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ELECTRONICS LABORATORY MANUAL

ELECTRONICS
LABORATORY
MANUAL

BY

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Second Impression

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ELECTRONICS LABORATORY MANUAL

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PREFACE

This manual is designed to serve as a laboratory textbook for electrical-engineering students who are taking their first course in electronics. It is believed that it will also serve as a useful guide for students in courses leading to degrees in aeronautical, chemical, industrial, and mechanical engineering.

In many instances students derive little benefit and waste valuable time because they do not understand at the time of performance of an experiment the reasons for the procedure followed or observations made, with the result that they are unable to draw logical conclusions from their laboratory work. Therefore, in an effort to improve the efficiency of laboratory instruction, each experiment has been explained in some detail.

The author wishes to express his appreciation to W. A. Murray, Professor and Head of the Department of Electrical Engineering, Dr. F. L. Robeson, Professor and Head of the Department of Physics, and Jay Hall, Assistant Professor of English—all of the Virginia Polytechnic Institute—for their helpful suggestions. The author extends his appreciation to Mrs. J. T. McCormack for her assistance in typing the manuscript.

Ralph R. Wright.

Blacksburg, Virginia,
May, 1945.

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EXPERIMENT 1

STATIC CHARACTERISTICS OF DIODES

The thermionic vacuum tube in its simplest form is a two-electrode type consisting of an emitter known as a cathode, which is surrounded by a metallic or carbon plate serving as an anode. The cathode acts as a source of electrons, while the anode serves as a collector of electrons. Electrons are released by application of heat to the cathode. The electrons released from the surface of the cathode are accelerated toward the anode, which is at a positive potential with respect to the cathode. The velocity with which electrons strike the anode may be expressed approximately by the following equation:

$$V = 5.95 \times 10^7 \sqrt{E_a}$$

where V = velocity, cm. per sec.
E_a = anode potential, volts

These electrons reach the anode at high velocities and on impact release their energy of motion in the form of heat. For this reason, it is necessary that anodes be large in size compared with cathodes and capable of dissipating appreciable heat. Structurally there are two general types of cathodes: the directly heated cathode, commonly known as the filamentary cathode, and the indirectly heated cathode, often referred to as the heater-type cathode.

The filamentary cathode in its simplest form consists of a wire of circular cross section coated with a thin layer of a mixture of barium and strontium oxides. The structure usually takes the form of a straight wire, a V or a W. Typical structures are shown in Fig. 1*a*.

The heater-type cathode was developed primarily to minimize the hum arising from the effects of a-c heater operation. This type of cathode consists of a heater wire which is enclosed by and insulated from a close-fitting metallic sleeve coated with an emitting material. The insulating material employed must insulate the heater wire and also be a fair conductor of heat, so that maximum emitting efficiency will be realized. Oxides of beryllium and aluminum are ceramic materials that are most often employed. The heater wire is usually made of an alloy of tungsten, while the metallic sleeve is made of nickel or konel metal and coated with oxides of barium and strontium. Typical structures of heater-type cathodes are shown in Fig. 1*b*.

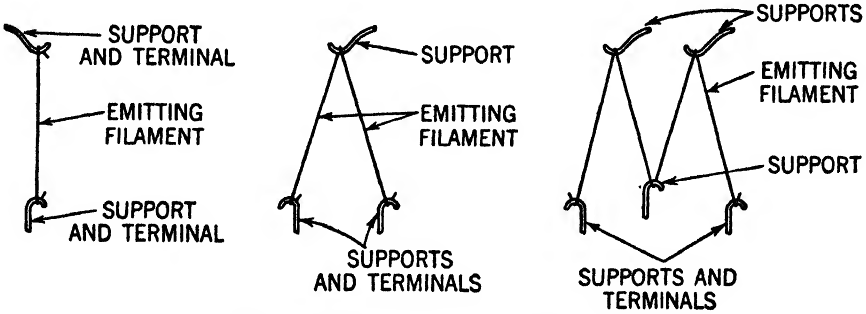

FIG. 1*a*.—Typical filamentary cathodes.

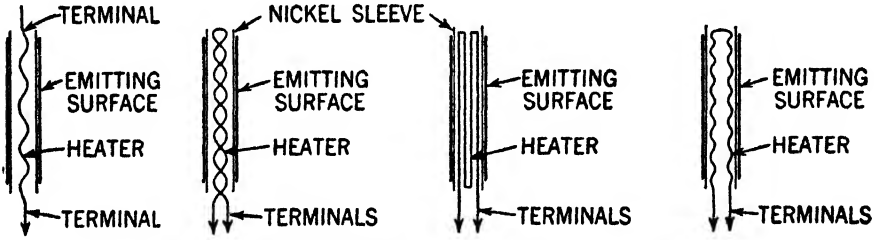

FIG. 1*b*.—Typical heater-type cathodes.

The high-vacuum two-electrode tube, better known as the diode, finds wide application in both receiving and transmitting service. In receiving service it is used as a detector of radio signals and as a rectifier for converting alternating current and voltage to direct current and voltage. This conversion is necessary for the functioning of the other tubes in a receiver. In transmitting service the diode is used as a rectifier to supply anode voltage for the other tubes in the transmitter and as a peak limiter on modulators. The diode performs these functions because of the fact that it will conduct current only when the anode is positive with respect to the cathode. Current will cease if the anode becomes negative with respect to the cathode. An ideal rectifier tube is one which offers zero impedance to the flow of electrons in one direction and infinite impedance to the flow of electrons in the opposite direction. No ideal tubes have yet been developed.

The characteristics of a diode may be determined by a few very simple tests. The first tube to be considered will be a 5Y3GT/G, which is a full-wave high-vacuum rectifier of the filamentary type. This tube has an oxide-coated filament which has a rating of 5 volts and 2 amp. The 5Y3GT/G is one of the most popular types of high-vacuum rectifiers. Its chief application is that of supplying anode potential for various amplifier tubes in a-c receiver circuits. Another tube to be considered in this experiment is the 1-V, which is a half-wave, high-vacuum rectifier tube employing a heater-type cathode. This tube is not found in many modern receivers. It is used chiefly for renewal purposes in radio equipment of either the a-c/d-c or the automobile type.

The static characteristics of the 5Y3GT/G and the 1-V may be obtained by employing the circuits of Figs. 1*c* and 1*d*, respectively.

There are two families of static characteristics that define the merits of a diode. The first family is obtained by holding the filament voltage constant and by determining the variation of plate current with plate potential. Several suitable values of filament voltage should be used in order that a typical family of curves may be plotted. The second family of characteristics is obtained by holding the plate potential constant and by determining the variation of plate current with filament current. It is usually desirable to plot curves for several different values of plate potential.

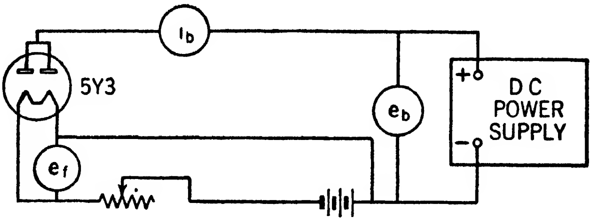

FIG. 1c.—Circuit for determining the static characteristics of a diode, employing a filamentary cathode.

If cathodes employing several different types of emitting materials, such as barium oxide, thoriated tungsten, and tungsten, are available, a comparison of the relative merits of the emitters can be made by plotting power-emission charts. The ratio of emission current per unit area of cathode surface to the heating power in watts per unit area is known as the emission efficiency.

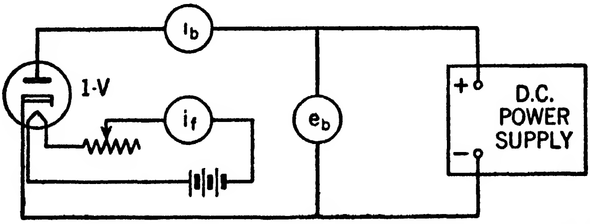

FIG. 1d.—Circuit for determining the static characteristics of a diode, employing a heater-type cathode.

In order to obtain points for a power-emission chart, it is necessary that the plate voltage be made sufficiently high to ensure that maximum emission current for a given filament power will always exist in the plate circuit. The value of plate potential necessary may be readily determined by referring to data obtained for static characteristic curves.

The circuit employed is similar to the circuit of Fig. 1*c*, with the exception that both voltmeter and ammeter must be used in the filament circuit to obtain the filament power. The filament power should be adjusted for about five different values of plate current. Curves of emission current vs. heating power plotted on power-emission paper will result in straight lines. The relative positions of the straight lines for the different cathodes tested will be an indication of the relative merit of each type of cathode coating.

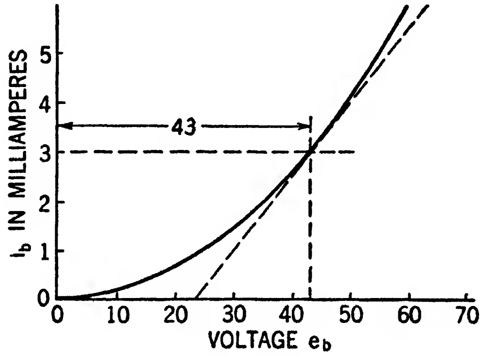

FIG. 1*e*.—Graphical method of determining r_p and r_{dc}.

The diode is a nonlinear circuit element, *i.e.*, the plate current is not directly proportional to the plate potential. The ratio of the plate potential to the plate current is called the static or d-c plate resistance, and the ratio of a small change in plate potential (Δe_b) to the change in plate current (Δi_b), produced by the small change in plate potential, is known as a-c or dynamic plate resistance. To illustrate, the static and dynamic resistance for one value of plate current will be determined.

The static or d-c resistance at 3 ma. is

$$r_{dc} = \frac{e_b}{i_b} = \frac{43}{0.003} = 14{,}333 \text{ ohms}$$

The dynamic resistance for the same value of plate current is

$$r_p = \lim_{\Delta e_b \to 0} \left(\frac{\Delta e_b}{\Delta i_b}\right) = \frac{de_b}{di_b} = \frac{20}{0.003} = 6{,}666 \text{ ohms}$$

It will be noticed that the static resistance is the reciprocal of the slope of the line drawn through the origin and the point in question. The dynamic plate resistance is the reciprocal of the slope of the line drawn tangent to the curve at the point in question.

In the region where the current is space-charge limited, the plate current is expressed approximately by the equation

$$i_b = K e_b^{\alpha}$$

Taking the logarithm of both sides of the above equation,

$$\log i_b = \alpha \log e_b + \log K$$

The resulting equation is that of a straight line

$$y = mx + b$$

where $y = \log i_b$
$m = \alpha$
$b = \log K$

Therefore, by plotting the plate current against plate voltage on logarithmic paper, α, the slope of the straight line, and K, the y intercept, may be determined.

When using logarithmic paper, it should be remembered that the scale may be changed by multiplying either the ordinate or the abscissa by any integral power of 10. The slope of the straight line does not change with a change in scale; thus, if it is impossible to obtain a y intercept along the line that intersects the abscissa at unity, the ordinates may be multiplied by the power of 10 necessary to give an intersection on the abscissa at unity.

Exercises

1. Obtain data for and plot curves of plate current vs. filament voltage for the 5Y3GT/G for the following plate voltages: 15, 25, and 60 volts.

2. Obtain data for and plot curves of plate current vs. plate voltage for a 5Y3GT/G for the following filament voltages: 2.4, 3, and 5 volts.

3. Obtain data for and plot power-emission charts for oxide-coated, thoriated tungsten and tungsten emitters. Calculate the emitting efficiency of each of these emitters.

4. Obtain data for and plot curves of dynamic and static plate resistance vs. plate voltages for a 5Y3GT/G for a filament voltage of 5 volts. These data may be obtained from the third curve of Exercise 2.

5. Determine K and α in the relation $i_b = Ke_b^{\alpha}$.

6. Obtain data for and plot curves of plate current vs. plate voltage for the 1-V for the following filament currents: 0.20, 0.25, and 0.30 amp.

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EXPERIMENT 2

STATIC CHARACTERISTICS OF A TRIODE

In 1907, Dr. Lee De Forest introduced a grid between the anode and the cathode of a diode, converting the tube into a triode. The grid is normally operated at a negative potential with respect to the cathode; thus, it does not attract electrons and no grid current exists. If the grid is operated at a positive potential with respect to the cathode, it will collect electrons and grid current will exist. In most applications grid current is undesirable. Because of its proximity to the cathode, the grid has much more influence on the electrostatic field near the cathode than does the anode. Thus, a small change in grid potential (Δe_c) will cause a greater change in plate current (Δi_b) than will result if the plate potential is changed by the same increment of voltage. By virtue of this fact the triode may be made to function as an amplifier.

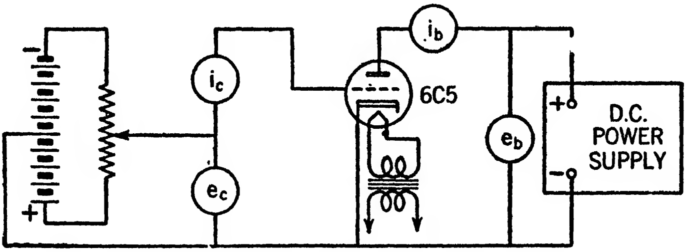

Fig. 2*a*.—Circuit for determining the static characteristics of a triode.

The static characteristics of a triode may be determined by employing the circuit shown in Fig. 2*a*.

The type of tube to be tested is a 6C5, which has an oxide-coated heater-type cathode emitter with a heater rating of 6.3 volts and 0.3 amp. The maximum plate current should not be allowed to exceed 15 ma.; an increase in plate current above this value may result in cathode disintegration.

There are three very important coefficients of a triode, viz., amplification factor μ; dynamic plate resistance r_p; and grid-plate transconductance s_m (often referred to as mutual conductance g_m).

The amplification factor μ is a measure of the relative effectiveness of grid potential to plate potential in controlling plate current. μ is defined mathematically as follows:

$$\mu = \lim_{\Delta e_b \to 0} \left(-\frac{\Delta e_b}{\Delta e_c} \right)_{i_b \text{ const.}} = -\left. \frac{de_b}{de_c} \right|_{i_b \text{ const.}} = -\frac{\partial e_b}{\partial e_c}$$

The value of μ may be determined for any value of grid and plate potential by "mechanical differentiation." Vary e_b slightly and note what change in e_c is necessary to keep the plate current constant. The amplification factor is then approximately equal to the ratio of the plate-voltage increment (Δe_b) to the negative of the grid-voltage increment ($-\Delta e_c$). The amplification factor may also be determined at any point by taking the slope of an ($e_b - e_c$) curve at the point in question.

The dynamic plate resistance r_p of a triode is the ratio of a small change in plate potential (Δe_b) to the change in plate current (Δi_b) produced by the change in plate potential, the grid potential remaining constant. r_p is defined mathematically as follows:

$$r_p = \lim_{\Delta e_b \to 0} \left(\frac{\Delta e_b}{\Delta i_b} \right)_{e_c \text{ const.}} = \left. \frac{de_b}{di_b} \right|_{e_c \text{ const.}} = \frac{\partial e_b}{\partial i_b}$$

This limit may be determined for any value of grid and plate voltage by changing e_b slightly and noting the change in i_b. The dynamic plate resistance r_p is equal to the ratio of the change in plate potential in volts (Δe_b) to the change in plate current in amperes (Δi_b). The dynamic plate resistance may also be obtained by taking the reciprocal of the slope of an ($i_b - e_b$) curve at the point in question.

The grid-plate transconductance s_m or mutual conductance g_m is a measure of the effectiveness of the grid potential in controlling plate current. g_m is defined mathematically as follows:

$$g_m = \lim_{\Delta e_c \to 0} \left(\frac{\Delta i_b}{\Delta e_c}\right)_{e_b \text{ const.}} = \left.\frac{di_b}{de_c}\right|_{e_b \text{ const.}} = \frac{\partial i_b}{\partial e_c}$$

This limit may be determined by noting the change in plate current (Δi_b) brought about by a slight change in grid voltage (Δe_c). The grid-plate transconductance is equal to the ratio of the change in plate current in amperes to the change in grid potential expressed in volts. g_m may also be determined by taking the slope of an ($i_b - e_c$) curve at the point in question.

It can be shown that the tube coefficients defined above are related as follows:

$$\mu = r_p g_m$$

$$r_p = \frac{\mu}{g_m}$$

$$g_m = \frac{\mu}{r_p}$$

The coefficients of a triode may be determined graphically as shown in Figs. 2*b*, 2*c*, and 2*d*. Figure 2*e* shows how the coefficients of a triode vary with respect to plate current.

