in components, frequency, and so on.

Alignment charts have been chosen for their simplicity, accuracy, and ease of use by anyone familiar with the logarithmic scales used on slide rules. In some cases tables of definite values for common sizes and frequencies are included for checking to prevent misplaced decimal points. However, a large portion of the values most commonly used may be determined directly with small chance of error. A piece of string, pencil, or folded sheet of paper may be used as a straightedge.

Ohm's Law. When any two quantities are known (volts, watts, milliamperes, or ohms), if a straight line is drawn connecting these two points the two unknown values will lie on this line.

Example A: A current of 30 ma flows in a resistance voltage divider. How many volts will be found across a 2500-ohm section of the divider?

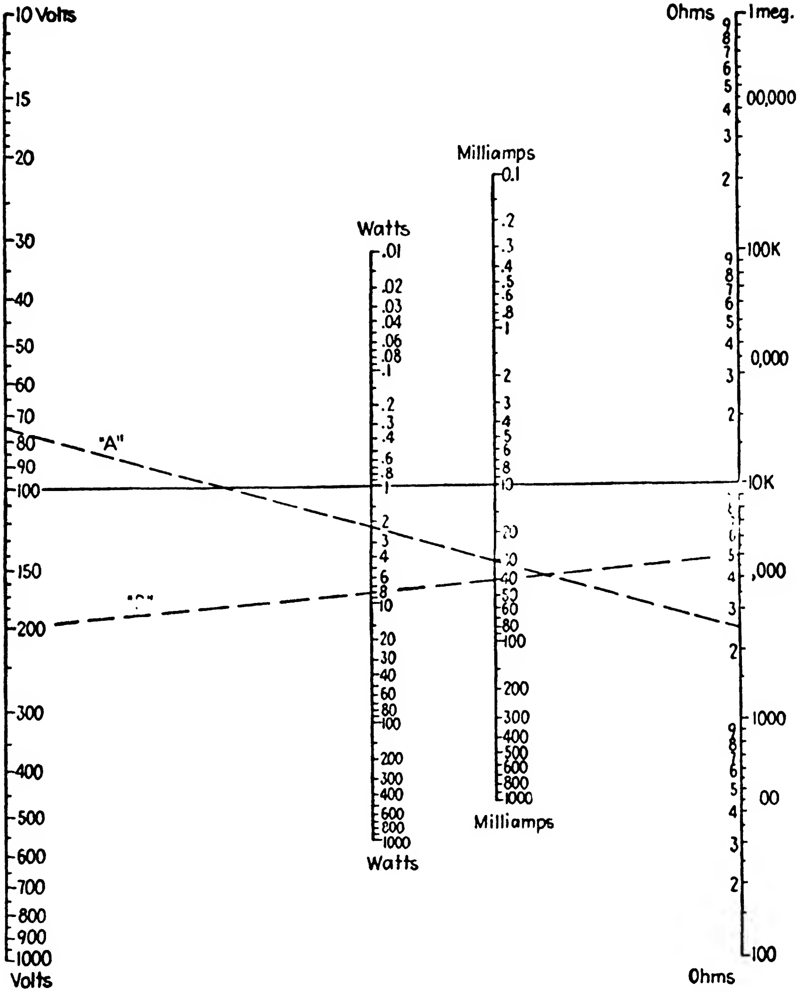


Fig. 11.1. Alignment chart for resistance.

What watts must the 2500-ohm resistor dissipate? Line *A* shows 75 volts and 2.25 watts.

Example B: 5000 ohms is connected across 200 volts. What is the current flow, and what watts are dissipated? Line *B* shows this to be 40 ma and 8 watts.

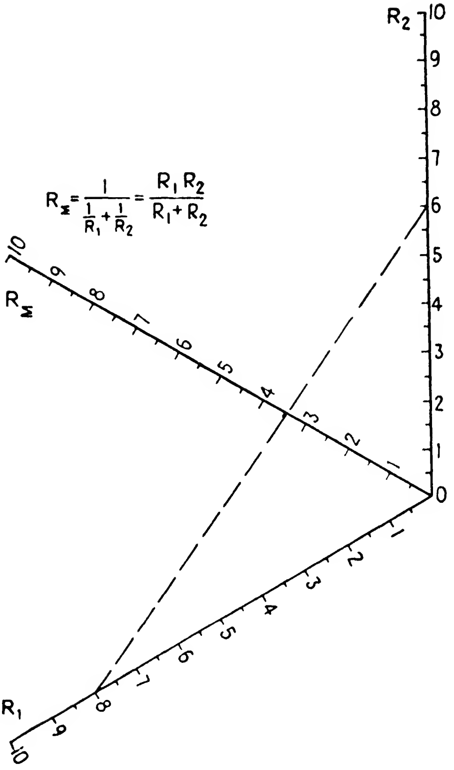


FIG. 11.2. Alignment chart for resistances or reactances in parallel.

Parallel Resistors or Capacitors. To find the resistances of two resistors in parallel, connect the resistor values on the outside legs by a straight line. This line will cut the midleg at the resultant value.

Example: What is the resistance of a 6-ohm and an 8-ohm resistor in parallel? *Ans.:* 3.43 ohms.

In a similar manner there may be found the value of paralleled inductances or capacitors or the focal length of a lens when the object and image distances are known.

Inductive Reactances.

L	60 cycles	100 cycles	1 kc	10 kc
1 millihenry	0.377	0.628	6.28	62.8
3 millihenrys	1.13	1.89	18.9	189
10 millihenrys	3.77	6.28	62.8	628
30 millihenrys	11.3	18.9	189	1.89 K
100 millihenrys	37.7	62.8	628	6.28 K
300 millihenrys	113	189	1.89 K	18.9 K
1 henry	377	628	6.28 K	62.8 K
3 henrys	1.13 K	1.89 K	18.9 K	189 K
10 henrys	3.77 K	6.28 K	62.8 K	628 K
30 henrys	11.3 K	18.9 K	189 K	1.89 megohms
100 henrys	37.7 K	62.8 K	628 K	6.28 megohms

Example: Find inductance of 0.3 henry at 100 cycles. A line joining the two points cuts the center line at 189 ohms. (Check against table.)

Inductive reactance *increases* with frequency.

Inductive reactance *increases* with number of henrys.

To determine reactance values for other inductances and frequencies, each time either cycle or henry scale is multiplied or divided by 10, multiply or divide reactance scale by 10 also. The table provides a quick check for the scale multiplier.

Example: Find inductance of 30 millihenrys (0.03 henry) at 10 kc (10,000 cycles). For 0.03 henry, divide henry scale by 10; for 10 kc, multiply cycle scale by 100. Reactance scale will be $\frac{1}{10} \times 100 = 10$ times.

Ans.: 10 × 189, or 1890 ohms (1.89 K)

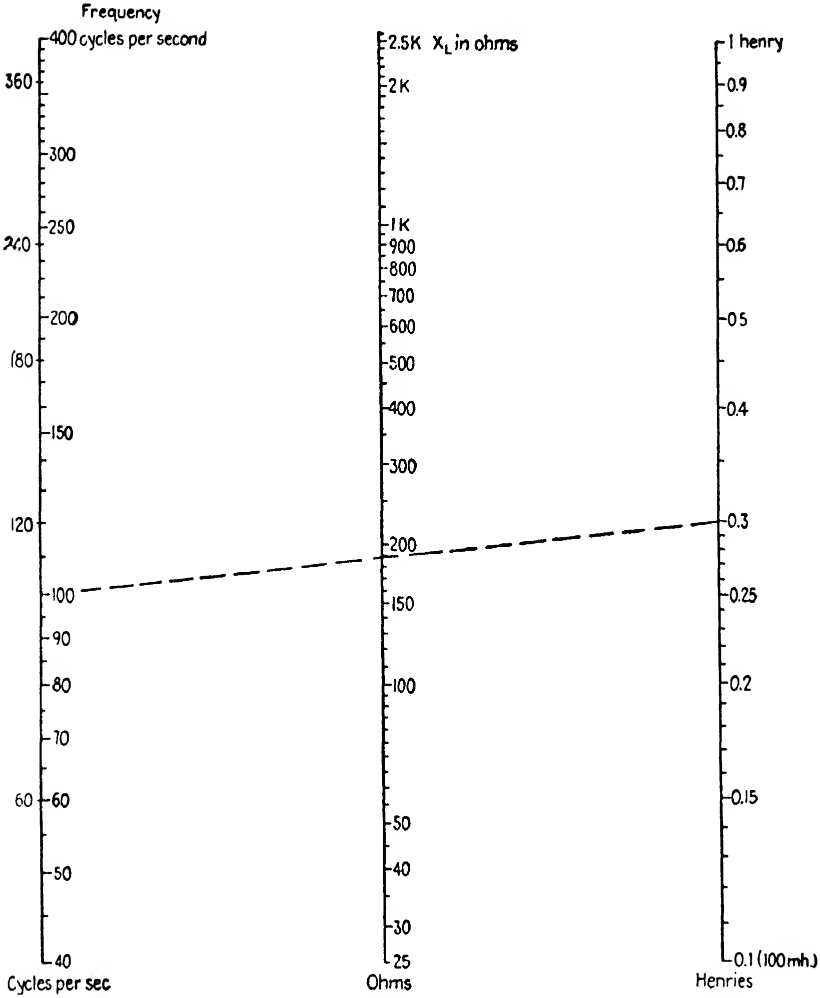


FIG. II.3. Alignment chart for inductive reactance.