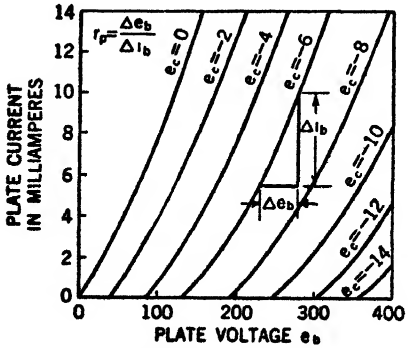

Fig. 2*b*.—Static characteristics of a triode. Curves of i_b vs. e_b.

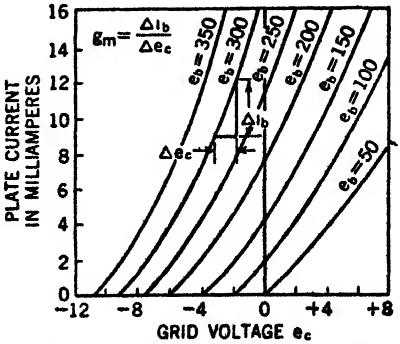

Fig. 2*c*.—Static characteristics of a triode. Curves of i_b vs. e_c.

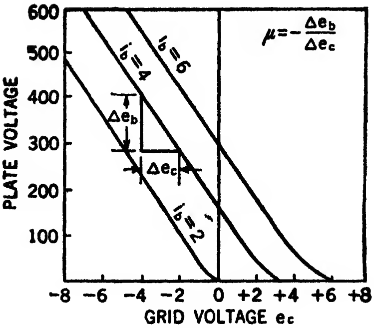

FIG. 2*d*.—Static characteristics of a triode. Curves of e_b vs. e_c.

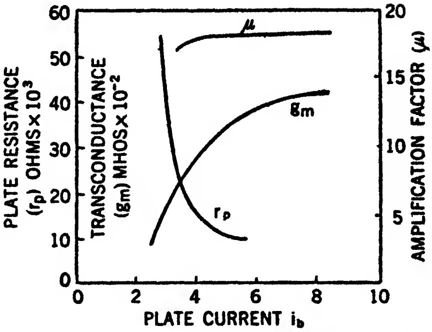

FIG. 2*e*.—Variation of triode coefficients with respect to plate current.

An approximate relationship between the plate voltage, grid voltage, and plate current of a triode for negative values of grid voltages is as follows:

$$i_b = K(e_b + \mu e_c)^\alpha$$

Take the logarithm of both sides of the equation

$$\log i_b = \alpha \log (e_b + \mu e_c) + \log K$$

K and α may be determined, as in Experiment 1, by plotting i_b against $(e_b + \mu e_c)$ on logarithmic paper. For negative values of e_c, the sign e_c is also negative.

α = slope of straight line on logarithmic paper

K = y intercept of straight line on logarithmic paper

Exercises

1. Obtain data for and plot curves of plate current vs. grid voltage for the following plate voltages: 50, 100, 150, 200, and 250 volts.

NOTE: Data for Exercises 1 and 2 may be obtained simultaneously.

2. Obtain data for and plot curves of grid current vs. grid voltage for the following plate voltages: 50, 100, and 150 volts.

3. Obtain data for and plot curves of plate current vs. plate voltage for the following grid voltages: 0, −2, −4, −6, and −8.

4. Obtain data for and plot curves of plate voltage vs. grid voltage for the following values of plate current: 4, 8, and 12 ma.

5. Determine by "mechanical differentiation" the amplification factor, dynamic plate resistance and the grid-plate transconductance at a plate voltage of 200 volts and grid voltage of -6 volts.

6. Using the information of the previous exercises, plot curves of amplification factor, dynamic plate resistance, and grid-plate transconductance vs. plate current.

7. Determine K and α for the tube used.

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EXPERIMENT 3

STATIC CHARACTERISTICS OF TETRODES, PENTODES, AND BEAM-POWER TUBES

Because of the capacitance existing between the grid and the plate of a triode, very serious difficulty is encountered when the triode is used as the basis of either a high-gain or a high-frequency amplifier. Large voltages in the plate circuit will be partially imposed upon the grid circuit through the grid-plate capacitance, resulting in oscillation, which is an extremely undesirable phenomenon in an amplifier circuit. To eliminate this condition, the tetrode or screen-grid tube was developed. By placing another grid between the control grid and the plate and by maintaining it free from alternating current, the capacitance between control grid and plate is reduced to a very low value. In addition to reducing the grid-plate capacitance the additional electrode reduces materially the effects of the plate potential on plate current without affecting the control of the grid on plate current; thus, the amplification factor is much greater for a tetrode than for a triode. Consider the internal structure of a tetrode as illustrated in Fig. 3*a*.

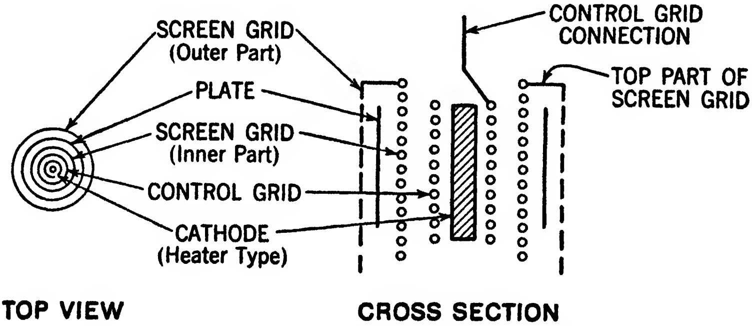

Fig. 3*a*.—Internal structure of a tetrode.

The static characteristics of a tetrode may be determined by use of the circuit given in Fig. 3*b*.

The unusual shape of the plate characteristics of the tetrode is due to the collection of secondary electrons by the screen grid. When the plate voltage is at a lower value than the screen-grid voltage, but sufficiently large to produce secondary electrons, the screen grid will draw secondary electrons away from the plate, resulting in high screen-grid current and low plate current. When the plate voltage becomes appreciably larger than the screen-grid voltage, the plate current is almost independent of the plate voltage. See Fig. 3*c* for typical characteristic curves. From these curves it will be noted that the total space current is approximately constant and almost independent of plate potential.

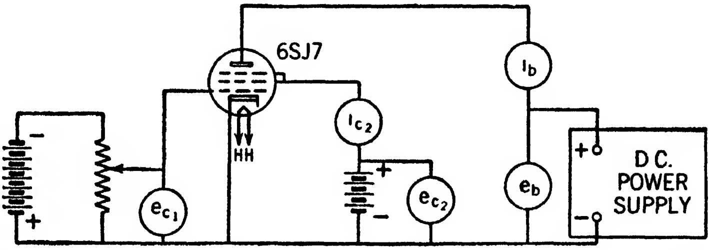

Fig. 3*b*.—Circuit for determining the static characteristics of a tetrode.

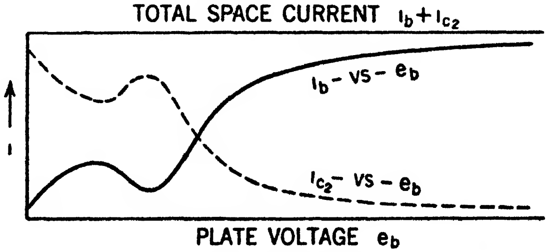

Fig. 3*c*.—Static characteristics of a tetrode. Curves of i_b and i_{c2} vs. e_b.

The effects of secondary emission may be eliminated by inserting another grid, called the suppressor grid, between the screen and the plate. Such a tube is known as a pentode. Typical characteristic curves are shown in Fig. 3*d*.

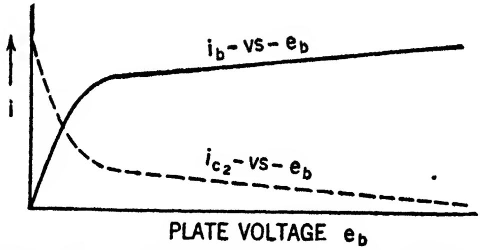

FIG. 3*d*.—Static characteristics of a pentode. Curves of i_b and i_{c_2} vs. e_b.

The structure of a typical pentode is illustrated in Fig. 3*e*.

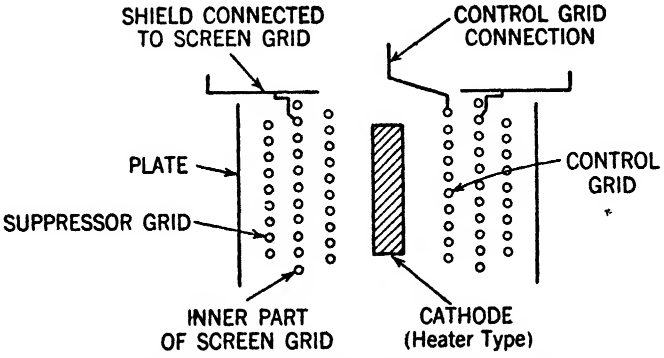

FIG. 3*e*.—Internal structure of a pentode.

The circuit connections necessary for the determination of the static characteristics of a pentode are shown in Fig. 3*f*.

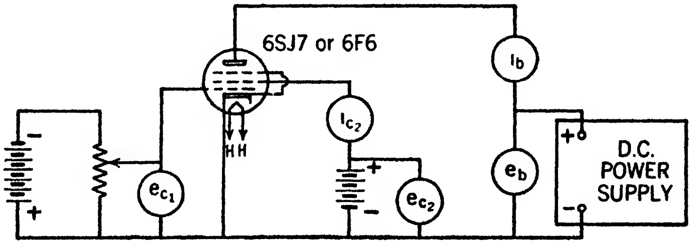

FIG. 3*f*.—Circuit for determining the static characteristics of a pentode.

The effects of secondary emission may be eliminated by means of beam-forming plates instead of employing a suppressor grid. A tube of this design is known as a beam-power tube. Such tubes are capable of delivering relatively large amounts of power at high efficiency and high sensitivity. Typical characteristics are shown in Fig. 3*g*.

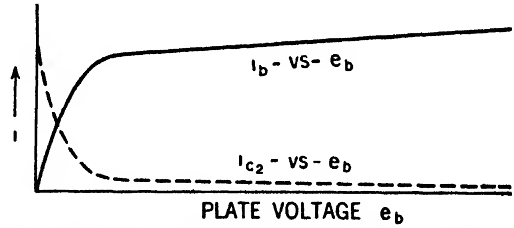

FIG. 3*g*.—Static characteristics of a beam-power tube. Curves of i_b and i_{c_2} vs. e_b.

The circuit of Fig. 3*h* may be employed in determining the characteristics of a beam-power tube.

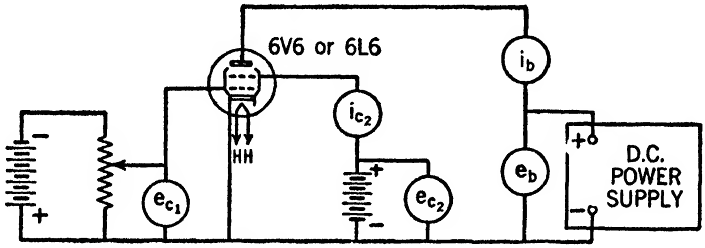

FIG. 3*h*.—Circuit for determining the static characteristics of a beam-power tube.

Exercises

1. Obtain data for and plot curves of plate and screen-grid current vs. plate voltage of a type 6SJ7 employed as a tetrode for the following control grid voltages: 0, −1.5, and −4 volts. Screen voltage set at 100 volts.

2. Obtain data for and plot curves of plate and screen-grid current vs. control-grid voltage of a type 6SJ7 employed as a tetrode for the following plate voltages: 100 and 250 volts. Screen voltage set at 100 volts.

3. Repeat Exercise 1, using a 6SJ7 pentode.

4. Repeat Exercise 2, using a 6SJ7 pentode.

5. Calculate from the curves of the above exercises the dynamic plate resistance, the grid-plate transconductance, and the amplification factor of the 6SJ7 (as a pentode) at a control grid bias of −4 volts, a screen-grid voltage of 100 volts, and a plate voltage of 250 volts.

6. Obtain data for and plot curves of plate and screen-grid current vs. plate voltage of a 6F6 power pentode for the following control grid voltages: −5 and −10 volts. Screen voltage set at 180 volts.

7. Repeat Exercise 6, using a 6L6 beam-power tube.

8. Repeat Exercise 6, using a 6V6 beam-power tube.

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Fink, "Engineering Electronics," pp. 122–131.
Glasgow, "Principles of Radio Engineering," pp. 201–204.
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Millman and Seely, "Electronics," pp. 551–569.
Morecroft, "Electron Tubes," pp. 105–112.
"RCA Receiving Tube Manual," pp. 7–10, 106–107, 122–124, 139–140, 146–148.
Reich, "Principles of Electron Tubes," pp. 63–73.
——— "Theory and Application of Electron Tubes," 2d ed., pp. 56–66.
Terman, "Fundamentals of Radio," pp. 73–79.
——— "Measurements in Radio Engineering," pp. 161–162.
——— "Radio Engineering," 2d ed., pp. 126–145.
——— "Radio Engineers' Handbook," pp. 298–316.

EXPERIMENT 4

VOLTAGE AMPLIFIERS

The development of the triode by Dr. Lee De Forest made possible the modern vacuum-tube amplifier, which is one of the most important devices known to the communications field. It makes possible the long-distance telephone, talking pictures, radio, television, and many other things too numerous to mention.

Triodes, tetrodes, pentodes, and beam-power tubes serve as the basis of vacuum-tube amplifiers. The simplest type of voltage amplifier, which employs a triode, is shown in Fig. 4*a*. An a-c signal is applied to the grid of the triode; this signal increased in magnitude but unchanged in form appears across the load resistance of the amplifier. If the output signal is the exact duplicate of the input signal except for magnitude, the amplifier is called ideal. No amplifiers are ideal, but many closely approach the ideal condition.

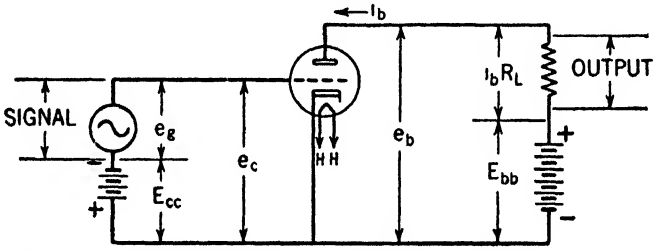


FIG. 4*a*.—Schematic circuit diagram of a voltage amplifier, employing a triode.

Consider the following fundamental analysis of a simple series-feed voltage amplifier.

The symbols employed, which are defined below, are those recommended in Standards on Electronics, Institute of Radio Engineers, 1938.

E_{bb} = plate supply voltage, called B supply
E_{cc} = control-grid supply, called C bias
E_g = effective value of varying component of grid voltage
E_p = effective value of varying component of plate voltage
I_p = effective value of varying component of plate current
e_b = instantaneous total plate voltage
e_c = instantaneous total grid voltage
e_g = instantaneous value of varying component of grid voltage
e_p = instantaneous value of varying component of plate voltage
i_b = instantaneous total plate current

From the circuit of Fig. 4*a*

$$e_c = e_g - E_{cc}$$

where E_{cc} is the magnitude of the grid supply voltage

$$e_g = \sqrt{2}E_g \sin \omega t$$

Then

$$e_c = \sqrt{2}E_g \sin \omega t - E_{cc}$$

Maximum value of i_b exists when

$$e_c = \sqrt{2}E_g - E_{cc}$$

and minimum value of i_b exists when

$$e_c = -\sqrt{2}E_g - E_{cc}$$

The amplification of the circuit of Fig. 4*a* may be determined graphically as follows:

Consider families of the characteristic curves for the tube used in the amplifier of Fig. 4*a*.

A load line should be drawn on the family of plate characteristics.

$$e_b = E_{bb} - i_b R_L \quad \text{(equation of load line)} \qquad (4a)$$

$$i_b = \frac{E_{bb}}{R_L} - \frac{e_b}{R_L} \qquad (4b)$$

$$\text{Slope of load line} = \frac{di_b}{de_b} = -\frac{1}{R_L}$$

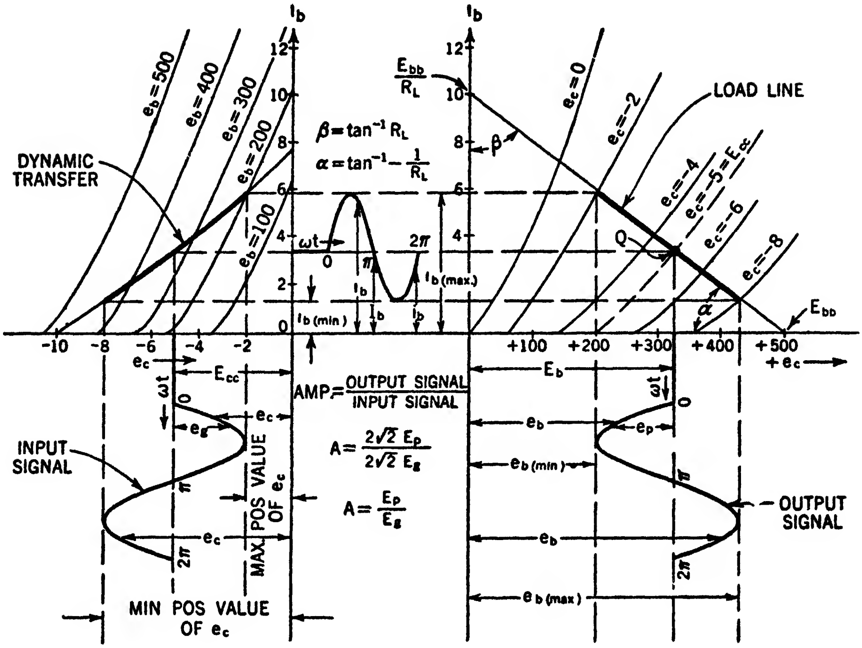


FIG. 4*b*.—Graphical analysis of the amplifier of Fig. 4*a*.

Thus

$$M_L = -\frac{1}{R_L} \quad \text{(slope of load line)} \tag{4c}$$

or

$$\text{Slope} = -\frac{\dfrac{E_{bb}}{R_L}}{E_{bb}} = -\frac{1}{R_L}$$

Since equation (4*a*) is that of a straight line, the load line may be drawn if two points are known or if one point and slope can be determined.

Two points may be determined readily by use of equation (4*b*).

$$i_b = f(e_b)$$

when

$$i_b = 0; \qquad e_b = E_{bb}$$

when

$$e_b = 0; \qquad i_b = \frac{E_{bb}}{R_L}$$

By use of either two points or one point and the slope, the load line is constructed.

The intersection of the load line with the curve $e_c = -E_{cc}$ is known as the operating or quiescent point Q. The dynamic characteristic is determined by transforming points from the load line to the mutual characteristics, as shown in Fig. 4*b*.

By assuming any input signal to the grid, it is now possible to determine both the magnitude and the wave form of the output signal. The construction is shown in some detail in Fig. 4*b*.

$$\text{Circuit amplification} = \frac{\text{plate swing}}{\text{grid swing}} = \frac{2\sqrt{2}E_p}{2\sqrt{2}E_g}$$

or

$$A = \frac{E_p}{E_g}$$

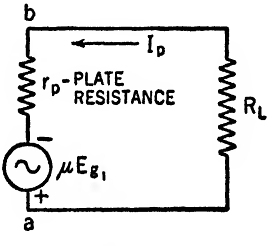
where E_p = r.m.s. value of output voltage
E_g = r.m.s. value of input voltage

The amplification may also be determined analytically by considering the equivalent circuit shown below:

$$I_pR_L + I_pR_p - \mu E_g = 0$$

$$I_p = \frac{\mu E_g}{R_L + r_p}$$

$$V_{ab} = I_pR_L = \frac{\mu E_g R_L}{R_L + r_p}$$



$$\text{Voltage amp.} = \frac{E_{ab}}{E_g} = \frac{-\mu R_L}{R_L + r_p}$$

where V_{ab} = voltage drop from *a* to *b*
E_{ab} = voltage rise from *a* to *b*
$E_{ab} = -V_{ab}$

In this experiment a cathode-ray oscillograph will be used to observe the input and the output signals. The ratio of output signal to input signal will be the amplification of the circuit. The circuit of Fig. 4*c* is to be used:

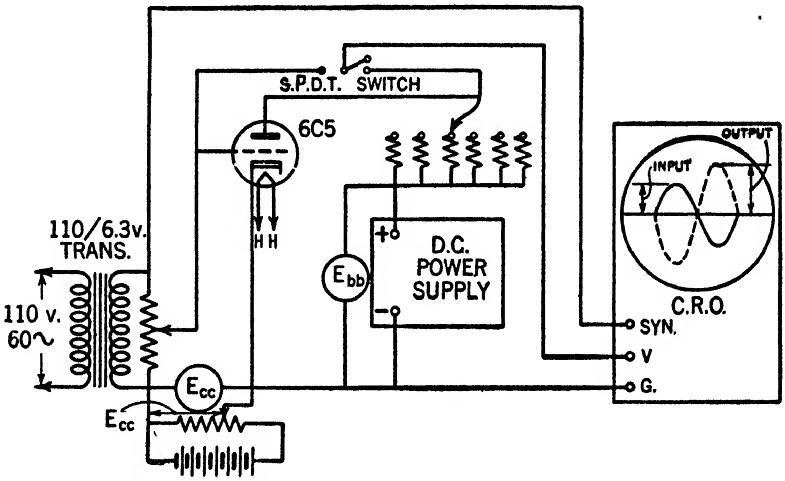


FIG. 4*c*.—Circuit arrangement for testing amplifier.

Exercises

1. Adjust E_{bb} to 350 volts and E_{cc} to -6 volts. The input signal should not be greater than 6 volts peak. Using the above values of potential, determine by means of the oscillograph the amplification for load resistances of 10,000, 25,000, 50,000, 100,000, 250,000, and 500,000 ohms.

2. Check the amplification analytically for each of the above loads. In order to obtain close checks, the variation in dynamic coefficients must be taken into account.

3. Check amplification graphically for loads of 25,000 and 50,000 ohms. Characteristics of 6C5 furnished with experiment.

4. Plot curves of amplification vs. load resistance:

a. For experimental values.

b. For calculated values.

References

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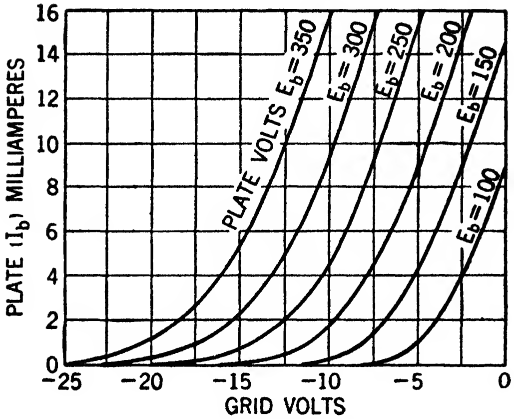
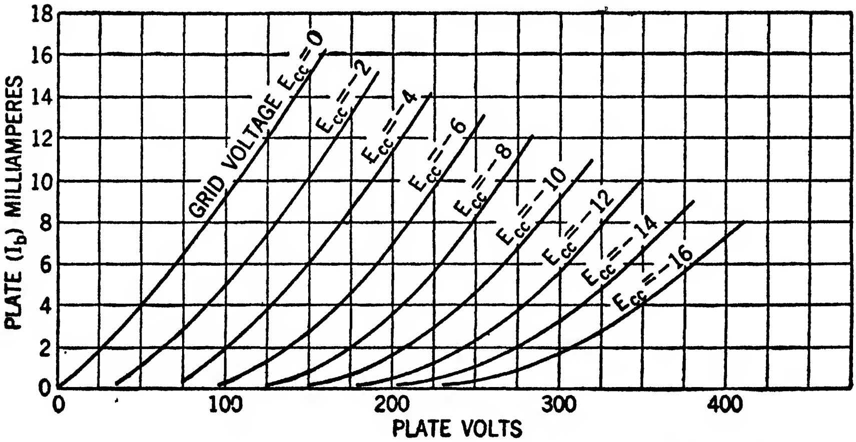
DOW, "Fundamentals of Engineering Electronics," pp. 266–272.
EASTMAN, "Fundamentals of Vacuum Tubes," 2d ed., pp. 54–64.
FINK, "Engineering Electronics," pp. 244–249.
GLASGOW, "Principles of Radio Engineering," pp. 136–138, 144–154.
HENNEY, "Electron Tubes in Industry," 2d ed., pp. 56–61.
——— "Radio Engineering Handbook," 3d ed., pp. 359–361.



Static characteristics of 6C5. To be used in performing Exercise.3



Static characteristics of 6C5. To be used in performing Exercise 3.

MIT Staff, "Applied Electronics," pp. 378–400.
Millman and Seely, "Electronics," pp. 512–523.
Morecroft, "Electron Tubes," pp. 84–85, 274–275.
"RCA Receiving Tube Manual," pp. 12–14, 100.
Reich, "Principles of Electron Tubes," pp. 74–84, 89–92, 96–97, 154–155.
——— "Theory and Application of Electron Tubes," 2d ed., pp. 67–71, 87–90, 97–99, 102.
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——— "Radio Engineering," 2d ed., pp. 167–174.
——— "Radio Engineers' Handbook," pp. 353–354.

EXPERIMENT 5

GAS DIODES

Gas-filled diodes are of two general types: the arc-discharge tube, which usually employs a hot cathode, and the glow-discharge tube, which is usually a cold-cathode type. The arc-discharge tube is characterized by a relatively low voltage drop between cathode and anode and high current density, while the glow-discharge tube is characterized by a relatively high voltage drop and low current density. The arc-discharge type will be considered first.

Gas diodes of the arc-discharge type are used extensively for supplying plate potential for transmitters. These tubes have two outstanding advantages over the high-vacuum diode as a means of supplying appreciable amounts of direct current. The voltage drop between cathode and anode is extremely small compared with the voltage drop in a high-vacuum diode. This results in a very high efficiency, which is an important factor if appreciable power is to be rectified. The tube drop is approximately constant for all values of plate current within the operating range of the tube; thus the regulation of power supplies employing gas tubes will be much better than that of power supplies of similar capacity that employ high-vacuum tubes.

Commercial gas diodes contain mercury vapor or one of the inert gases such as argon, krypton, neon, and helium. These gases will not enter into chemical reaction with the cathode coating.

If the filament of a hot-cathode gas diode is at operating temperature and the anode is made positive with respect to the cathode, electrons will be attracted toward the anode as in the case of a high-vacuum diode. The probability that these electrons will collide with gas atoms is very high. If an electron possesses sufficient kinetic energy when it collides with a gas atom, it will dislodge electrons from the atom, producing positive ions and free electrons. The potential necessary to give the electrons sufficient velocity to produce free electrons on collision with atoms is known as the ionization potential. The ionization potential is different for each inert gas.

Once ionization is accomplished, the positive ions are attracted to the cathode and neutralize existing space charge, which means that the current in a gas tube is never space-charge limited. Figures 5*a* and 5*b* illustrate the difference in the rectification characteristics of gas diodes and high-vacuum diodes.

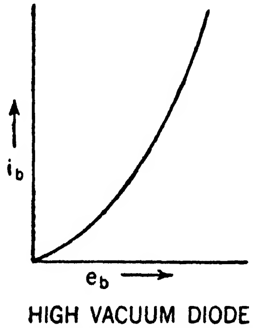

Fig. 5*a*.—Rectification characteristic of a typical high-vacuum diode.

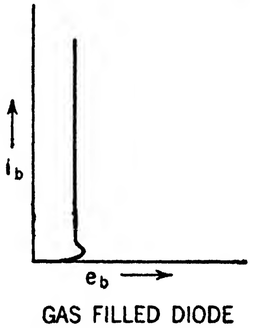

Fig. 5*b*.—Rectification characteristic of a typical gas diode.

The standard operative test for a gas diode is to determine the regulation from no-load to full-load current, employing a resistive load. The tube to be tested here is an RCA-866A/866 which has the following rating:

Filament voltage	2.5 volts
Filament current	5 amp.
Peak inverse voltage:	
Condensed Hg temp. of 25 to 60°C	10,000 max. volts
Condensed Hg temp. of 25 to 70°C	5,000 max. volts
Average plate current	0.25 max. amp.
Peak plate current	1.0 max. amp.
Tube voltage drop	10 volts

The circuit necessary for conducting the test mentioned is shown in Fig. 5*c*.

If the 866A/866 under consideration is a new tube, the filament should be heated for 15 min. so the mercury will be distributed properly before plate potential is applied.

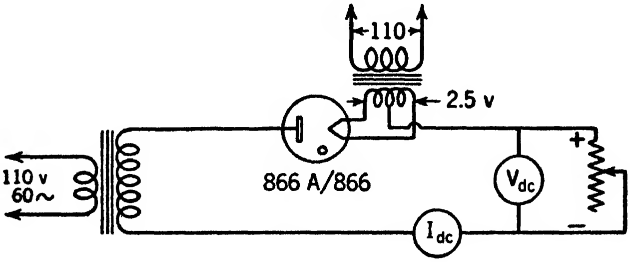

FIG. 5*c*.—Circuit for determining the regulation of a gas diode.

If the tube has been used before and has been kept in a vertical position so that the mercury is not spattered on the filament and plate, it is necessary to heat the filament only 30 sec. before applying plate potential. If plate potential is applied before the filament has reached operating temperature, cathode disintegration will result. After necessary precautions have been taken, the load current should be varied from zero to approximately 150 per cent rated current and readings of voltage and current taken. A good tube should give a regulation of less than 10 per cent.

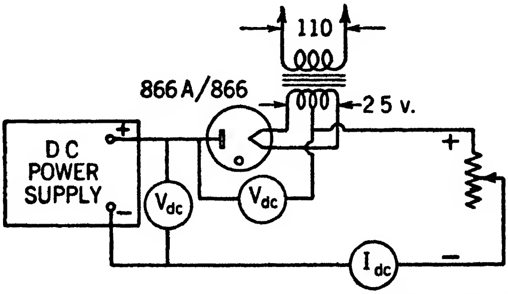

FIG. 5*d*.—Circuit for determining the condition of the emitting surface of the cathode of a gas diode.

The condition of the emitting surface of the cathode may be determined by employing the circuit shown in Fig. 5*d*.

With direct voltage applied to the circuit shown above, vary the magnitude of the load current from 0 to 150 per cent of its rated value. If the voltage drop across the tube exceeds 20 volts at 150 per cent rated current, the cathode has lost most of its emitting properties and the tube should be replaced.

The glow-discharge diode is used extensively as a voltage regulator. It may be a component part of an electronic voltage regulator such as the one shown in Experiment 8, or it may be employed as the only tube in a less complex type of regulator. By virtue of the fact that the voltage drop across a glow tube is substantially constant over a large range of current, it can be employed as a voltage regulator. The gases usually employed in voltage regulator tubes are argon, helium, and neon.

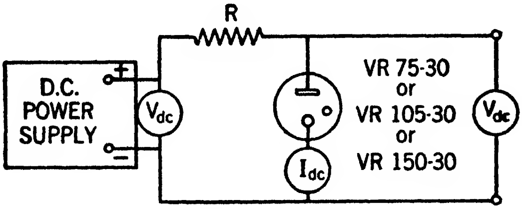

FIG. 5e.—Voltage-regulator circuit, employing a gas diode of the glow-discharge type.

Three of the more common types of voltage regulator tubes are: VR 75-30, VR 105-30, and the VR 150-30. As the symbol indicates, the first tube listed is a voltage regulator that will regulate at 75 volts if the current does not exceed 30 ma. The symbols for the other two tubes are similar.

The circuit shown in Fig. 5*e* may be employed to determine the regulation characteristics of either of the voltage-regulator tubes mentioned above. It is important that the series resistor be sufficiently large to limit the current to 30 ma. for all values of input voltage to be used.

In the past, glow tubes have been used as the basis of relaxation oscillators; at the present time, however, the gas triode has almost entirely superseded the glow tube in this usage. The circuit shown in Fig. 5*f* is that of a saw-tooth relaxation oscillator employing a 2-watt neon lamp.

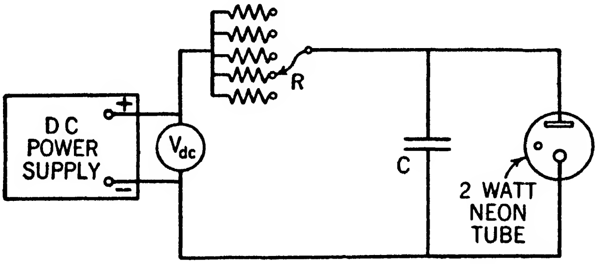

FIG. 5*f*.—Circuit of relaxation oscillator.