Capacitive Reactances.

C, μf	60 cycles	100 cycles	1 kc	10 kc
0.0001	26.5 megohms	15.9 megohms	1.59 megohms	159 K
0.0003	8.84 megohms	5.31 megohms	531 K	53.1 K
0.001	2.65 megohms	1.59 megohms	159 K	15.9 K
0.003	884 K	531 K	53.1 K	5.31 K
0.01	265 K	159 K	15.9 K	1.59 K
0.03	88.4 K	53.1 K	5.31 K	531
0.1	26.5 K	15.9 K	1.59 K	159
0.3	8.84 K	5.31 K	531	53.1
1.0	2.65 K	1.59 K	159	15.9
3.0	884	531	53.1	5.31
10.0	265	159	15.9	1.59

Example: Find reactance of 0.3 μf at 100 cycles. A line between the two points cuts the center line at approximately 5310 ohms, or 5.31 K (check table). Note that the center scale increases *downward*.

Capacitive reactance *decreases* as frequency *increases*.

Capacitive reactance *decreases* as microfarads *increase*.

Each time the cycle scale or the microfarad scale is *multiplied* by 10, the ohm reactance scale is *divided* by 10, and vice versa.

Example: Find reactance of 0.0003 μf at 10 kc. The microfarad scale is divided by 1000; hence, multiply the ohm scale by 1000. The cycle scale is multiplied by 100; hence, divide the ohm scale by 100. $\frac{1}{100} \times 1000 = 10$.

Ans.: 5.31 K × 10 = 53.1 K ohms.

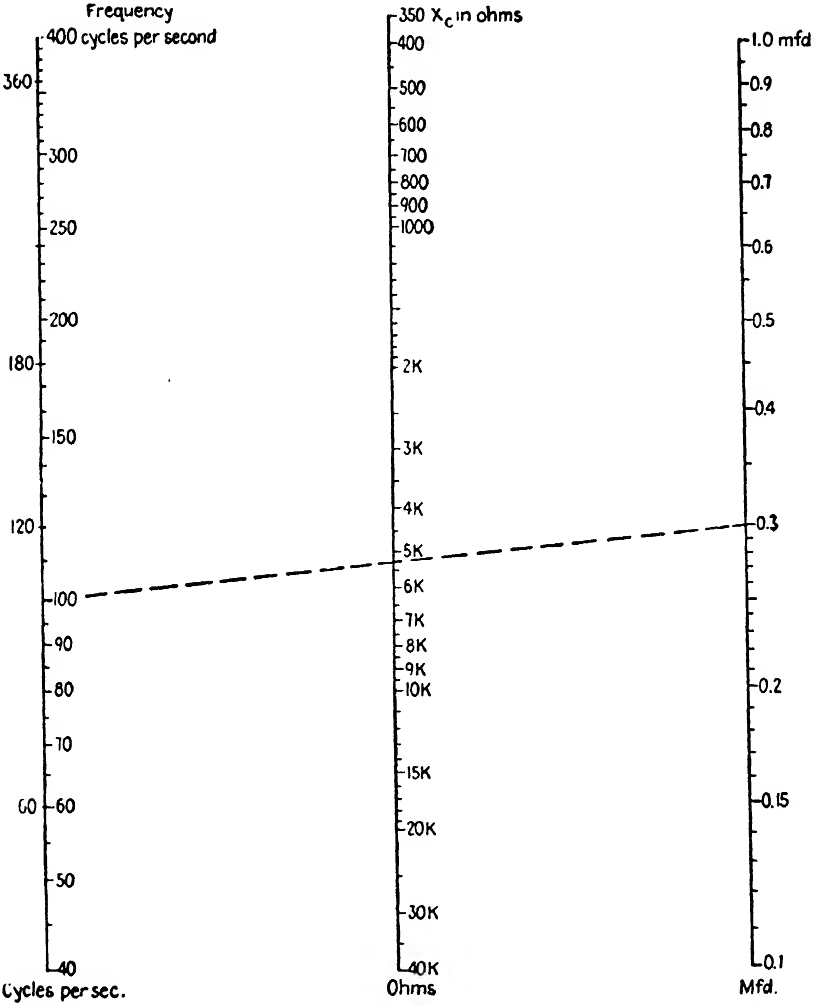


FIG. II.4. Alignment chart for capacitive reactance.

Phase-shift Bridge Circuits.

Example: Resistance-inductance bridge.
$R = 5000$ ohms
$L = 30$ henrys ($X_L = 11{,}300$ ohms at 60 cycles)
Alignment as shown by dotted line.
Grid phase angle is 133 deg.

If R, X_L, or X_C falls outside of the values given, multiply or divide both components by 10, 100, etc., to bring values within scale reading. (If the angle a is desired, it is equal to one-half of A. *The opposite internal angle is* $90° - a$.)

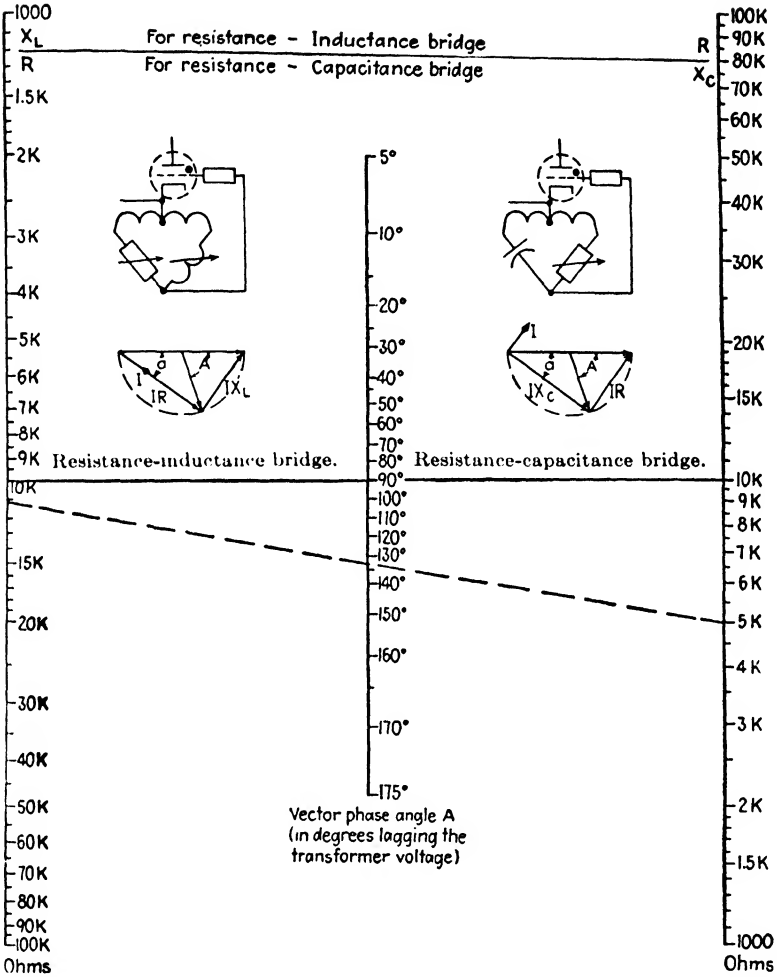


FIG. II.5. Alignment chart for obtaining the phase angle of a bridge composed of RL, or RC and a midtapped transformer.