The frequency may be controlled by variation in either *R* or *C* and is expressed approximately by the following equation:

$$f = \left[\frac{1}{RC \log_e \left(\frac{E_{bb} - E_d}{E_{bb} - E_f} \right)} \right]$$

where E_{bb} = supply voltage
E_f = ionization potential
E_d = deionization potential

The wave form produced by this oscillator is similar to a saw-tooth wave. See Fig. 5*g*.

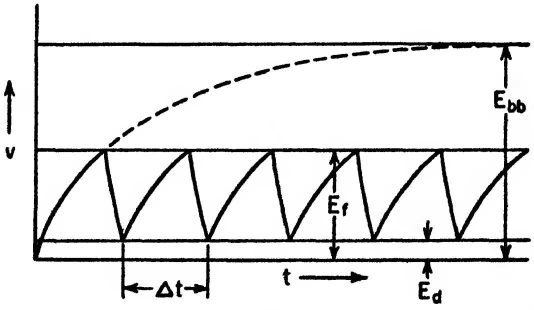

FIG. 5*g*.—Wave form of relaxation oscillator of Fig. 5*f*.

Exercises

1. Obtain data for and plot a curve of load voltage vs. load current for an 866A/866.

2. Obtain data for and plot a curve of tube drop vs. load current for an 866A/866.

3. Obtain data for and plot curves of power supply voltage and tube voltage vs. tube current for a VR 75-30.

4. Repeat Exercise 3 for a VR 105-30.

5. Repeat Exercise 3 for a VR 150-30.

6. Obtain data for and plot a curve of frequency vs. R for the saw-tooth oscillator shown in Fig. 5*f*. It is suggested that C be fixed at 1 μf and R be varied from 1 to 5 megohms in 1-megohm steps. The frequency may be determined by watching the neon lamp and counting the number of flashes per minute. A potential of 110 volts or greater should be applied.

References

Dow, "Fundamentals of Engineering Electronics," pp. 94, 458–471, 480–492.
EASTMAN, "Fundamentals of Vacuum Tubes," 2d ed., pp. 92–101, 144–149.
FINK, "Engineering Electronics," pp. 133–145.
HENNEY, "Electron Tubes in Industry," 2d ed., pp. 39–41.
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MIT STAFF, "Applied Electronics," pp. 205–219.
MILLMAN and SEELY, "Electronics," pp. 324–326, 340–350.
MORECROFT, "Electron Tubes," pp. 117–125.
REICH, "Principles of Electron Tubes," pp. 233–244, 250–257.
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TERMAN, "Radio Engineers' Handbook," pp. 344–347.

EXPERIMENT 6

GAS TRIODES AND APPLICATIONS

Grid-controlled hot-cathode arc-discharge tubes, also known as thyratrons, find extensive use in industrial circuits. A few of the many applications include temperature control of ovens, resistance welding control, regulated power supplies, voltage regulators for d-c generators and alternators, frequency regulators for alternators, speed controllers for motors, parallel-switching circuits, high-speed counting circuits, relay control, inverters for converting direct current to alternating current, grid-controlled rectifiers, saw-tooth oscillators, frequency converters, and stroboscopes.

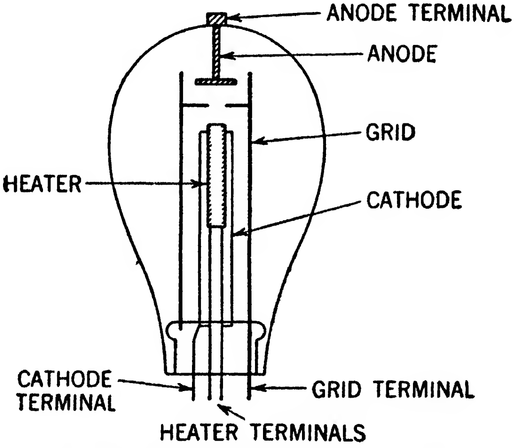


Fig. 6*a*.—Internal structure of a gas triode.

Consider the typical gas triode shown in Fig. 6*a*. The structure is somewhat similar to that of a high-vacuum triode, but the theory of operation is by no means the same. The grid electrode functions as a one-way valve. It has the ability to initiate current, but, once current exists, a change in control-grid voltage has no influence on the magnitude of the plate current, and it is impossible to stop the plate current by applying negative potential to the grid. The only way to stop the plate current is to decrease the plate potential to a value lower than the deionization potential of the tube for a period sufficient for the gas to deionize.

The gases most often employed in thyratrons are mercury vapor, argon, and neon. The pressure is of the order of 10^{-3} mm. Hg. Consider what takes place within a gas triode when put into operation. Assume that the grid bias is set at a value sufficiently negative to prevent current for the plate potential applied, that is, the grid bias is beyond cutoff. Now, if the grid bias is gradually reduced, conduction will occur at the same point at which it would were the tube completely evacuated, but instead of remaining at a low value, which would be expected in the case of a high-vacuum triode, the current will jump instantaneously to a large value, the magnitude of which will be determined almost entirely by the plate potential and load resistance. When plate current exists, positive ions are attracted to the negative grid; thus the grid becomes surrounded by a sheath of positive ions that neutralize the effects of the negative grid potential and leaves the grid ineffective as a control device. The space charge around the cathode is also neutralized in the same manner. As mentioned previously, it is necessary to reduce the plate potential to a value below the ionization potential in order to extinguish the arc of a thyratron. If the anode potential is reduced to such a value that the anode will no longer attract electrons, they will be returned to the cathode and the positive ions will return to the anode; thus conduction will cease. Current will continue, however, if the plate potential is not held at zero long enough for the ions to be removed from the space between the cathode and the anode. This period, which is known as the deionization time, ranges from 10 to 1,000 μsec. for different types of tubes.

In the operation of gas tubes of the hot-cathode type, it is necessary for the cathode to reach operating temperature before plate potential is applied. Most commercial applications incorporate time-delay switches which do not allow plate potential to be applied before the cathode has had sufficient time to reach operating temperature. If anode potential is applied before normal cathode emission has been obtained, the voltage drop will increase above the ionization potential of the gas and result in cathode disintegration.

The thyratron to be considered in this experiment is an FG-81-A, which is an argon-filled tube, manufactured by the General Electric Company.

Technical Information Concerning the FG-81-A as Furnished by the General Electric Company

Number of electrodes	3
Cathode, coated-filament type	
Voltage, volts	2.5
Current, amp., approx.	5.0
Heating time, typical sec.	5
Tube voltage drop, volts	
Maximum	24
Minimum	8
Approx. starting characteristics, volts	

Anode Voltage	Grid Control Voltage
500	−5.25
100	−3.75
50	0

Approx. anode to grid capacitance, $\mu\mu f$	4.4
Deionization time, μsec, approx.	1,000
Ionization time, μsec, approx.	10

Maximum-peak anode voltage, volts	
Inverse	500
Forward	500
Maximum negative grid voltage, volts	
Before conduction	70
During conduction	10
Maximum anode current, amp.	
Instantaneous, 25 cycles and above	2.0
Instantaneous, below 25 cycles	1.0
Average	0.5
Surge, for design only	20
Maximum grid current, amp.	
Instantaneous	0.25
Average	0.05
Maximum time of averaging current, sec.	15
Temperature limits, ambient C	−20 to +50

Figure 6*b* shows the circuit diagram for determination of the grid-control characteristic of a type FG-81-A thyratron. A very important use of the thyratron is its use as a grid-controlled rectifier. The rectified current may be varied by amplitude control, as illustrated in Fig. 6*c*, or by phase control, as illustrated in Fig. 6*d*.

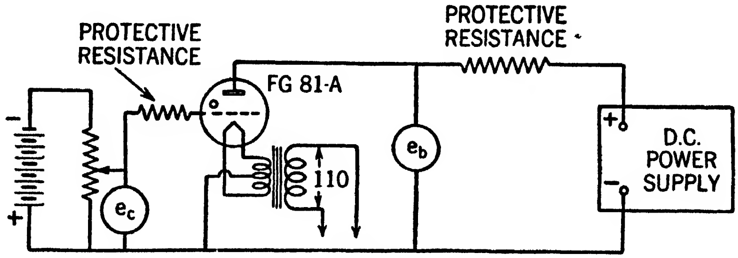


Fig. 6*b*.—Circuit for determining the grid-control characteristic of a thyratron.

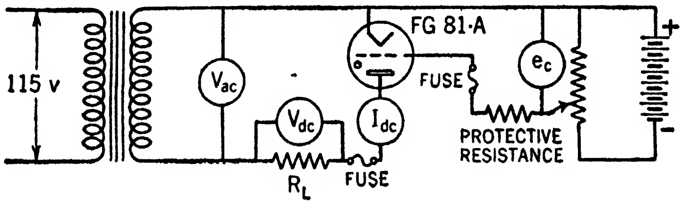


Fig. 6*c*.—Rectifier circuit in which current is controlled by the magnitude of the negative grid bias.

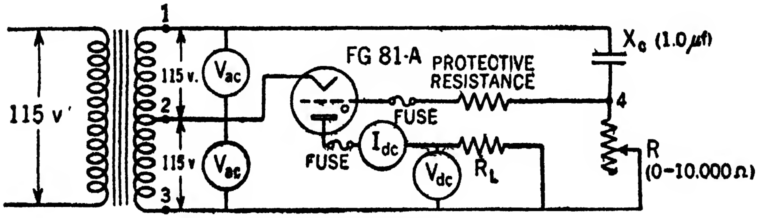
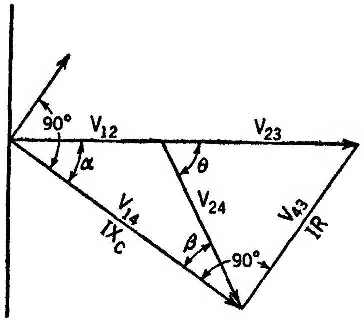


Fig. 6*d*.—Rectifier circuit in which current is controlled by varying the phase angle between the grid voltage and plate voltage.

The phase angle between plate voltage and grid voltage may be changed over a range of approximately 180 deg. by use of the phase-shift network shown in Fig. 6*d*. The phase angle θ may be determined by measuring the alternating voltages existing across C and R; thus $\theta = 2 \tan^{-1} \frac{V_R}{V_C}$; or it may be determined analytically by referring to the vector diagram for the circuit of Fig. 6*d*, which follows.



$$\alpha = \tan^{-1}\frac{IR}{IX_c}$$

$$\alpha = \tan^{-1}\frac{R}{X_c}$$

$$\alpha + \beta = \theta$$

$$\alpha = \beta$$

Then

$$\theta = 2\alpha$$

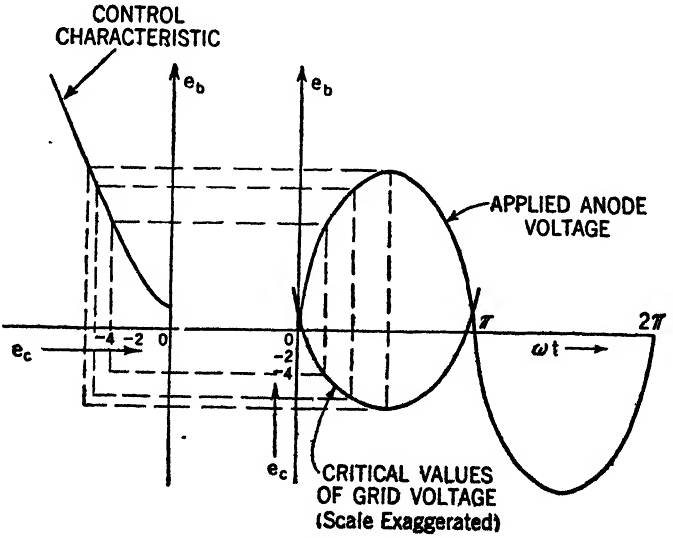
or

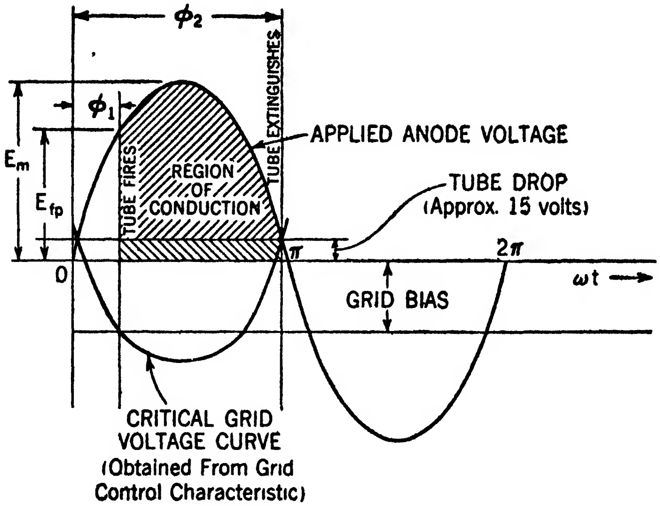
$$\theta = 2\tan^{-1}\frac{R}{X_c}$$

Vector diagram of phase-shift network of Fig. 6*d*.

The rectified current may be determined analytically for amplitude and phase control as follows:

a. **Amplitude Control** (direct voltage applied to grid)





$$I_{ave} = I_{dc} = \int_{\phi_1}^{\phi_2} \frac{(E_m \sin \omega t - 15)d\omega t}{2\pi R_l}$$

where R_l = load resistance

ϕ_1 = angle at which anode potential has become sufficiently large to make the tube fire at the grid voltage being applied. Let this value of anode potential be denoted by E_{fp}

Then

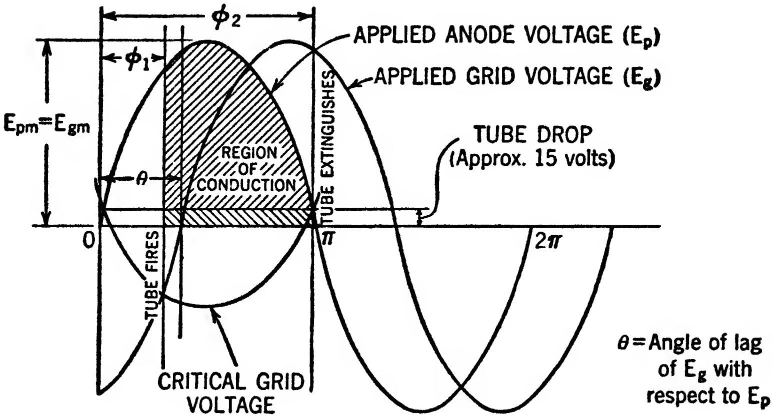
$$E_{fp} = E_m \sin \phi_1$$

$$\sin \phi_1 = \frac{E_{fp}}{E_m}$$

ϕ_2 = angle at which tube ceases to fire

$$\sin \phi_2 = \frac{TD \text{ (tube drop)}}{E_m} = \frac{15}{E_m}$$

b. Phase Control (alternating voltage applied to grid)



As in the case of amplitude control

$$I_{ave} = I_{dc} = \int_{\phi_1}^{\phi_2} \frac{(E_m \sin \omega t - 15)d\omega t}{2\pi R_l}$$

where $\sin \phi_2 = \dfrac{TD \text{ (tube drop)}}{E_m} = \dfrac{15}{E_m}$

The approximate value of ϕ_1 may be determined as follows:

Let* K = ratio of E_p to E_g necessary for firing (ratio may be obtained from grid-control characteristic)

Then

$$\frac{E_{mp} \sin (\phi_1)}{E_{mg} \sin (\phi_1 - \theta)} = K$$

$$\sin \phi_1 = (K)\left(\frac{E_{mg}}{E_{mp}}\right) \sin (\phi_1 - \theta)$$

$$\sin \phi_1 = (K)\left(\frac{E_{mg}}{E_{mp}}\right) (\sin \phi_1 \cos \theta - \cos \phi_1 \sin \theta)$$

---

* Since K is not constant, this analysis is only approximate. Values of anode current, calculated by using the value of $\ddot{u}^6$ as determined from this analysis, check reasonably well with experimental values.

Consider a specific example:

$$E_{mg} = 155; \qquad E_{mp} = 155$$

$$R = 1{,}520; \qquad X_c = 5{,}670$$

$K = -30$ (obtained from grid-control characteristic of assumed tube)

Find ϕ_1

$$\theta = 2 \tan^{-1} \left(\frac{R}{X_c}\right) = 2 \tan^{-1} 0.268$$

$$\theta = 2(15)^\circ = 30^\circ$$

$$\sin \phi_1 = -30 \frac{155}{155} (0.866 \sin \phi_1 - 0.5 \cos \phi_1)$$

$$\sin \phi_1 = -26 \sin \phi_1 + 15 \cos \phi_1$$

$$27 \sin \phi_1 = 15 \cos \phi_1$$

$$\tan \phi_1 = {}^{15}\!/\!_{27}$$

$$\phi_1 = 29^\circ$$

Exercises

1. Using the circuit diagram shown in Fig. 6*b*, obtain the grid-control characteristic of a type FG-81-A thyratron.

2. Obtain a curve of average anode current vs. grid voltage for the grid-controlled rectifier shown in Fig. 6*c*. Note wave form of voltage across load with cathode-ray oscillograph.

3. Obtain a curve of average anode current vs. phase angle for the grid-controlled rectifier shown in Fig. 6*d*. Note wave form across load with cathode-ray oscillograph.

4. From analytical consideration, determine the theoretical values for three points on the curves obtained in Exercises 2 and 3.

References

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EXPERIMENT 7

CATHODE-RAY OSCILLOGRAPH

The modern cathode-ray oscillograph has grown to be one of the most versatile electronic instruments that has ever been developed. The cathode-ray oscillograph consists of a cathode-ray tube and associated circuits and has an endless number of applications. A few of the uses are as follows: testing of amplifiers, oscillators, receivers, transmitters, circuit breakers, relays, transmission lines, and the study of transients. The cathode-ray tube with suitable receiving circuits makes television possible. The use of the cathode-ray oscillograph is not limited to the electrical engineering field. It has many important applications in other fields, such as the study of mechanical unbalance in machinery, the study of vibrations, the study of stresses in metals, the plotting of pressure-volume curves, and the comparison of time intervals of extremely short duration.

In the past, both high-vacuum and gas-filled cathode-ray tubes have been manufactured, but at present the gas tube has been almost entirely superseded by the high-vacuum tube; accordingly, only the high-vacuum tube will be considered here.

There are two distinct types of high-vacuum cathode-ray tubes, viz., the E.E. tube, in which the electron beam is electrostatically focused and electrostatically deflected, and the M.M. tube, which employs magnetic deflecting coils as well as a magnetic focusing coil. Both permanent magnets and electromagnets are used to produce magnetic deflection.

The E.E. tube is more suitable for general applications, but the M.M. tube is found to be superior for certain highly specialized applications.

Consider the typical medium-voltage cathode-ray tube shown in Fig. 7*a*.

Electrons are emitted from the indirectly heated oxide-coated cathode *K*, which is heated by a 6.3- or 2.5-volt heater *H*. Because of the difference in potential existing between the cathode and the accelerating anode A_2, the electrons are accelerated toward A_2. The velocity with which they pass through anode A_2 is expressed approximately by the equation $V = 5.95 \times 10^7\sqrt{E_a}$, where E_a = difference in potential between cathode and A_2 and V = velocity of the electrons in centimeters per second. The magnitude of the beam current from cathode to screen is determined by the grid bias. All oscillographs incorporate a grid adjustment on the control panel so that the intensity of the beam may be controlled at will. The focusing anode A_1 is a long metal cylinder with several baffles which tend to bring the electrons to a focus so that a sharp and well-defined trace will result on the screen. The magnitude of the potential applied to A_1 is approximately one-fourth of that applied to A_2. The knob on the control panel of an oscillograph labeled focusing is a means of adjusting the potential on anode A_1.

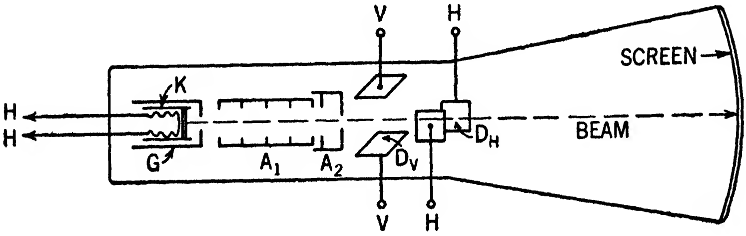


FIG. 7*a*.—Medium-voltage cathode-ray tube (E.E. type).

When electrons strike the screen, visible light rays are produced. In order that visible rays be produced, the screen must be of such a nature that it will give off visible rays when excited by an external source and it must be able to retain this light for a short period after the excitation has been taken away.

A few of the more common screen materials are as follows:

Zinc Silicate, Zn_2SiO_4. This screen material, which is commonly known as willemite, gives a yellow-green trace of medium persistency; it is ideal for tubes that are to be employed for visual study. Most general-purpose cathode-ray oscillographs employ tubes with willemite screens.

Calcium Tungstate, $CaWO_4$. This gives a blue-violet trace of extremely short persistency. Tubes employing this type of screen material find their chief application in making high-frequency photographic recordings.

Zinc Sulfide, ZnS. This gives rise to a blue-white trace of a relatively long duration. It is used as a coating for tubes designed to study transient phenomena.

The luminous output of any cathode-ray tube screen depends upon three factors, viz.,

a. Beam current.
b. Accelerating potential.
c. Physical and chemical properties of the screen.

There are two sets of deflecting plates, labeled D_v and D_h. Applying a voltage to the horizontal deflecting plates D_h will deflect the beam in the horizontal plane, and a voltage applied to the vertical deflecting plates D_v will deflect the beam in the vertical plane.

The deflection of the beam on the screen may be expressed approximately by the following equation:

$$D = \frac{E_d l L}{2 d E_a}$$

where E_a = difference in potential between cathode and accelerating anode
E_d = potential applied to deflection plates

The dimensions, all of which are expressed in centimeters, are illustrated in Fig. 7*b*.

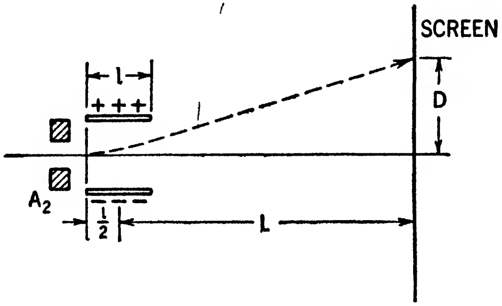


FIG. 7*b*.—Sketch illustrating electrostatic deflection.

The connection diagram for a medium-voltage cathode-ray tube is shown in Fig. 7*c*.

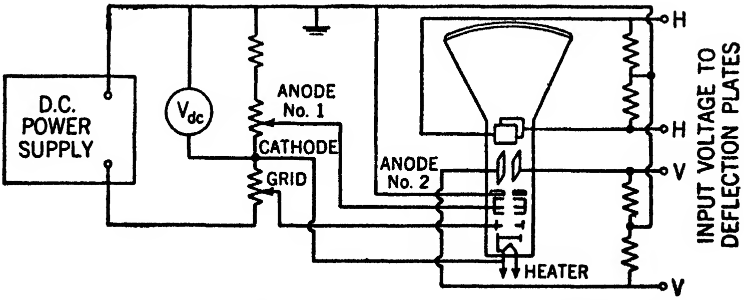


FIG. 7*c*.—Circuit diagram for medium-voltage cathode-ray tube.

Figure 7*d* is a sketch of an M.M. tube.

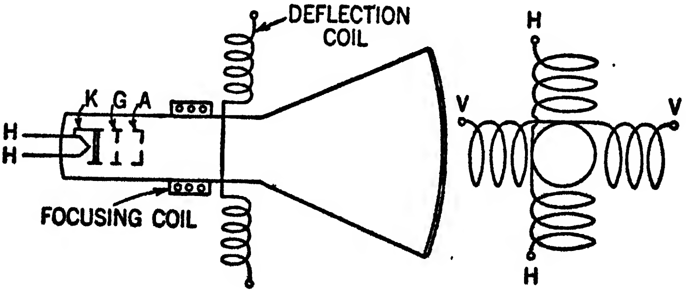


FIG. 7*d*.—Sketch of an M.M. tube.

The deflection of the beam on the screen, in the case of an M.M. tube or a tube employing electrostatic focusing and magnetic deflection, is expressed approximately by the following equation:

$$D = \frac{0.3lLB}{\sqrt{E_a}}$$

where E_a = accelerating potential
B = flux density in gauss normal to the beams of electrons

The dimensions, all of which are expressed in centimeters, are illustrated in Fig. 7*e*.

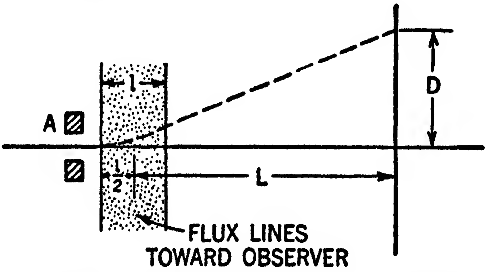


FIG. 7*e*.—Sketch illustrating magnetic deflection.

When sinusoidal voltages are impressed simultaneously in both vertical and horizontal deflection plates, a Lissajous figure will be obtained on the screen. The resulting figure for a frequency ratio of 2 : 1 may be obtained graphically by the simple construction shown in Fig. 7*f*. This affords an excellent method of comparing frequencies. The ratio of the number of tangencies to line aa^1 to the number of tangencies to line bb^1 is the frequency ratio.

The equation for the resulting figure may be obtained as follows:

$$X = K_1e_x = K_1E_x \sin \omega t$$

$$Y = K_2e_y = K_2E_y \sin 2\omega t$$

$$\sin \omega t = \frac{X}{K_1E_x}$$

$$Y = 2K_2E_y \sin \omega t \cos \omega t$$

$$Y = 2K_2\left(\frac{X}{K_1E_x}\right)E_y\sqrt{1-\left(\frac{X}{K_1E_x}\right)^2}$$

$$Y^2 = \frac{4K_2^2E_y^2X^2}{K_1^2E_x^2}\left(1-\frac{X^2}{K_1^2E_x^2}\right)$$

$$Y^2 = AX^2 - BX^4$$

It is usually desirable to show the unknown voltage as a function of time. This may be accomplished by making the spot sweep periodically across the screen and return instantaneously to its zero position. If the voltage applied to the horizontal deflecting plates varies linearly with respect to time in the form of a saw-tooth wave and its frequency is equal to the frequency of the unknown voltage applied to the vertical deflecting plates, 1 cycle of the unknown voltage will be shown on the screen. Figure 7*g* shows the circuit of a saw-tooth oscillator which employs a gas triode.

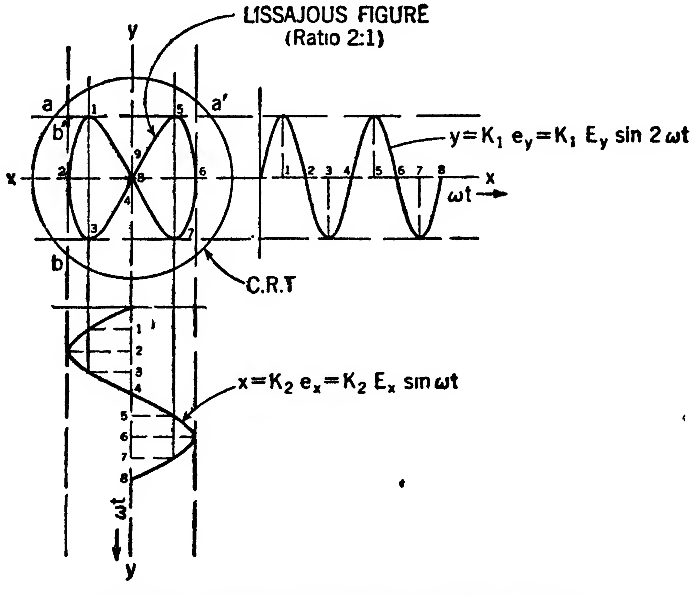


FIG. 7*f*.—Graphical analysis of Lissajous figure.

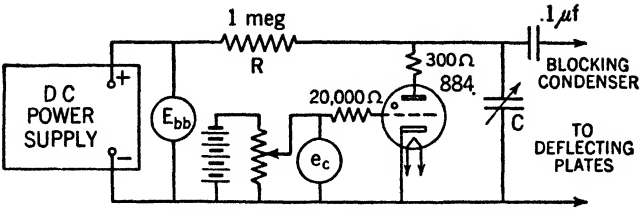


FIG. 7*g*.—Circuit diagram of saw-tooth oscillator.

The saw-tooth wave obtained from the above circuit is shown in Fig. 7*h*.

Consider what happens when the circuit of Fig. 7*g* is put into operation. Before the tube fires, a simple *RC* circuit exists; when potential E_{bb} is applied to the *RC* circuit, the condenser *C* charges exponentially through the resistor *R*.

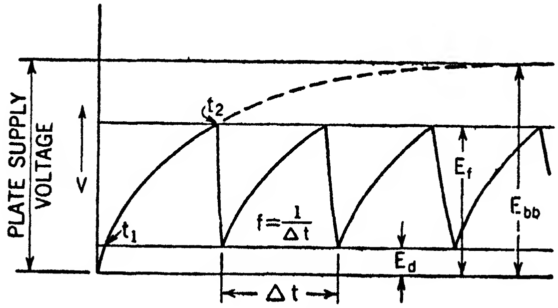


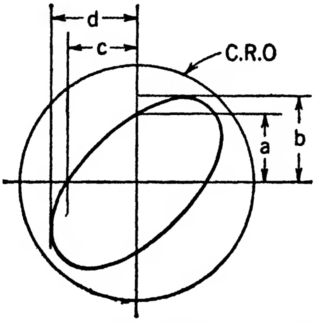
FIG. 7*h*.—Saw-tooth wave.

When the voltage across the condenser reaches the firing voltage of the tube (884 gas triode), the tube fires and the condenser discharges through the tube until its potential is less than the deionization potential of the tube; then the tube extinguishes itself and the cycle is repeated. In order to obtain a linear-sweep voltage, the firing potential should be made small. In most practical applications the magnitude of the sweep voltage obtained from the saw-tooth oscillator is less than 10 per cent of E_{bb} and is amplified before being applied to the horizontal deflecting plates.

$$\text{Frequency of saw-tooth wave} = \frac{1}{\Delta t} = \left[\frac{1}{RC\log_e\left(\dfrac{E_{bb}-E_d}{E_{bb}-E_f}\right)}\right]$$

where E_{bb} = supply voltage
E_f = voltage at which tube fires
E_d = deionization potential of tube

One extremely useful application of the cathode-ray oscillograph is that of determining the phase angle between two sources of voltage. The phase angle may be determined by impressing one source of voltage on the horizontal deflecting plates and the other on the vertical deflecting plates. Proper interpretation of the pattern on the screen will give the correct phase angle. Consider the diagram of Fig. 7*i*.



$\sin \theta = \frac{a}{b}$
or
$\sin \theta = \frac{c}{d}$

where θ = phase angle

FIG. 7*i*.—Analysis of phase-shift pattern on screen of cathode-ray tube screen.

The phase-shift network of Fig. 7*j* will, with the proper choice of *R* and *C*, give any desired angle between 0 and 180°.

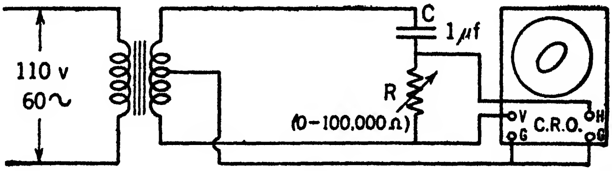


FIG. 7*j*.—Phase-shift network.

Exercises

1. By applying a variable 60-cycle source of voltage to the proper set of deflecting plates, obtain points for and plot curves of horizontal sensitivity in millimeters per volt vs. deflecting voltage for two different accelerating anode voltages.

NOTE: Variable source of alternating voltage should be connected directly to the deflecting plates.

$$\text{Sensitivity} = \frac{D}{2\sqrt{2}V}$$

where D = deflection, mm.
V = r.m.s. value of deflecting voltage

2. Repeat Exercise 1 for vertical sensitivity.

3. Obtain points for and plot curves of horizontal and vertical sensitivity in millimeters per ampere vs. coil current for two different accelerating anode voltages.

4. Connect up the phase-shift network in Fig. 7*j* and note Lissajous figures for phase angles of 0, 45, 90, and 180°. Explain each figure obtained.

5. Connect a 60-cycle source to one set of plates and the output of an oscillator to the other set and note Lissajous figures for the following oscillator settings: 90, 120, 180, 240, 300, and 360 cycles.

6. Connect up the sweep circuit shown in Fig. 7*g* and adjust its frequency so as to obtain a 60-cycle wave on the screen. Insert a small 60-cycle voltage in series with the grid of the 884 and synchronize the sweep.