APPENDIX III

STANDARD CURVES

Deg	Sine
0–180–360	0.0
10–170–190–350	0.174
15–165–195–345	0.259
20–160–200–340	0.342
30–150–210–330	0.500
40–140–220–320	0.643
45–135–225–315	0.707
50–130–230–310	0.766
60–120–240–300	0.866
70–110–250–290	0.940
80–100–260–280	0.985
90–270	1.000

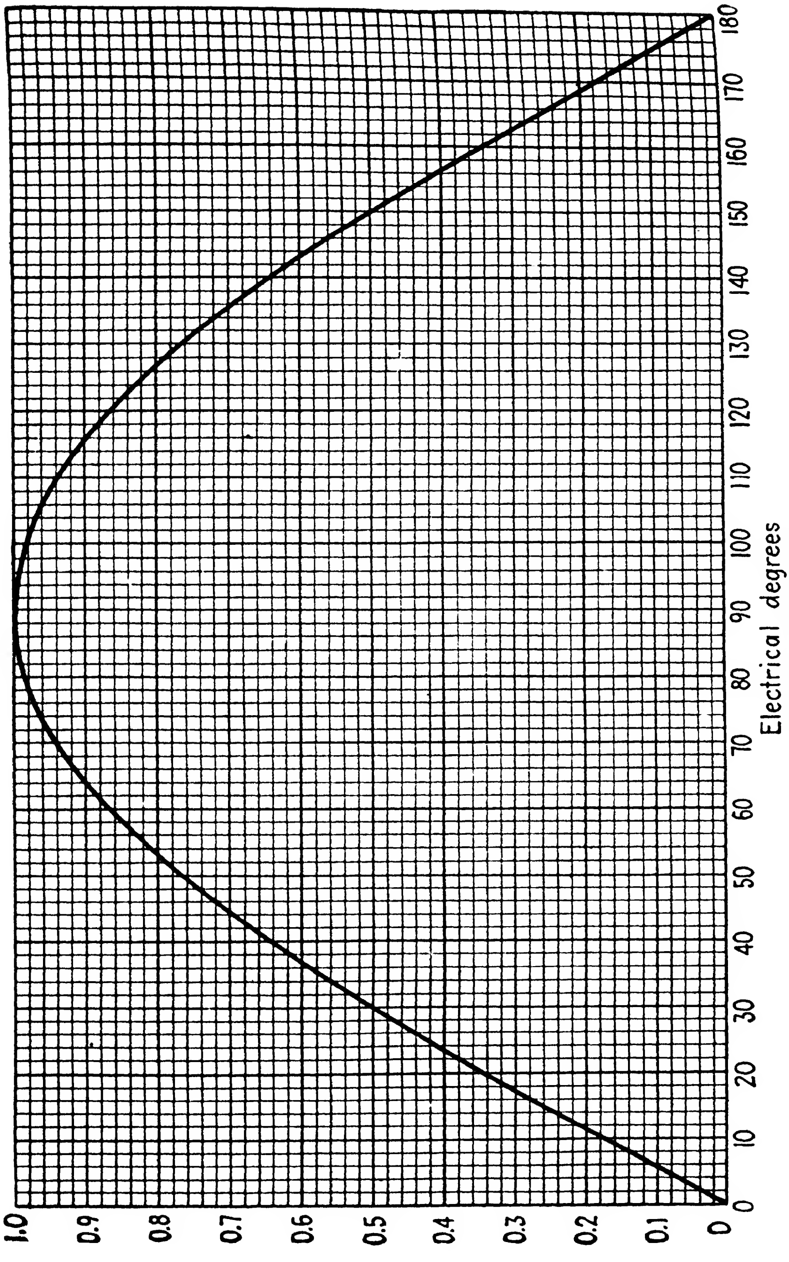


Fig. III.1. The sine curve.

PERCENTAGES

Time constant	Dis-charge	Charge
0	100	0
10	90	10
20	81.8	18.2
30	74.1	25.9
40	67	32
50	60.6	39.4
60	54.9	45.1
70	49.6	50.4
80	44.4	55.6
90	40.6	59.4
100	36.8	63.2
150	22.3	77.7
200	13.5	86.5
300	5.0	95

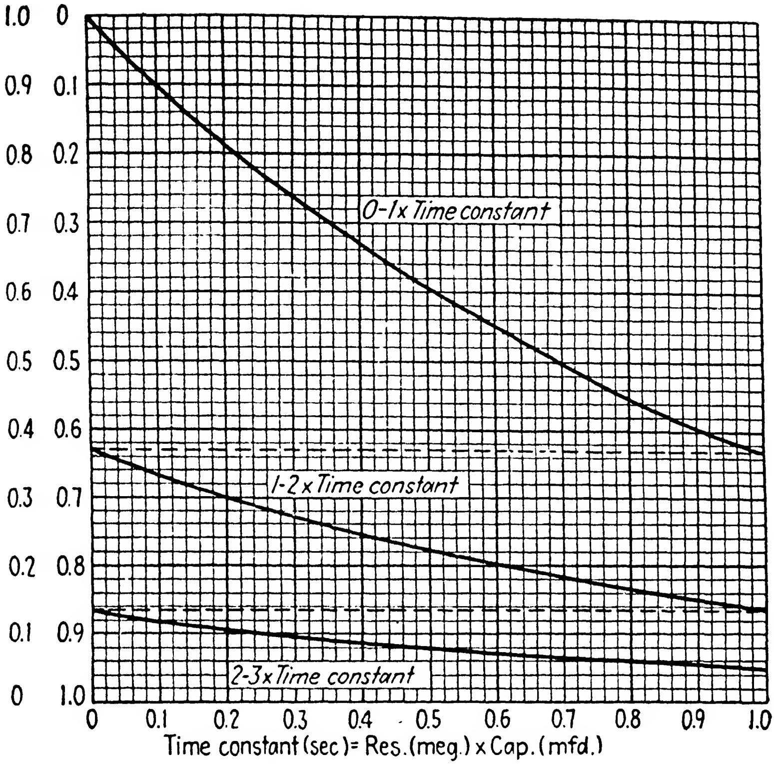


FIG. III.2. The exponential charge or discharge curve.

APPENDIX IV

RECTIFIER WAVE SHAPES

All voltage values are in ratio of d-c volts output.

Type	New circuit figure numbers	No. tubes	Voltage		Ripple			Current peak to average per tube		Conduction angle, deg. per tube
			Secondary a-c volts to neutral	Peak inverse volts	Ripple factor, rms	Peak to trough	Frequency (times line frequency)	*L*-load	*R*	
Single-phase half-wave (freewheel).	11.6	1	2.22	1.57	1.21	3.14	1x	1		0-180
Biphase half-wave......	12.2	2	1.11	3.14	0.472	1.57	2x	2	3.14	0-180
Single-phase full-wave	12.3	4	1.11*	1.57	0.472	1.57	2x	2	3.14	0-180
Three-phase half-wave..	12.4	3	0.855	2.09	0.177	0.604	3x	3	3.63	30-150
Three-phase full-wave ..	12.8	6	0.855*	1.05	0.040	0.140	6x	3	3.63	30-150
Four-phase half-wave..	12.7	4	0.785	2.22	0.099	0.326	4x	4	4.45	45-135
Six-phase half-wave......	12.5	6	0.741	2.09	0.040	0.140	6x	6	6.28	60-120
Double Y with interphase	12.6	6	0.855	2.09	0.040	0.140	6x	3‡	3.63	30-150

* Between terminals.

‡ In this circuit two tubes divide the rectifier output current. In the other circuits the rectifier current is the peak current of one tube.

APPENDIX V

PHOTOELECTRIC PHENOMENA

1. Spectral Response of Phototube Cathode Surfaces. The composition of the material in the cathode surface of the phototube determines the relative sensitivity of the tube to light of various colors as well as the total over-all sensitivity. Figure V.1 shows the actual sensitivity of certain cathode surfaces for equal energy of light of different colors or wave lengths. The part of the radioelectronic radiation spectrum that affects our eyes as light covers the range of 400×10^{-9} meter (violet) to

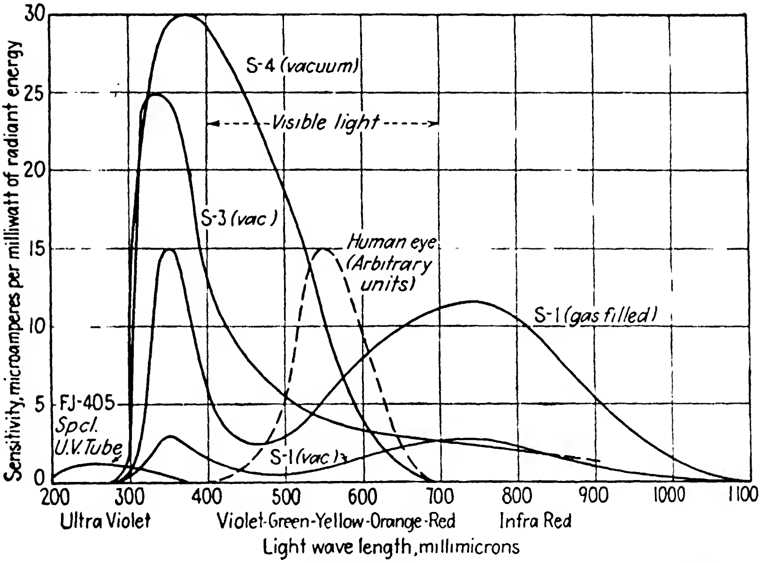


FIG. V.1. Response of some phototube-cathode surfaces to equal light at each wave length.