7. Examine, operate, and obtain a thorough understanding of a commercial cathode-ray oscillograph.

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EXPERIMENT 8

POWER-SUPPLY SYSTEMS

The most common type of power supply is one which consists of a rectifier and a smoothing filter. Such a power supply is essential to the operation of all receivers and transmitters that depend on alternating current as a source of power. Most rectifier circuits used as a basis of anode-power systems employ either high-vacuum diodes or mercury-vapor hot-cathode types, the former being used as a source of anode power for receiving tubes and the latter for transmitting tubes. There are special types of power supplies which are used to obtain high-voltage direct current from low-voltage d-c sources. Several such devices for "stepping up" direct voltage are synchronous vibrators, nonsynchronous vibrators, and dynamotors. The operation of each of these will be considered in this experiment.

A rectifier is a device employed for converting alternating current into direct current. Half-wave rectifiers utilize only half of each cycle, while full-wave rectifiers utilize the complete cycle. The alternating component of the direct voltage is called the ripple voltage; the ripple factor is defined as the ratio of amplitude of the ripple voltage to the average value of the direct voltage. The magnitude of the ripple voltage is decreased by inserting a smoothing filter between the rectifier and the load.

Figure 8*a* shows the schematic diagram of a full-wave rectifier employing either choke or condenser-input filters. When switch *S* is open, the circuit is that of a choke-input filter; if the switch *S* is closed, the circuit is converted to a condenser-input filter.

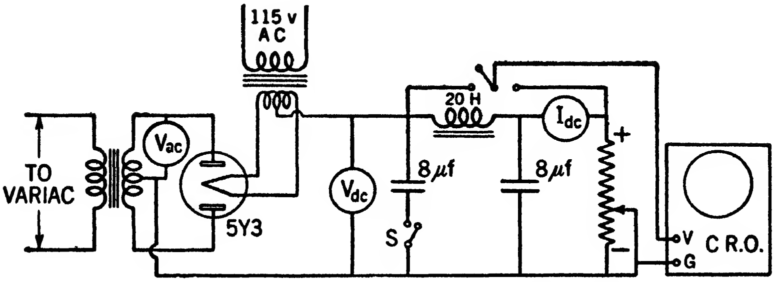

FIG. 8a.—Full-wave rectifier and smoothing filter.

The ripple factor for the kth harmonic at the input to the filter may be defined as

$$\rho_k = \frac{E_{rk}}{E_{dc}}$$

where E_{rk} = amplitude of the kth harmonic component of the ripple voltage at the input to the filter
E_{dc} = average value of the total voltage

The ripple factor at the output of the filter may be defined as

$$\rho_k' = \frac{E'_{rk}}{E'_{dc}}$$

where E'_{rk} = amplitude of the kth harmonic component of the ripple voltage at the output of the filter
E'_{dc} = average value of the total voltage at the output of the filter

The smoothing factor α_k of a filter for the kth harmonic of the ripple frequency is defined as the ratio of the ripple factor at the input of the filter to ripple factor at the output of the filter.

$$\alpha_k = \frac{\rho_k}{\rho_k'} \qquad \text{or} \qquad \rho_k' = \frac{\rho_k}{\alpha_k}$$

The fundamental ripple frequency, which, for a full-wave rectifier, is twice the frequency of the applied alternating current, is the largest component of the ripple voltage.

Since the effectiveness of a filter increases with higher order harmonics, it is usually only necessary to design a filter to smooth out the fundamental component of ripple voltage and the other components will automatically be taken care of. The value of ρ_r for a full-wave choke-input filter is approximately 0.667 and for a condenser-input filter the ripple factor is expressed approximately by the following equation:

$$\rho_r = \frac{1}{\pi f_r RC}$$

where f_r = fundamental ripple frequency

$R = \frac{E_{dc}}{I_{dc}}$ = d-c resistance

C = capacity of input condenser, farads

The smoothing factor of a filter consisting of one choke and one condenser is expressed approximately by the following equation:

$$\alpha_k = (\omega_k^2 LC - 1)$$

For two similar sections

$$\alpha_k = (\omega_k^2 LC - 1)^2$$

If the two sections are not similar, then

$$\alpha_k = (\omega_k^2 L_1 C_1 - 1)(\omega_k^2 L_2 C_2 - 1)$$

In addition to the full-wave rectifier of Fig. 8*a*, the following types of power-conversion circuits are to be considered in this experiment:

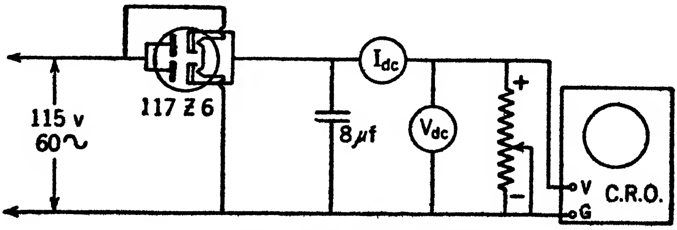

FIG. 8*b*.—Half-wave rectifier.

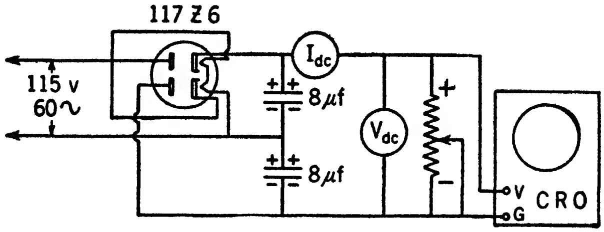

Fig 8c.—Voltage doubler.

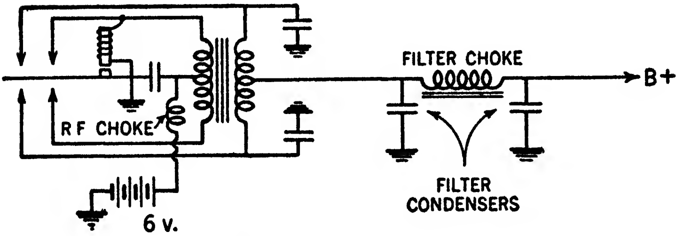

Fig. 8d —Synchronous vibrator.

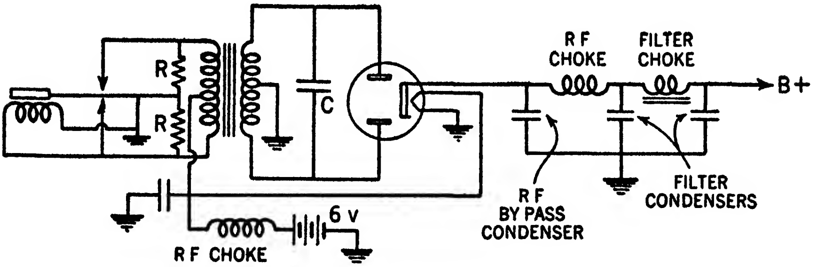

Fig. 8e.—Nonsynchronous vibrator.

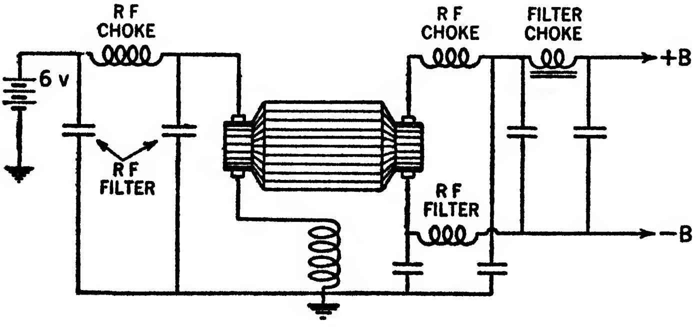

Fig. 8f.—Dynamotor.

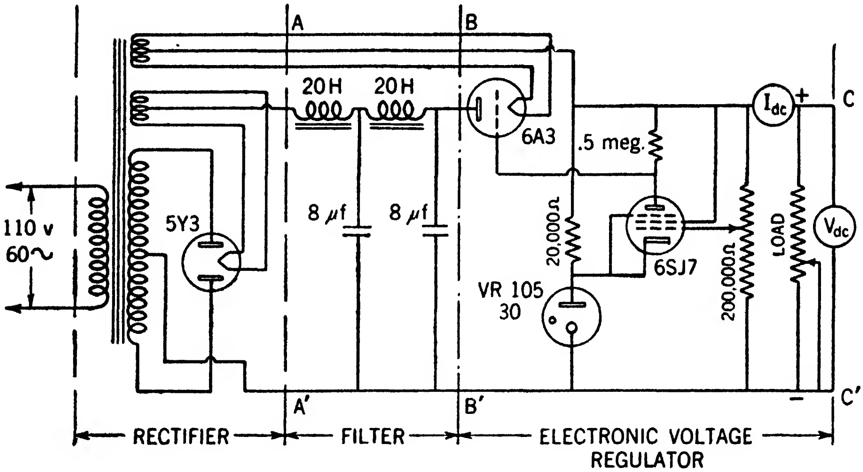

FIG. 8g.—Voltage-regulated power supply.

Exercises

1. Connect up the power supply, employing choke input as shown in Fig. 8*a* (switch *S* open). Obtain data for and plot voltage-regulation curves for the following plate voltage: 350, 300, and 250 (r.m.s. values).

2. Repeat Exercise 1 for a condenser-input filter (switch *S* closed).

3. Obtain oscillogram of the voltage and current at various points along the filter for both choke and condenser input. Using a wave analyzer,* determine the ripple factor and the smoothing factor for the fundamental. Explain oscillograms and check calculated values of ripple and smoothing factors with experimental values.

4. Obtain a voltage-regulation curve for the half-wave rectifier shown in Fig. 8*b* and note oscillogram of voltage for several values of current.

5. Repeat Exercise 4 for the voltage doubler shown in Fig. 8*c*.

6. Examine the circuit of a synchronous vibrator, obtain an understanding of its operation, and plot a regulation curve.

7. Repeat Exercise 6 for a nonsynchronous vibrator.

8. Repeat Exercise 6 for a dynamotor.

9. Repeat Exercise 6 for the electronic voltage regulator shown in Fig. 8*g*.

* In laboratories that are not equipped with wave analyzers, the smoothing factor may be determined approximately by analysis of the wave form obtained by means of a cathode-ray oscillograph.

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EXPERIMENT 9

AUDIO-FREQUENCY VOLTAGE AMPLIFIERS

Amplifiers are known as power or voltage amplifiers according to whether the object of the amplifier is to develop as much power or voltage as is possible across the load impedance. Amplifiers are also classified according to the frequency range over which they will respond. There are four divisions under this classification, viz., d-c amplifiers, a-f amplifiers, radio-frequency amplifiers, and video-frequency amplifiers. Direct-current amplifiers are designed to amplify d-c signals; a-f amplifiers respond to signals that lie within the audible range, *i.e.*, from 20 cycles to approximately 20,000 cycles. Amplifiers that respond to frequencies above 20,000 cycles are known as radio-frequency amplifiers; while video-frequency amplifiers are capable of amplifying frequencies from 10 to 1,000,000 cycles or higher.

Audio-frequency voltage amplifiers are employed to amplify signal voltages whose frequencies lie within the audible range to a level necessary for the operation of power amplifiers. Such an amplifier is said to have a flat frequency response if its amplification is uniform for all frequencies within the a-f range. All a-f amplifiers introduce some frequency distortion, *i.e.*, the amplification is not uniform for all frequencies in the a-f range. Frequency distortion is usually most pronounced at low and high frequencies. It may be reduced to a minimum by careful design.

Two types of a-f voltage amplifiers that find wide usage in modern receivers are the resistance-coupled amplifier and the transformer-coupled amplifier. Both types will be considered in this experiment.

Figure 9*a* shows the circuit to be employed for the determination of the voltage amplification of a resistance-coupled amplifier employing a triode. It is suggested that the values of typical circuit constants and potentials be obtained from the "RCA Receiving Tube Manual."

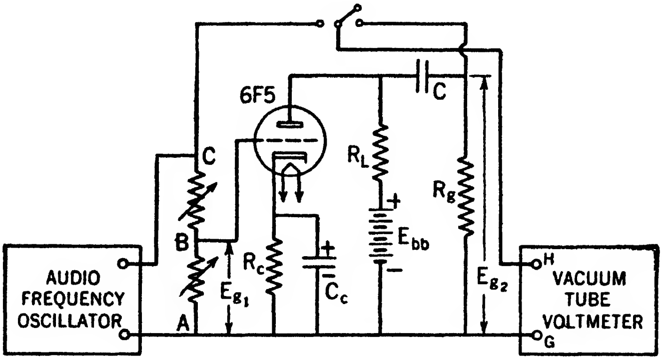


FIG. 9*a*.—Resistance-coupled amplifier, employing a triode.

The voltage gain at any frequency may be determined by measuring E_{g2} and E_{g1} and determining the ratio of E_{g2} to E_{g1}; *i.e.*, the voltage gain, $A = \frac{E_{g2}}{E_{g1}}$. In most cases E_{g1} will be very small and difficult to measure directly; thus, it is desirable to use an indirect method of measurement. Consider the input circuit employed in the circuit diagram of Fig. 9*a*, which is reproduced in Fig. 9*b*.

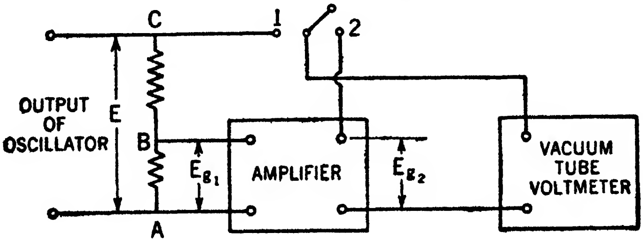


FIG. 9*b*.—Input circuit to amplifier.

R_{BC} should be a precision resistor with a relatively high value, say 100,000 ohms, and R_{AB} should be a precision decade resistor with a range from 0 to 10,000 ohms or greater. Let it be assumed that the output of the oscillator is adjusted to some suitable value of voltage and frequency such as 5 volts at 1,000 cycles (output determined by vacuum-tube voltmeter when switch is in position 1). Now assume the switch thrown to position 2 and R_{AB} varied until the vacuum-tube voltmeter reads 5 volts. The switch should be moved from position 2 to position 1 and back again in order to determine whether or not the input voltage has changed; if a change is detected, readjustment should be made. With the oscillator output set at some fixed voltage, say 5 volts at 1,000 cycles, and resistance R_{AB} adjusted to a value which will result in the same voltage across the output terminals of the amplifier, the gain may be determined as follows:

$$A = \frac{E_{g2}}{E_{g1}}$$

$$E_{g1} = E\left(\frac{R_{AB}}{R_{AB} + R_{BC}}\right)$$

$$A = \frac{E_{g2}}{E_{g1}} = \frac{E_{g2}}{E}\left(\frac{R_{AB} + R_{BC}}{R_{AB}}\right)$$

If R_{AB} is adjusted so that $E = E_{g2}$, then

$$A = \frac{R_{AB} + R_{BC}}{R_{AB}}$$

The gain should be determined for sufficient values of frequencies to cover the entire frequency range of the amplifier.

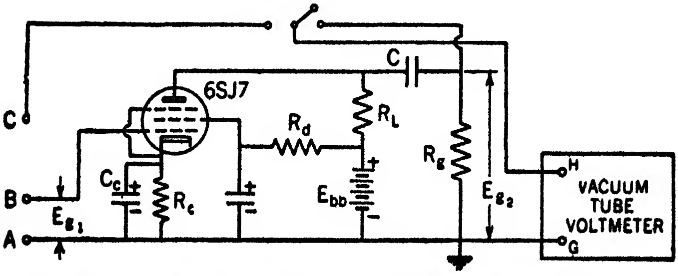


FIG. 9c.—Resistance-coupled amplifier, employing a pentode.

The same procedure may be followed in determining the frequency response of the resistance-coupled amplifier, employing a pentode, which is shown in Fig. 9*c* (circuit constants may be found in "RCA Receiving Tube Manual"), and also the transformer-coupled amplifier which is shown in Fig. 9*d*.

Consider the circuit shown in Fig. 9*a*. The grid bias is obtained by means of a cathode resistor; the grid is negative with respect to the cathode by the magnitude of the direct voltage drop across this resistor. The plate-to-cathode operating voltage is less than the battery voltage by the summation of the voltage drops across the cathode resistor and the resistance R_L. R_L is the load across which the amplified voltage is developed. The coupling condenser C serves to prevent any d-c voltage from being applied to the grid of the following tube, and the function of R_g is to maintain grid potential for the same tube.