700×10^{-9} meter (deep red). This is usually expressed as 400 to 700 millimicrons or 4000 to 7000 angstrom units. As

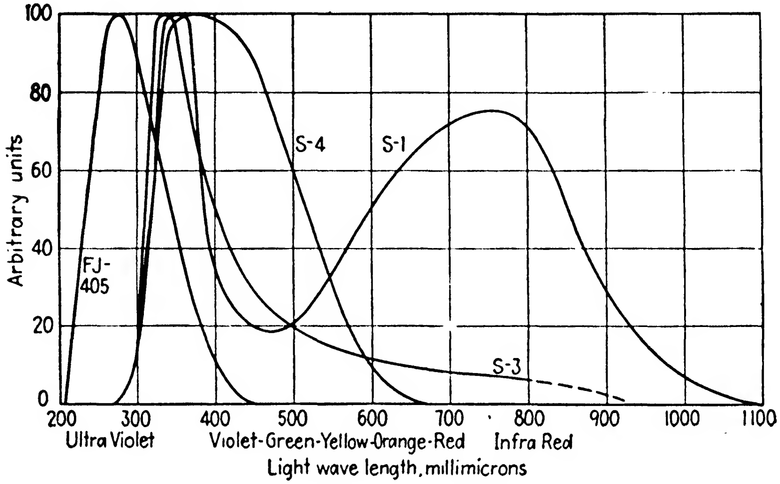


FIG. V.2. Comparative spectral response distribution for phototube cathodes.

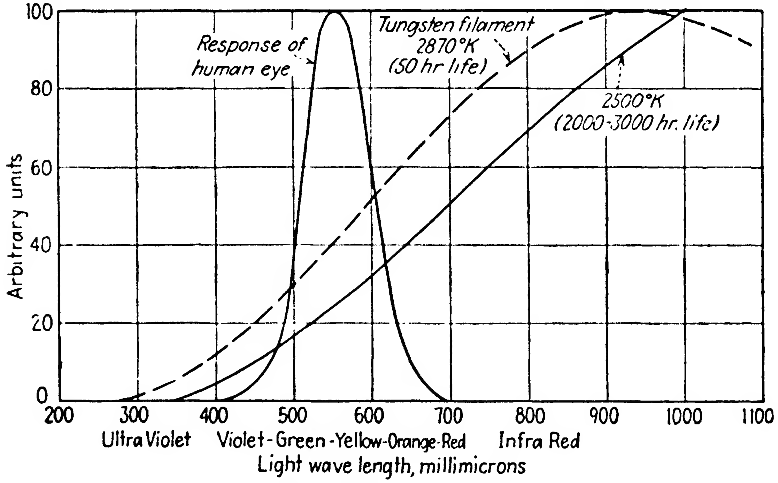


FIG. V.3. Spectral distribution of light energy from tungsten filaments.

may be noted from Fig. V.1, the sensitivity of the phototubes is not limited to the same range as that of the eye.

Figure V.2 provides another study of the relative color sensitivity. In this figure each curve is drawn to an arbitrary 100 per cent sensitivity at the maximum value for each surface. The broken line of Fig. V.1 indicates the relative sensitivity of the human eye to the various colors.

Response to Incandescent Light. The light source used for most photoelectric work is not an ideal one producing equal light for all colors, but usually an incandescent lamp having a light distribution approximately as shown in Fig. V.3. If this factor is taken into consideration, the actual response to be obtained from the phototube when excited by such a light or by this light reflected from a colored surface is distorted to that shown in Fig. V.4. (The eye-sensitivity curve peak has also been shifted to the red.)

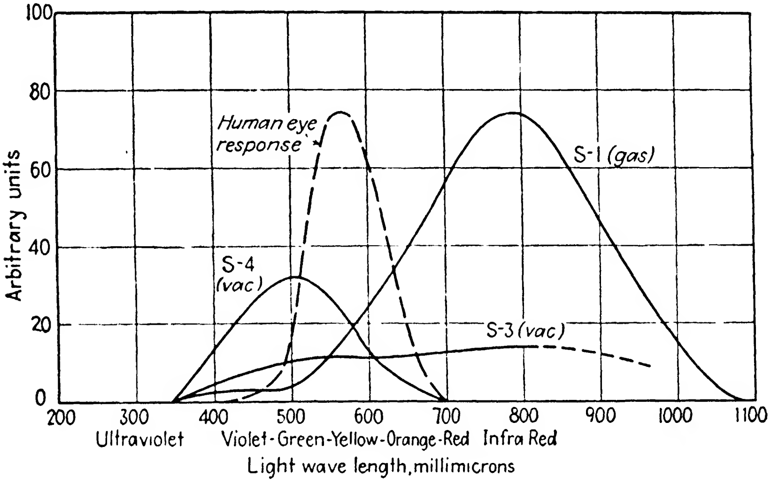


FIG. V.4. Relative response of phototube cathodes to light from a 2500° K filament.

2. Simple Optical Systems. It is said that a light ray travels in a straight line. This is true only so long as the light continues in one medium such as air at constant temperature, a vacuum, or glass. The bending of the rays better to perform useful purposes is the object of optical systems.

The Radiation of Light Energy. If we consider our light source as a point with the light radiating from it in all directions, it is clear that the energy leaving the source in the form of light will cover the inner surface of a larger and larger imaginary sphere as it gets farther away from the source. Since there is a definite amount of energy being radiated and the surface of a sphere increases as the square of the radius, the amount of light energy that can strike each square inch or square foot of the sphere must become less by the same amount, or must vary inversely as the square of the distance from the source. If we consider only a small cone of light rather than the total radiation around the sphere, the same truth holds (Fig. V.5). Since the energy in the cone of light must remain constant, the intensity of the light striking a surface must vary inversely as the square of the distance from the source.

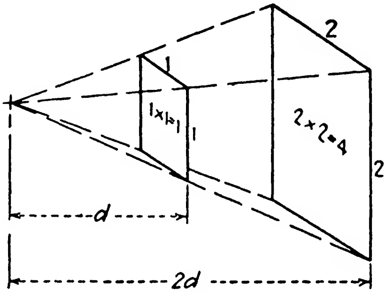


FIG. V.5. The area covered by a given cone of light varies with the square of the distance.

Light intensity is comparable with voltage and is expressed in *foot-candles*—the intensity of light at a distance of 1 ft from a standard light candle made to certain strict specifications. The light-flux energy unit, the lumen, corresponding to the watt, is a light intensity of 1 foot-candle on an area 1 ft square. For example, assume a standard candle located at the center of a sphere of 1 ft radius. The brilliance of the light is 1 candle power. The intensity at the surface of the sphere is 1 foot-candle. The sphere has a surface area of 12.6 sq ft. Thus the total flux is 12.6 lumens. If the light source has a brilliance of 2 candle power, the intensity at the sphere would be 2 foot-candles and the total lumens would be 25.2.

Mirrors. The light rays may be deflected from their original direction by means of mirrors, either flat or curved. The ray reflected from the mirror always has the same angle with respect to the mirror as the incident ray and will be reflected on the opposite side of the line perpendicular to the mirror at the point of incidence. If the mirror is a flat, or plane, mirror, the light rays will continue to expand in their original cone formation (Fig. V.6). However, if the mirror is curved, the light rays either may be bent farther away from each other or may be bent back toward each other to converge at a point again. In the case of a mirror of parabolic shape, the point at which light rays from a great distance, as from the sun, converge after striking the mirror is called the *focal point* of the mirror and the distance from this to the center of the mirror surface is the *focal length* of the mirror. Of course, a point source of light at this focal point will project rays from the mirror which are parallel (see Fig. V.7).

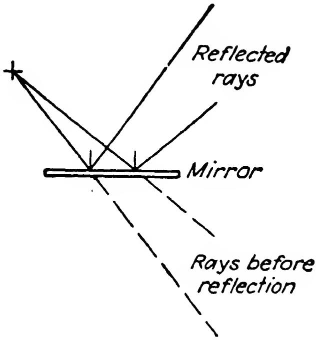


FIG. V.6. The action of a plane mirror.

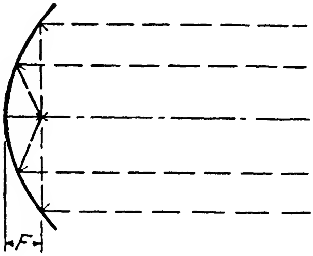


FIG. V.7. The parabolic mirror reflector. *F* indicates the focal length.

Types of Mirror. Mirrors may be *first surface*, which means that the light strikes the silver or other reflecting surface directly, or they may be the *second-surface* type in which the silvering is plated on the back of glass. The first-surface type is the more efficient since the light does not have to pass through glass. However, the second-surface type offers better protection for the silvered surface and is much used in industrial work.

The first-surface mirror absorbs between 5 and 10 per cent of the light as it reflects it. The second-surface mirror may absorb 10 to 20 per cent.

Prisms. Another method of bending or deflecting the rays of light is by permitting them to pass through a different medium, which is usually some form of glass. This principle is used in a prism, a triangular block of glass, so shaped and placed that the light enters through one plane and leaves by another at an angle with the first, after having been slowed down and bent through the desired angle. If the light ray is bent sharply in the same direction, both on entering and leaving the glass, the short wave lengths (blue) will be bent more than the long ones (red) and a rainbow effect is produced (chromatic aberration). However, in most photoelectric work the bending is so slight that this effect may be neglected.

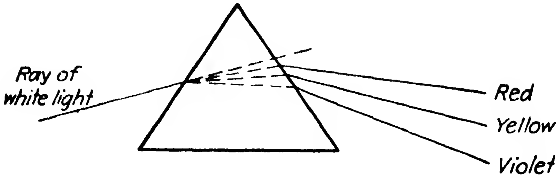


FIG. V.8. The prism bends the short wave length (violet) more than it bends the long wave length (red).

At some glass-air surfaces, a ray striking the internal surface of the glass at a sharp angle may be totally reflected and not reach the air at all. In a total reflecting prism, the light may be bent through 180 deg and return in the direction from which it came. This type of prism is similar in action to a mirror (Fig. V.9). It is somewhat more efficient, absorbing only 5 to 8 per cent of the light striking it.

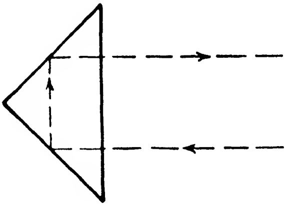


FIG. V.9. Total reflection obtained by double reflection within a prism.

Lenses. As in the case of mirrors, glass may be curved in shape to cause the rays of light to converge or to diverge more rapidly than normal. Such pieces of glass are known as *lenses*. Like mirrors, they cannot create light energy; they can only take the energy that strikes them and redirect it along a more useful path. For example, a diverging cone of light may strike a lens and be reconverged to a small cross section. Thus a spot of light of high intensity may be focused where desired.

The Lens Focal Length. If light rays that are almost parallel, such as those from the sun, are directed through a *positive lens* whose center part is thicker than its edge, the rays may be made to converge to a point. This is called the *focal point* of the lens, and the distance from it to approximately the center of the lens is called the *focal length* of the lens.

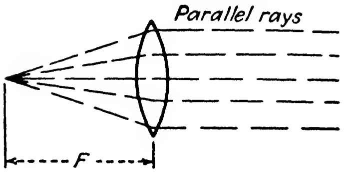


FIG. V.10. The focal length of a simple lens.

Thus, by definition, a ray of light passing through the focal point in one side of a lens will emerge on the other side parallel to the axis of the lens. Also, since light passing through the center of the lens passes through two parallel surfaces of glass, its direction will not be changed. Moreover, it can be shown through simple geometry that if the source of the light rays is not at an extremely great distance but is close by, the distance from the light source S_1 to the lens and the distance from the lens to the point at which the rays converge on the other side of a lens S_2 are related to the focal length f of the lens by the simple formula $1/S_1 + 1/S_2 = 1/f$ (see Fig. V.11).

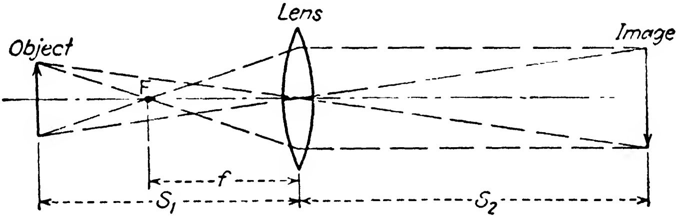


FIG. V.11. The formula for a simple lens, $1/F = 1/S_1 + 1/S_2$.

Practical Light Sources. We have talked so far of a point source of light. We know that in practical applications this is an impossibility. Although for photoelectric work we use automobile head-lamp bulbs and other forms of lamps with a concentrated filament to secure a source of the smallest practical size, these filaments must have finite dimensions. When the light from a definite filament is projected through the lens, the rays from each point on the filament will converge to a point on the opposite side of the lens. However, as stated above, the rays passing through the center of the lens are not bent, so that those passing from the top of the filament will appear somewhat below the axis of the lens as they converge again. In the same manner, those from the bottom of the filament will appear above the axis of the lens. If at this focusing point we place a sheet of paper or ground glass, we see an upside-down image of the filament that compares in size with that of the original filament as the distance of the image from the lens compares with the distance of the filament itself from the lens.

Since the energy received by the lens from the light source is constant, the intensity of the light at the filament image must, of course, vary inversely with the *area* of the image. This means that it must vary *inversely* as the *square* of the distance of the image from the lens.

Of course, the larger the lens and the closer the filament is to it, the larger the cone of light received by the lens from the filament. However, this requires that the lens bend the light rays more until a practical limit is reached in the size and shape of the lens. Usually, a lens focal length of 1½ to 2 times its diameter is about the practical minimum. (This ratio is called the *f*-number of the lens.)

Two-lens Systems. Two lenses placed close to each other act almost as a single lens. However, if they are spaced farther apart, but less than the focal length, a slightly different formula is used to indicate the effective focal length of the system.

$$F = \frac{f_1 f_2}{f_1 + f_2 - d}$$

when d is the distance between the lenses.

If the lenses are spaced farther apart than the focusing point for the previous lens system, the image formed by the first lens may be taken as the object that is focused again by the second lens (Fig. V.12).

Efficiency and Apertures. The light that is selected from the light source by the first lens in an optical system is the only light that is available, and this is reduced each time that the light passes from air to glass or from glass to air. At some point

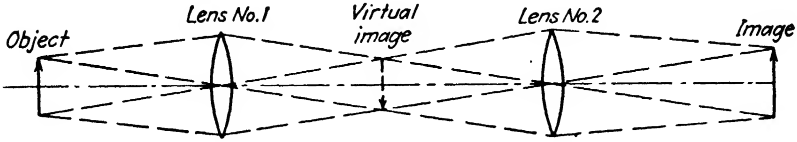


FIG. V.12. A two-lens optical system.

farther in the system, it may be necessary to decrease the light that has been passed by the first lens by using a slit or opening smaller than the available cross section of the light beam at that point. That point in the system where the opening limits the portion of the original light which finally reaches the end of the system is called the *aperture*.

Reflection from Specular and Diffuse Surfaces. For many photoelectric applications, we must work with light reflected from

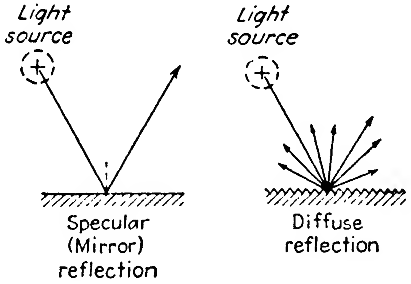


Fig. V.13. Specular and diffuse reflection.

a surface. Reflection is of two kinds: (1) *specular*, which is mirror reflection, except, usually, with greater losses, and (2) *diffuse*, in which reflection is from a surface so rough that the light rays are reflected in many directions and no image of the original source can be seen (Fig. V.13). (This paper reflects light by diffuse reflection.) The brilliance of light reflected from such a surface is usually expressed, not in candle power, but in *lamberts*, the equivalent of a lumen radiated from a square centimeter. (The millilambert, 0.001 lambert, is a more convenient unit.)

Light from such a diffuse surface can be projected through an optical system to produce images of the surface, just as light from a concentrated source can be. However, because the light is now diffused in many directions, a much smaller percentage reaches the lens and a much lower light intensity in the image results.

Lens Quality. The sharpness of the image projected by the lens depends on the quality of the lens used. For accurate photographic work, highly corrected lenses made of a number of pieces of special glass are used to cause all colors to focus at nearly the same point. However, for most photoelectric work—counting opaque objects, limit switches, etc.—simple lenses made of a single piece of glass are adequate. For special work, such as color-register control or in spectrophotometers, more elaborate lenses are used. See Fig. V.14 for a typical example of a photoelectric optical system for scanning a surface by reflected light.

The Bausch & Lomb Optical Company, Rochester, N. Y., makes and stocks a wide variety of unmounted lenses that may be used for photoelectric work. These are described in their catalogue D-10. Often simple lenses such as those used in spectacles may be obtained from local optical dealers. Opticians usually specify focal lengths in *diopters.* A diopter is the reciprocal of the focal length in meters (40 in., approximately). Thus a 10-diopter lens has a focal length of 4 in.