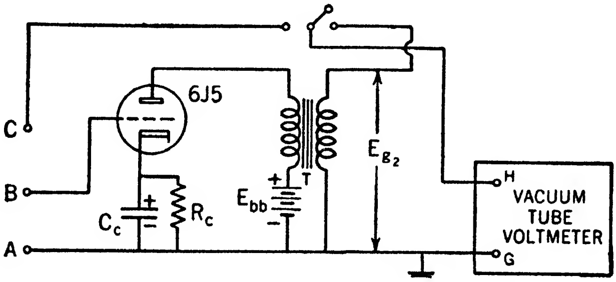
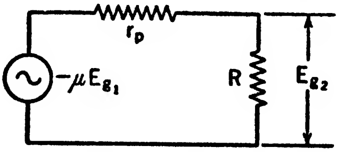


Fig. 9*d*.—Transformer-coupled amplifier, employing a triode.

At extremely low frequencies the reactance of the coupling condenser becomes appreciable; thus, some of the amplified signal appears across X_c and results in a decrease in voltage across the grid leak R_g. This accounts for the decrease in voltage when attempt is made to use an a-f amplifier at very low frequencies. The decrease in amplification at high frequencies is due to the decrease in the reactance X_t (reactance due to the capacitance of tubes and leads). The reactance X_t decreases with an increase in frequency and results in a decrease in effective load impedance. At mid-band frequencies the voltage drop across X_c is negligible and the shunting effect of X_t is negligible.

The equivalent circuit of the resistance-coupled amplifier is different for different frequencies.

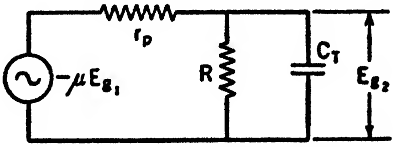
EQUIVALENT CIRCUIT FOR MID-BAND FREQUENCY



$$A_m = -\frac{\mu R}{r_p + R} = -g_m R_0$$

where A_m = amplification at mid-band frequency
μ = amplification of tube
g_m = mutual conductance
R_0 = the equivalent resistance of r_p, R_l, R_g in parallel
$R = \dfrac{R_l R_g}{R_l + R_g}$

EQUIVALENT CIRCUIT FOR HIGH FREQUENCIES



$C_T = C_p + C_g$

$$A_h = \frac{1}{\sqrt{\frac{R_0^2}{X_t^2} + 1}} \cdot \frac{-\mu R}{r_p + R}$$

or

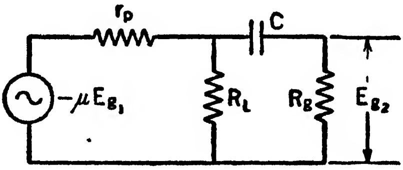
$$A_h = \frac{1}{\sqrt{\frac{R_0^2}{X_t^2} + 1}} \cdot [-g_m R_0]$$

where A_h = amplification at high frequencies

C_p and C_g represent the internal capacitance of the plate circuit of tube 1 and the grid circuit of tube 2 respectively.

X_t = equivalent reactance of C_p and C_g in parallel

EQUIVALENT CIRCUIT FOR LOW FREQUENCIES



$$A_L = \frac{-g_m R_0}{\sqrt{1 + \frac{X_x^2}{R_x^2}}}$$

$$R_x = R_g + \frac{r_p R_l}{r_p + R_l}$$

where X_x = reactance of coupling condenser

The same analogy may be employed for a resistance-coupled amplifier employing a pentode.

The mid-band amplification of a transformer-coupled amplifier is expressed approximately by the following relationship:

$$A_m = \mu n$$

where μ = amplification of tube

n = turns ratio of transformer

Exercises

1. Obtain data for and plot a frequency-response curve for the resistance-coupled amplifier shown in Fig. 9*a*.

2. Repeat Exercise 1 for a resistance-coupled amplifier employing a pentode, Fig. 9*c*.

3. Repeat Exercise 1 for the transformer-coupled amplifier shown in Fig. 9*d*.

4. From tube and circuit constants, calculate the mid-band amplification for each of the amplifiers tested.

5. From experimental data determine the magnitude of both the shunting capacitance and the coupling capacitance existing in the amplifier tested in Exercise 1.

References

Chaffee, "Theory of Thermionic Vacuum Tubes," pp. 288–294, 396–416.
Dow, "Fundamentals of Engineering Electronics," pp. 266–292.
Eastman, "Fundamentals of Vacuum Tubes," 2d ed., pp. 244–280.
Fink, "Engineering Electronics," pp. 275–286.
Glasgow, "Principles of Radio Engineering," pp. 144–170.
Henney, "Radio Engineering Handbook," 3d ed., pp. 359–382.
MIT Staff, "Applied Electronics," pp. 459–504.
"RCA Receiving Tube Manual," pp. 12–14, 198–203.
Reich, "Principles of Electron Tubes," pp. 132–155.
——— "Theory and Application of Electron Tubes," 2d ed., pp. 144–162.
Terman, "Fundamentals of Radio," pp. 91–113.
——— "Measurements in Radio Engineering," pp. 179–186.
——— "Radio Engineering," 2d ed., pp. 167–210.
——— "Radio Engineers' Handbook," pp. 353–376.

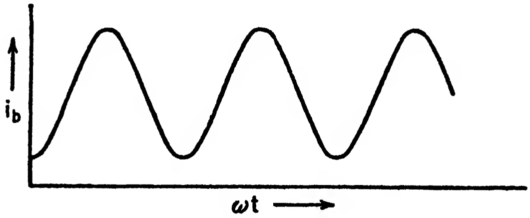
EXPERIMENT 10

AUDIO-FREQUENCY POWER AMPLIFIERS

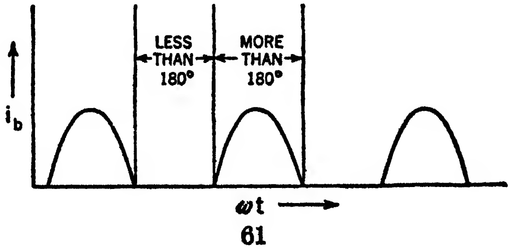
In contrast with the voltage amplifier, the power amplifier is designed to develop as much "undistorted" power as is possible across the load impedance. The word undistorted as used above means a distortion of less than 5 per cent amplitude distortion, which is low enough to escape detection by the human ear and thus can be readily tolerated in most applications. The a-f power amplifier finds wide usage in all radio receivers, public-address systems, transmitters, and telephone systems.

Power amplifiers, in addition to being classified as radio frequency or audio frequency, are classified according to their operation as follows:

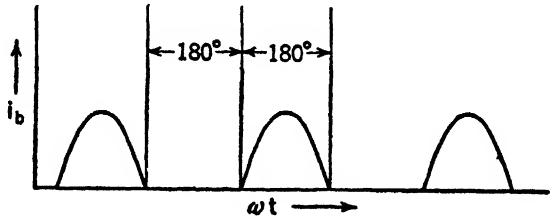
Class A. Amplifier in which the grid is biased so that the plate current exists at all times during operation.



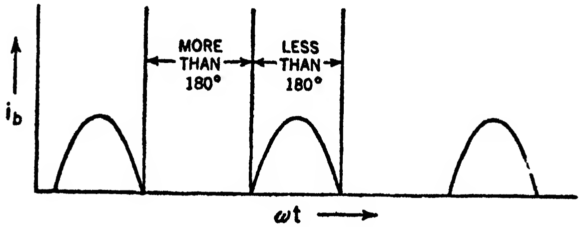
Class AB. Amplifier in which the grid is biased so that the plate current exists for appreciably more than half of each cycle but not for the entire cycle.



Class B. Amplifier in which the grid is biased so that plate current exists for approximately one-half cycle.



Class C. Amplifier in which grid is biased so that the plate current exists for appreciably less than one-half cycle.

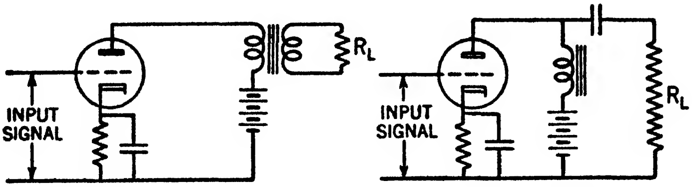


Subscripts are used to denote whether or not grid current exists during any part of the cycle. A Class A_1 amplifier would be an amplifier in which no grid current exists at any time. A Class A_2 amplifier is an amplifier in which grid current exists for a short period during each cycle. These subscripts are applicable to each of the amplifiers mentioned previously.

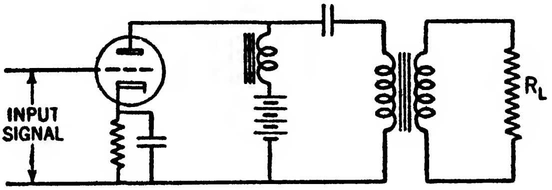
Radio-frequency power amplifiers are usually Class B or Class C; a-f power amplifiers employing one tube are Class A, while push-pull a-f amplifiers are usually operated as Class B or Class AB.

Several typical circuits for power amplifiers are shown in Fig. 10*a*.

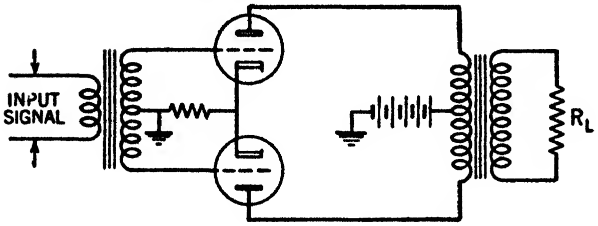
In this experiment two amplifier circuits are to be tested. The first to be considered is shown in Fig. 10*b* and consists of a simple shunt-feed amplifier employing a triode (6F6 made to function as a triode by connecting the screen grid directly to the plate). This amplifier can be made to operate as either Class A_1 or Class A_2. For typical circuit constants and operating conditions, the "RCA Receiving Tube Manual" should be consulted.



TRANSFORMER COUPLING SHUNT-FEED



TRANSFORMER COUPLING WITH SHUNT-FEED



PUSH-PULL

Fig. 10*a*.—Typical power-amplifier circuits.

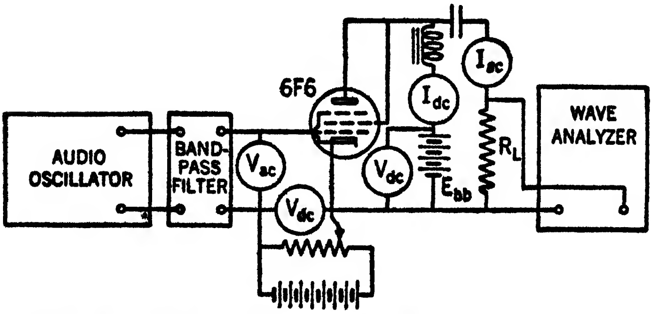


Fig. 10*b*.—Shunt-feed power amplifier, employing a pentode made to function as a triode.

An ideal a-f power amplifier is one in which the wave form of the output voltage is a replica of the input voltage except for magnitude. No amplifiers are ideal, but some approach very closely to ideal conditions. In Experiment 9, frequency distortion was considered; here, amplitude distortion is to be studied. When the ratio of output signal to the input signal varies with the magnitude of the input signal, amplitude distortion is said to exist.

The amplitude distortion of an amplifier may be determined experimentally by impressing a pure sine wave across the input circuit and determining the magnitude of the various harmonic voltages in the output wave by means of a wave analyzer.* The magnitude of the amplitude distortion due to any harmonic is the ratio of the r.m.s. value of the harmonic voltage under consideration to the fundamental expressed in percentage. The total harmonic distortion is the ratio of the square root of the sum of the squares of the harmonic voltages to the fundamental expressed in percentage.

The plate efficiency is defined as the ratio of the a-c power output to the d-c power supplied to the plate circuit. It may be readily determined from the meter readings of the circuit shown in Fig. 10*b*.

$$\text{Plate efficiency} = \frac{I_{ac}^2 R_L}{(I_{dc})(E_{dc})}$$

The percentage harmonic distortion, power output, and percentage efficiency may be determined analytically from the tube characteristics and circuit parameters. An analytical treatment will be found in any standard text on electronics.

At the present time pentodes and beam-power tubes find much wider usage as Class A power amplifiers than do triodes. The pentode tube gives greater sensitivity as well

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*** In laboratories not equipped with wave analyzers, the amplitude distortion may be determined approximately by analysis of wave form obtained by means of a cathode-ray oscillograph.**

as higher efficiency but at the same time introduces more distortion; however, if operated properly, the pentode is usually more desirable than the triode for the conventional type of amplifier which is employed in most modern receivers.

The beam-power tube has the same advantages as the pentode does when compared to the triode and in addition has several other desirable properties. A smaller signal is required to develop full output in the case of the beam-power tube than in the case of a power pentode, and for this reason the beam-power tube is said to have greater sensitivity. Beam-power tubes give rise to much less third harmonic distortion than do pentodes; thus, they are particularly well suited for push-pull operation, which eliminates second harmonic distortion, resulting in very high-fidelity amplification.

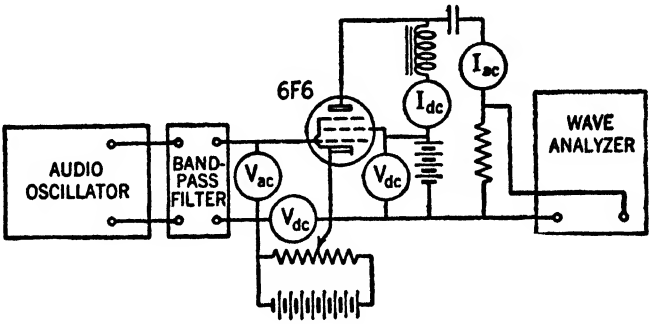
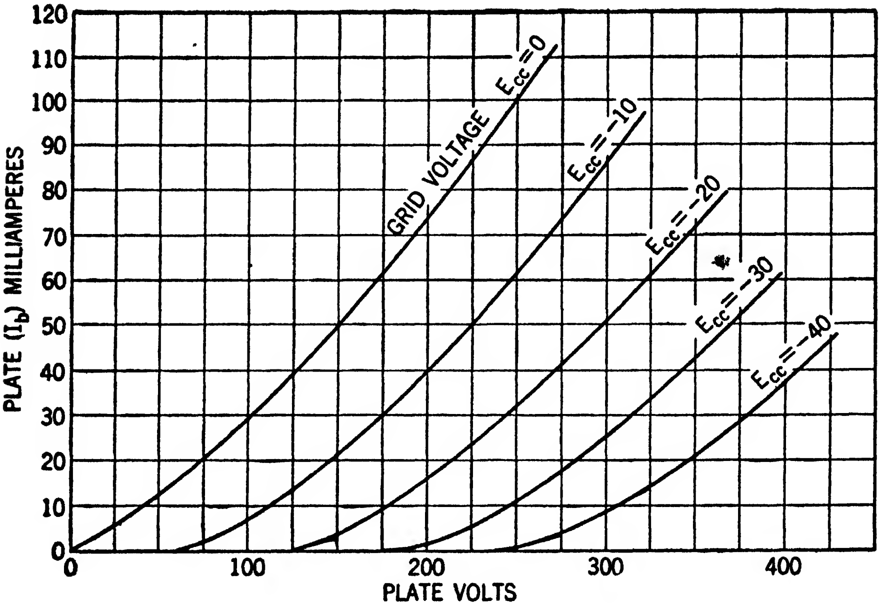


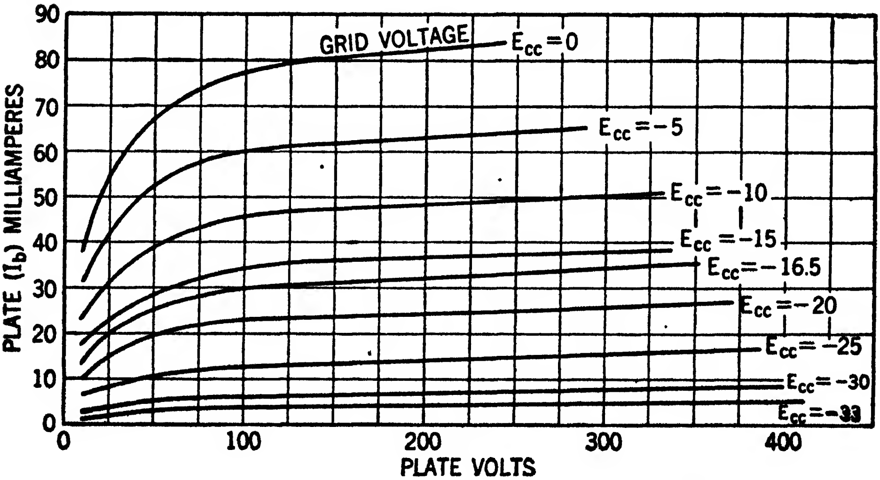
FIG. 10c.—Shunt-feed power amplifier, employing a pentode.