3. Light Filters. Light filters, composed of colored glass or dyed gelatin, are placed in the optical system between light source and phototube to permit a selected band of colors to be transmitted more readily than the others. It must be distinctly understood that the action of filters is purely subtractive. They can hinder or prevent the passage of light of different colors to a varying degree but cannot increase the amount of light of any color beyond that present in the beam from the light source. Indeed, as has been noted (page 362), every glass-air surface causes some reflection and loss of transmission, and, therefore, even the most favored color band is dimmed somewhat. Thus occasionally it will be found that, while the use of a filter will produce a greater *percentage* difference in the amount of light in the desired and undesired bands, the light in the desired band may be so decreased that better over-all results may be obtained by omitting the filter.

Light Absorbed Becomes Heat. The filter prevents the passage of light radiation by absorbing its energy as heat within

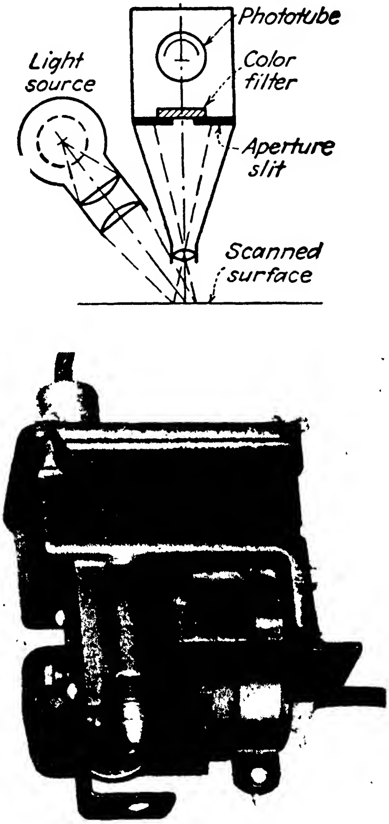


FIG. V.14. A typical photoelectric optical system as used in the GE CR-7505P108 scanning head. (*Courtesy of General Electric Company*)

the filter. This heat raises the temperature of the filter until a balance is reached at which the heat can again be radiated to the surrounding air. If the filter is small and the light is intense, the filter may be heated to an excessive temperature. If the filter is in a tight mount, its expansion may strain and crack it. If the filter is gelatin cemented in glass, the cement may melt or the gelatin film may split. The obvious cure is better ventilation of the filter, a better mount, a cooler location for the filter, or, if no other means is possible, a larger filter in a broader portion of the beam to spread the heat over a larger surface.

Practical Filters. An ideal filter would transmit 100 per cent of the light in the desired band and then cut off sharply at the desired wave length to zero transmission. Available filters, unfortunately, fall considerably short of this ideal.

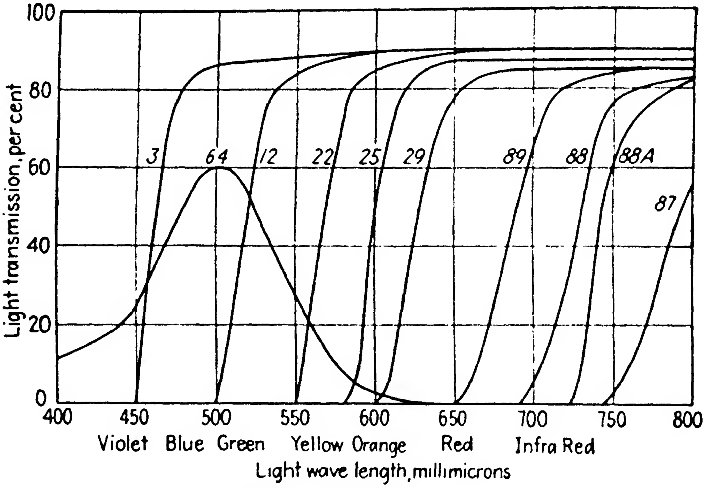


FIG. V.15. Average transmission curves for some representative gelatin filters.

Light-transmission curves for a few representative filters are shown in Figs. V.15 and V.16. Those in Fig. V.15 are of the dyed-gelatin type. From the efficiency standpoint, transmission of the desired band and sharpness of cutoff, they seem the most desirable. However, the gelatin is fragile and must be properly mounted and carefully protected for best results. Industrial filters are usually made by cementing the gelatin between two sheets of glass. This gives satisfactory performance if the filter is properly mounted and is not subjected to excess heat or moisture. The colored-glass filters, some of which are shown in Fig. V.16, on the other hand, contain the coloring matter as an integral ingredient in the glass and hence are inherently more stable and sturdy than the gelatin type. Therefore, there are many installations, particularly out of doors, for which the glass filter is preferable.

Gelatin Filters. Perhaps the gelatin filter most generally used is the Wratten filter made by the Eastman Kodak Company at Rochester, N.Y. For most industrial uses it should be ordered cemented in B-glass, a good quality of ground and polished glass.

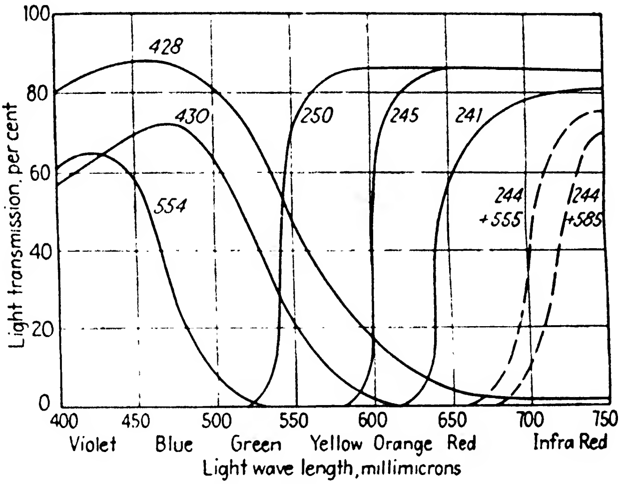


FIG. V.16. Average transmission curves for some representative glass filters.

A-glass mounts are superior optical flats but are much more expensive and need not be used unless it is absolutely necessary to place the filter in the path of an image-forming lens system where the B-glass might cause possible distortion. Stock sizes should be ordered, if possible, to ensure lower costs and quicker delivery. Complete filter characteristics and available sizes and shapes are described in the Eastman booklet, "Wratten Light Filters," obtainable from many dealers in photographic supplies or directly from the Eastman Kodak Company at Rochester.

Glass Filters. Colored-glass filters may be obtained from the

Corning Glass Works at Corning, N.Y., and are described in detail in their catalogue, "Glass Color Filters." As the coloring matter in the glass filter is within the glass itself, the density of the filter depends on the glass thickness, and, therefore, this must be specified in ordering. Stock thicknesses should be used whenever possible.

These glass filters may be obtained in either the molded or the polished form. Generally, the polished form should be used at the light source because of its lower losses and minimum distortion. The less expensive molded type is suitable for mounting directly in front of the phototube where a small amount of light diffusion is not objectionable.

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APPENDIX VI

CLOSED-CYCLE OR REGULATING SYSTEMS

Vectors and Complex Algebra. Vectors may be described in two ways:

1. By coordinates in the complex (also called the imaginary or j) plane; by the *real* component, positive east and negative west, and the j, or *imaginary* component, positive north and negative south. In Fig. VI.1*a* one vector is described as $4 + 3j$ and the other, $-3 + 4j$. The length of each is $\sqrt{3^2 + 4^2}$ or 5.

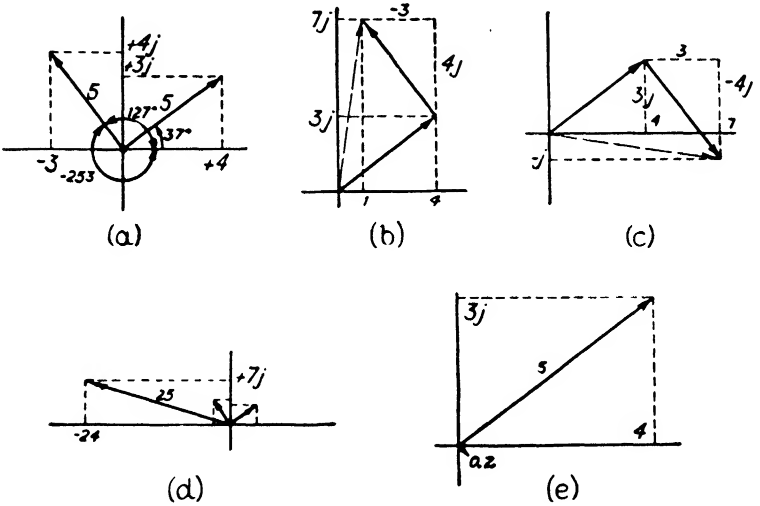

FIG. VI.1. Vector arithmetic.

2. By the *polar* form which gives the length and the angle with respect to a reference direction, usually east, the positive real axis. Counterclockwise angles are considered positive (which means that lag angles should be shown negative in a rigorous solution). The two vectors of Fig. VI.1*a* are $5\underline{/37^\circ}$ ($= \tan^{-1} \frac{3}{4}$) and $5\underline{/127^\circ}$ or $5\underline{/-253^\circ}$, if we were dealing in negative angles.

A vector in one form may be converted to the other by simple trigonometry.

Complex form: $A + jB$ $A = D \cos a$
Length: $A^2 + B^2$ $B = D \sin a$
Angle: $\tan^{-1} B/A = a$

Addition and Subtraction of Vectors. Addition is accomplished by adding the real and j parts separately. For example, in Fig. VI.1*b* we see that $(4 + j3) + (-3 + j4) = 1 + j7$. To subtract, reverse the signs of the subtrahend and add. For example, as in Fig. VI.1*c*, $(4 + j3) - (-3 + j4) = 4 + j3 + 3 - j4 = 7 - j$.

Multiplication and Division. These operations are best done in the polar form (as in the Bode attenuation curves). To multiply, we multiply the lengths and add the angles. To divide, we divide the lengths and subtract the angles. (Adding or subtracting logarithms or decibels is, of course, the same thing as multiplying or dividing.) However, these operations can also be done in the complex form if desired.

Vector Multiplication. For example, let us multiply the two vectors of Fig. VI.1*a*.

Polar form:

$$5\underline{/37^\circ} \times 5\underline{/127^\circ} = 25\underline{/164^\circ}$$

Complex form:

$$\begin{aligned}(4+j3)(-3+j4) &= -12+j16-j9-12\\ &= -24+j7\end{aligned}$$

$$\sqrt{24^2 + 7^2}\ \underline{/\tan^{-1} - 7/24} = 25\underline{/164^\circ}$$

(Remember that $j = \sqrt{-1}$ so $j^2 = -1$)

This is represented graphically in Fig. VI.1*d*.

Vector Division. For an example of division let us take a simple inversion such as

$\frac{1}{4 + j3}$ or $\frac{1}{5\underline{/37^\circ}}$. The polar form is obviously $0.2\underline{/-37^\circ}$.

In complex form

$$\frac{1}{4 + j3} = \frac{4 - j3}{(4 + j3)\,(4 - j3)} = \frac{4 - j3}{16 + 9} = 0.16 - j0.12$$

$$\sqrt{0.16^2 + 0.12^2}\ \underline{/\tan^{-1} - 0.12/0.16} = 0.2\underline{/-37^\circ}$$

This is represented graphically in Fig. VI.1*e*.

Transfer Function of a D-C Motor. The separately excited d-c motor with adjustable armature voltage is one of our most flexible, efficient, and compact means for converting electrical to mechanical energy and is often found in electromechanical regulating systems. The most important lag in such a system element is the response of the mechanical inertia of the motor armature and load to the motor torque due to the reaction of armature current and motor field. The motor system element is indicated

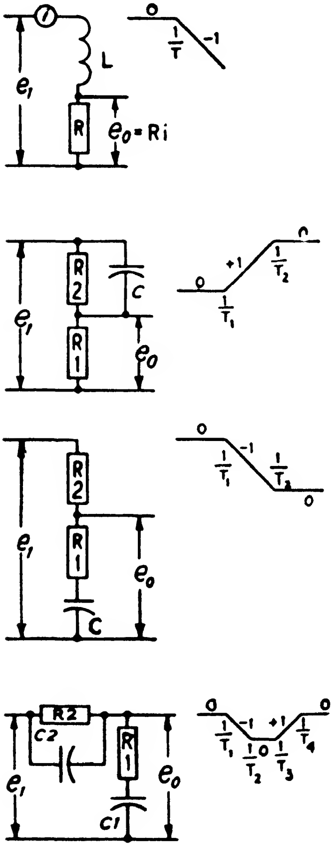

FIG. VI.2. Lead and lag networks with transfer functions.

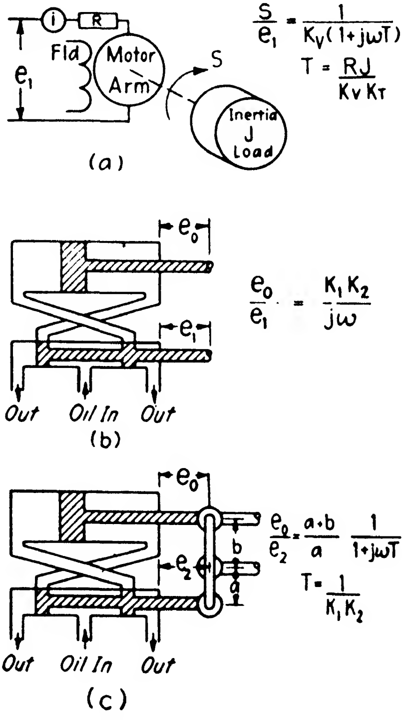

FIG. VI.3. Means for obtaining mechanical motion. (*a*) D-c motor; (*b*) hydraulic piston; (*c*) hydraulic positioner or servo.

in Fig. VI.3, and its transfer function may be expressed as follows:

$$\frac{S}{e_1} = \frac{1}{K_v(1 + j\omega T_m)}$$

where S = motor speed, radians/sec

e_1 = input voltage

K_v = motor back-emf constant, volts radian/sec

T_m = motor time constant

This indicates that the motor acts as a simple lag network with a time constant T_m. We have neglected the armature circuit inductance lag and others which are too small to seriously affect the transfer function in the critical frequency range.

T_m may be found from the following formula:

$$T_m = \frac{JR}{K_t K_v}$$

where J = inertia of armature and load, referred to armature shaft, slugs

R = resistance of armature circuit, ohms

K_v = motor back-emf constant as above

K_t = motor torque constant, lb ft, amp

However, in more easily obtained constants

$$T_m = \frac{J' \times R \times I \times (S')^2}{V \times HP} \times 4.31 \times 10^{-9} \text{ sec}$$

where J' = armature and load inertia, lb-in.^{2}
(taken from manufacturer's tables or computed)

R = armature circuit resistance, ohms
(measured directly or computed)

I = rated armature full load, amp
(from motor nameplate)

$(S')^2$ = rated motor revolutions/min, squared
(from motor nameplate and squared)

V = back-emf volts at rated speed
(nameplate rated applied volts $-$ RI drop)

HP = motor horsepower rating
(from motor nameplate)

Hydraulic-element Transfer Function. Hydraulic drives for short, straight motions are often used because of the simplicity of the action and the low inertia of the single moving part. Assuming negligible inertia, reduction in oil flow due to loading, compressibility, etc., we can say that the piston movement is proportional to the change in oil volume in the cylinder and the rate of oil flow is proportional to the valve opening. (See Fig. VI.3*b*.)

Hence
$$\frac{e_0}{e_1} = \frac{K_1K_2}{j\omega}$$

where K_1 = flow of oil, cu in./sec per in. of valve opening
K_2 = piston movement per cu in. of oil (inverse area)

This function is that of an integrating element with no internal lags.

Hydraulic Positioner. This action is similar to the one above except that the piston and valve are linked together so that the piston motion tends to close the valve. The transfer function becomes (see Fig. VI.3*c*)

$$\frac{e_0}{e_1} = \frac{a+b}{a} \cdot \frac{1}{1+j\omega T}$$

where $T = \dfrac{1}{K_1K_2}$

This indicates a servo system having a lag corner at K_1K_2 radians/sec.

Bode-diagram Phase-shift Ruler. This is a ruler for determining the total phase shift at any frequency from the Bode attenuation curve for a minimum phase-shift network.

Lay out the ruler scale on stiff cardboard as follows:

1. Place an index mark at the ruler center, and lay the ruler on the semilog paper used for the Bode attenuation diagram parallel to the abscissa frequency scale so that the index falls on one of the decade graduations. Call this point ω_x. The next higher decade graduation is $10\omega_x$ and the next lower is $\omega_x/10$, etc. (see Fig. VI.4*a*).

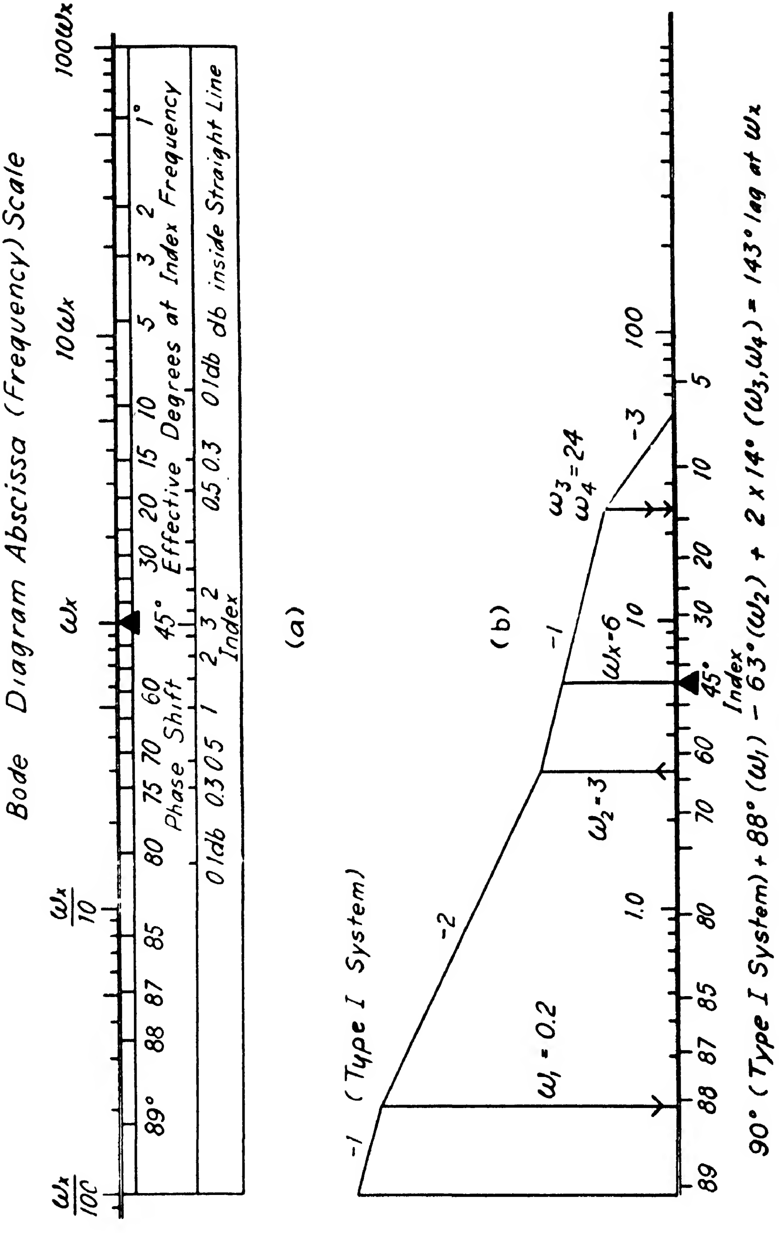

FIG. VI.4. The phase-shift ruler. (a) Construction; (b) example of application.

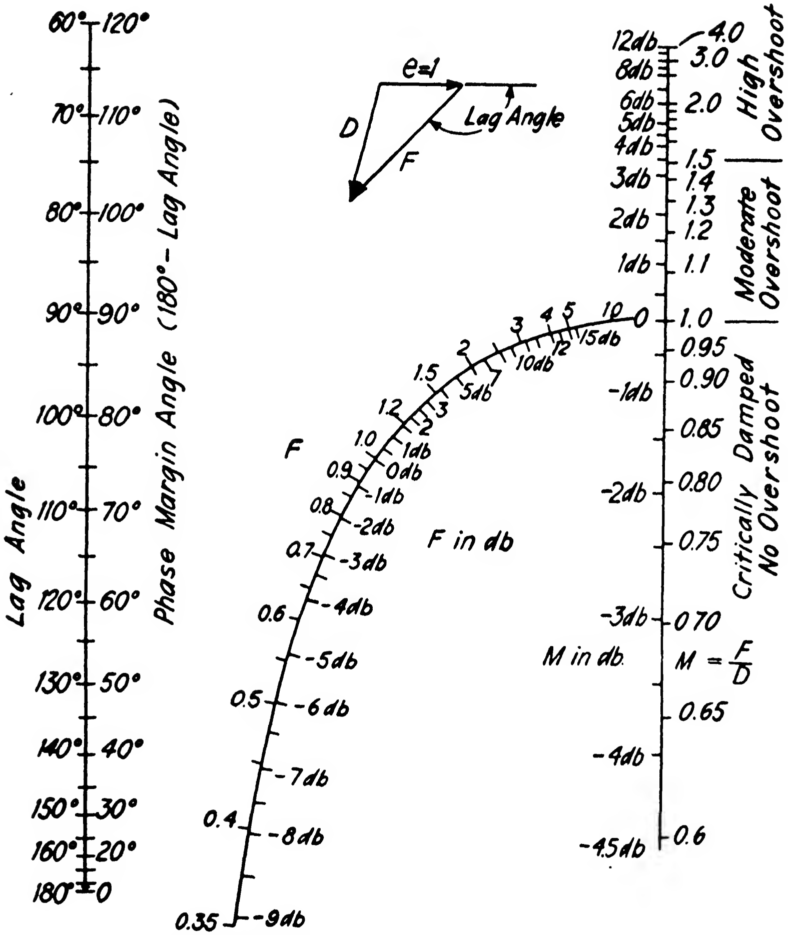

FIG. VI.5. Alignment chart for finding M or F/D. Place a straightedge to cut length of F and the lag angle. Read M.

2. Plot graduations on the ruler according to the following tabulation:

ω/ω_x	Deg	ω/ω_x	Deg	ω/ω_x	Deg
57.3	1	1.73	30	0.36	70
28.6	2	1.43	35	0.27	75
19.1	3	1.19	40	0.16	80
11.4	5	1.0	45	0.088	85
5.67	10	0.84	50	0.052	87
3.73	15	0.70	55	0.035	88
2.75	20	0.58	60	0.018	89
2.14	25	0.47	65		

3. This scale gives the effect of a corner on the lag angle at the frequency of the index point. The sum of the effects of all corners is the total angle at that index point. A number of such points may be determined to plot the total lag curve in the region of interest, usually near 0 db on the attenuation curve.

4. The db correction to be applied to the approximate straight-line attenuation curve resulting from the cumulative effect of nearby corners may also be drawn on the ruler following this tabulation (see Fig. VI.4*a*):

ω/ω_x	DECIBELS (db)
0.17 and 6.0	0.1
0.27 and 3.7	0.3
0.34 and 2.9	0.5
0.51 and 2.0	1.0
0.64 and 1.57	1.5
0.76 and 1.31	2.0
0.88 and 1.14	2.5
1.0	3.0

5. The ruler is accurate only for the frequency-scale graduations on which it was constructed. If differently graduated paper is used, a new ruler can be made up with the aid of the above tables in a few minutes.

Example:

To determine the total lag angle for $\omega_x = 6$ for the Bode attentuation curve of Fig. VI.4*b*, place the index at $\omega = 6$. Note that this is a Type 1 system having an initial -1 slope. There is a lag corner at 0.2, a lead corner at 3, and a double lag corner at 24. Calculate the total lag angle as follows (either mentally or on scratch paper): 90 deg due to the initial -1 slope, plus 88 deg due to the corner at 0.2, minus 63 deg due to the lead corner at 3, plus 2 times 14 deg or 28 deg due to the double lag corner at 24, or a total lag angle of 143 deg at $\omega = 6$. (The small arrows may be used to help remind one of the direction and number of corners at each frequency.)

The db correction can also be computed quickly. Only two corners require much correction: 1 db up for the 3 corner, and 2 times 0.3 or 0.6 down for the 24 corner. Hence, the true curve lies about 0.4 db *above* the straight line at $\omega = 6$.

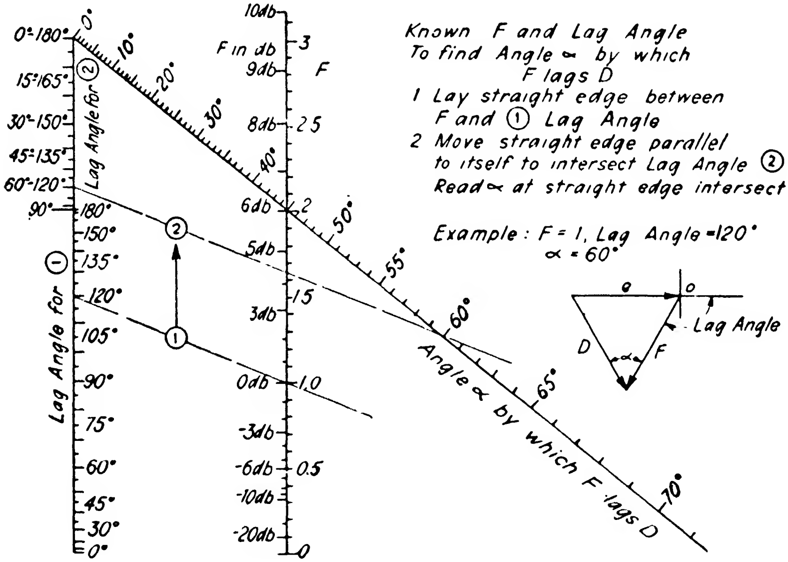

FIG. VI.6. Alignment chart to find the angle α by which F lags D.

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