The percentage harmonic distortion, power output, and plate efficiency may be determined experimentally for a power amplifier employing a pentode or beam-power tube in the same manner as for a triode.

Figure 10c is the circuit diagram of a power amplifier employing a 6F6 as a pentode. For circuit parameters and typical operating conditions for the 6F6, the "RCA Receiving Tube Manual" should be consulted.



Static characteristics of 6F6 (triode connection). To be used in performing Exercise 5.



Static characteristics of a 6F6 (pentode connection). To be used in performing Exercise 5.

Exercises

1. Obtain data for and plot curves of power output, percentage second harmonic distortion, percentage third harmonic distortion, percentage total harmonic distortion, and plate efficiency vs. input signal for the amplifier shown in Fig. 10*b*.

2. Obtain data for and plot a curve of power output vs. load resistance for the amplifier of Fig. 10*b*.

3. Repeat Exercise 1, employing the 6F6 as a pentode as shown in Fig. 10*c*.

4. Repeat Exercise 2, employing a 6F6 as a pentode.

5. From analytical considerations determine the power output, percentage efficiency, and percentage distortion; check with experimental results of Exercises 1 and 3.

References

CHAFFEE, "Theory of Thermionic Vacuum Tubes," pp. 288–314.
DOW, "Fundamentals of Engineering Electronics," pp. 283–292.
EASTMAN, "Fundamentals of Vacuum Tubes," 2d ed., pp. 296–338.
FINK, "Engineering Electronics," pp. 249–252, 277–279.
GLASGOW, "Principles of Radio Engineering," pp. 177–209.
HENNEY, "Radio Engineering Handbook," 3d ed., pp. 254–258, 362–363, 382-385.
MIT STAFF, "Applied Electronics," pp. 412–451.
MILLMAN and SEELY, "Electronics," pp. 625–670.
REICH, "Principles of Electron Tubes," pp. 157–171.
——— "Theory and Application of Electron Tubes," 2d ed.. pp. 276–345.
TERMAN, "Fundamentals of Radio," pp. 145–170.
——— "Radio Engineering," 2d ed., pp. 276–345.
——— "Radio Engineers' Handbook," pp. 377–395.

EXPERIMENT 11

POWER RECTIFICATION AND INVERSION

Although there have been many attempts to devise a means for transmission of large amounts of d-c energy, none has thus far proved economically feasible. For this reason, when a large amount of power is to be transmitted, it is transmitted in the form of a-c rather than d-c energy. There are a great many applications that require large amounts of direct current; transportation systems and electrochemical industries are the largest consumers of d-c energy. Since millions of kilowatt-hours of d-c energy are being consumed daily in this country, large power rectifiers justify the attention of all who expect to make a career of engineering. Conversion of alternating to direct current on a large scale is essential to many vital industries.

Conversion may be carried out by means of synchronous converters, motor-generator sets, and mercury-arc rectifiers. Mercury-arc rectifiers are fast replacing motor-generator sets and synchronous converters as means of converting alternating to direct current.

Large power rectification is accomplished by means of polyphase rectifier units. Polyphase rectifiers have marked advantages over single-phase rectifiers. In the first place, most a-c power is transmitted as three-phase power and thus polyphase rectifiers are more applicable to the type of distribution employed. Other advantages include higher ripple frequencies, lower ripple factors, and high transformer-utilization factors.

Steel-tank mercury-arc rectifiers and ignitrons are used for rectifying large amounts of power, while thermionic gas diodes are used for the rectification of moderate amounts of power. In this experiment three-phase rectification will be accomplished, employing hot-cathode gas tubes of the FG-32 type.

TECHNICAL INFORMATION CONCERNING THE FG-32 AS FURNISHED BY THE GENERAL ELECTRIC COMPANY

Number of electrodes	2
Cathode, indirectly heated type:	
Heater voltage, volts	5.0
Heater current, amp., approx.	4.5
Heating time, min., typical	5
Tube voltage drop, volts:	
Maximum	24
Minimum	5
Net weight, oz., approx.	4
Shipping weight, lb., approx.	3
Maximum peak inverse anode voltage, volts	1,000
Minimum anode current, amp.:	
Instantaneous *	15
Average †	2.5
Surge, for design only	200
Temperature limits, condensed mercury C.	+30 to +80

* When the operating frequency is less than 25 cycles, the maximum instantaneous anode current rating is reduced to twice the average current rating.

† Maximum time of averaging anode current is 15 sec.

Figure 11*a* is the circuit diagram of a three-phase half-wave rectifier. This rectifier circuit employs a polyphase

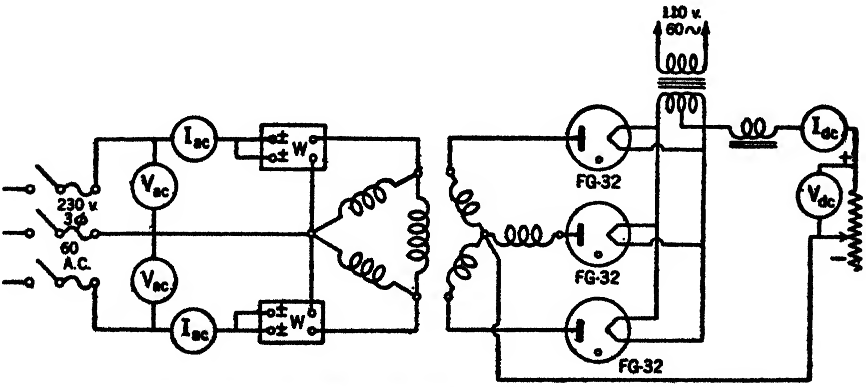


FIG. 11*a*.—Three-phase half-wave rectifier, employing a polyphase transformer.

delta-Y-connected transformer designed to prevent d-c saturation of the core.

If a suitable polyphase transformer is not available, three separate transformers may be connected up distributed Y, thus eliminating d-c saturation. The circuit diagram for such a setup is shown in Fig. 11*b*.

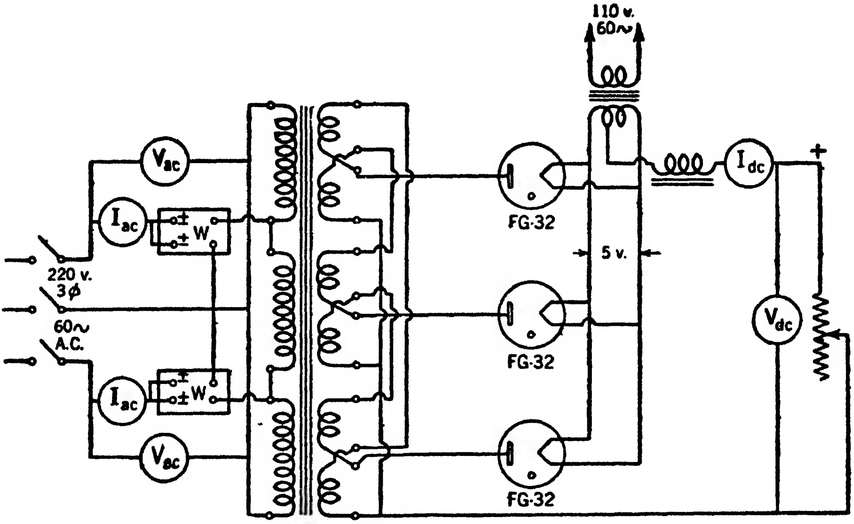


FIG. 11*b*.—Three-phase half-wave rectifier, employing three single-phase transformers.

Inversion

It is sometimes desirable to change large amounts of d-c energy to a-c energy. The process of changing direct to alternating current, which is known as inversion, may be accomplished by the use of rotating machinery or by gas-tube rectifiers. Thyratrons, ignitrons, and mercury-pool tubes are employed in inverter circuits. Thyratrons are used in low-power circuits, while ignitrons and mercury-pool tubes are used for larger power applications.

Figure 11*c* is that of a simple inverter circuit employing two thyratrons of the FG-81A type. Technical information concerning the FG-81A may be obtained from Experiment 6.

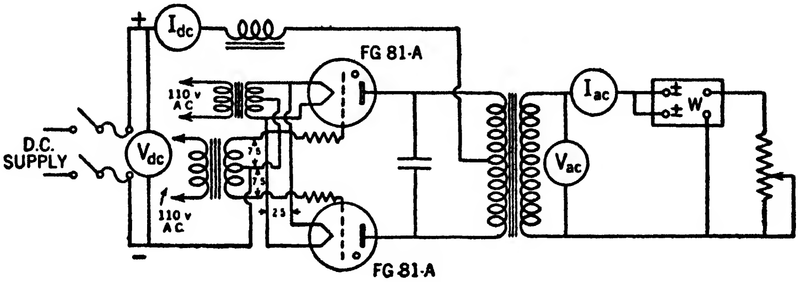


FIG. 11c.—Inverter circuit.

Exercises

1. Connect up the three-phase half-wave rectifier circuit shown in Fig. 11*a* and obtain data for and plot curves of efficiency and d-c load voltage vs. d-c output power.

2. Obtain oscillograms of (*a*) the current of each tube, (*b*) load current, and (*c*) voltage input to filter.

3. Connect up the three-phase half-wave rectifier shown in Fig. 11*b* and repeat Exercises 1 and 2.

4. Connect up the inverter circuit of Fig. 11*c* and plot a curve of efficiency vs. power output.

5. Obtain oscillograms of wave forms of various points along the inverter circuit.

References

DOW, "Fundamentals of Engineering Electronics," pp. 480–504.
EASTMAN, "Fundamentals of Vacuum Tubes," 2d ed., pp. 166–174.
FINK, "Engineering Electronics," pp. 255–270.
HENNEY, "Electron Tubes in Industry," 2d ed., pp. 176–182, 238–244.
MIT STAFF, "Applied Electronics," pp. 330–376.
MILLMAN and SEELY, "Electronics," pp. 381–413.
MORECROFT, "Electron Tubes," pp. 192–197.
REED and CORCORAN, "Electrical Engineering Experiments," pp. 483–485.
REICH, "Principles of Electron Tubes," pp. 292–300.
——— "Theory and Application of Electron Tubes," 2d ed., pp. 491–505.
TERMAN, "Fundamentals of Radio," pp. 266.
——— "Radio Engineering," 2d ed., pp. 480–482.
——— "Radio Engineers' Handbook," pp. 593–599.

EXPERIMENT 12

PHOTOTUBES AND PHOTOCELLS

There are three general classes of photosensitive devices, viz., photoelectric tubes, photovoltaic cells, and photoconductive cells.

Photoelectric tubes are the most used class of photosensitive devices. They are also known as photoemissive tubes and phototubes, the latter being the more common term. Phototubes are diodes in that they contain only two electrodes, a cathode and an anode. These electrodes, however, do not bear any close resemblance to those of the high-vacuum thermionic diode. The cathode is of relatively large surface in order to obtain maximum emission. It is usually constructed in the form of a half-cylinder, which ranges in size from 0.5 to 2.5 sq. in. for various types of commercial phototubes. The half-cylinder is made of nickel, copper, or silver and is coated with a material which possesses a low work function. Cesium oxide, which responds well to visible and infrared light, is the most common cathode material. The anode is a straight cylindrical wire of small cross section, lying along the center line of the half-cylinder. The anode is made as small as possible in order to prevent appreciable shading of the cathode surface.

Sketches of the electrodes of a typical phototube are shown in Fig. 12*a*.

There are two distinct types of phototubes: high-vacuum and gas-filled tubes. Gas-filled tubes are more sensitive than high-vacuum tubes, but they are more easily damaged by overloads and their characteristics are not as stable as those of the high-vacuum type. From the foregoing statements it follows that gas phototubes are more suitable where large sensitivity is necessary and precision is not at a great premium. The motion-picture industry employs gas phototubes in connection with talking pictures. High-vacuum phototubes are used in connection with work that requires higher precision than that obtainable by gas tubes, such as light measurements, etc.

Phototubes, whether they be gas-filled or high-vacuum, require a difference in potential between cathode and anode in order that electrons flow from cathode to anode. The magnitude of the current is controlled by the amount of photoelectric emission.

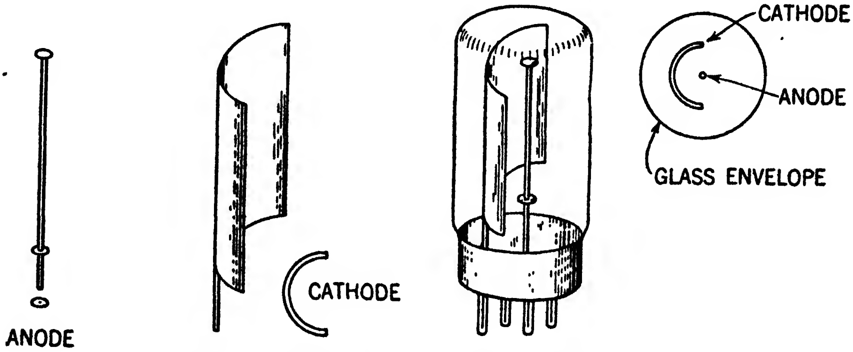


Fig. 12a.—Internal structure of a typical phototube.

The photovoltaic cell differs from the phototube in that it generates an electromotive force when light rays impinge upon it. It is a device that transforms light energy directly into electrical energy. The exact nature of the conversion is not understood. There are several types of photovoltaic cells, but only two are of any commercial importance, viz., iron-selenium cells (photronic cells) and copper-oxide cells (photox cells).

The iron-selenium cell consists basically of a thin layer of iron-selenide coated on an iron disk, which in turn is coated with a translucent metal and mounted firmly in a suitable insulated case containing a transparent window in order to allow light to fall upon the coating of translucent metal. Copper-oxide cells are very similar to iron-selenium cells.

They employ a copper disk instead of iron and the copper is oxidized on one side, which is coated with a translucent metal, such as a thin sheet of silver. Figure 12*b* illustrates the basic circuit components of both types of photovoltaic cells mentioned.

The output of a photovoltaic cell cannot be readily amplified by the conventional type of vacuum-tube amplifier circuit; thus its use is limited to the operation of very small relays, etc., that may be operated from the output of the cell itself without amplification. This is a serious disadvantage of the photovoltaic cell and renders it unsuitable for many applications.

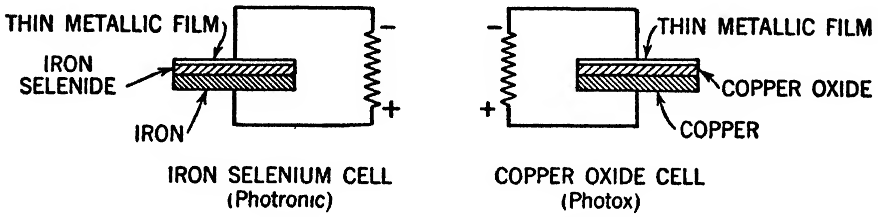


FIG. 12*b*.—Basic circuit elements of photovoltaic cells.

The photoconductive cell is a photosensitive device which might be described as a nonlinear circuit element. The resistance of a photoconductive cell is a function of light falling on it.

Two types of photoconductive cells are selenium cells and thalofide cells. Because of the small commercial value of these cells, they will not be discussed further.

In view of the fact that phototubes are by far the most used of photosensitive devices, the experimental procedure suggested herein will be concerned only with this type of photoelectric device.

The characteristics of a phototube may be determined by a few simple tests. It is usually desirable to show the anode current as a function of light intensity. A suitable setup for determining these characteristics is shown in Fig. 12*c*.

Special care must be taken in designing the photometer box. It must be lightproof throughout. Any extraneous light will give erroneous results. The filament of the standard lamp employed should be supplied with direct current from a storage battery and should not be allowed to vary over 1 per cent from the value specified to give rated candle power. In the selection of a standard lamp it is best to select one which approximates as nearly as possible a point source of light. A mask placed directly in front of the phototube, with an opening exposing only the window area of the phototube, will ensure greater precision in determining the luminous flux on the cathode.

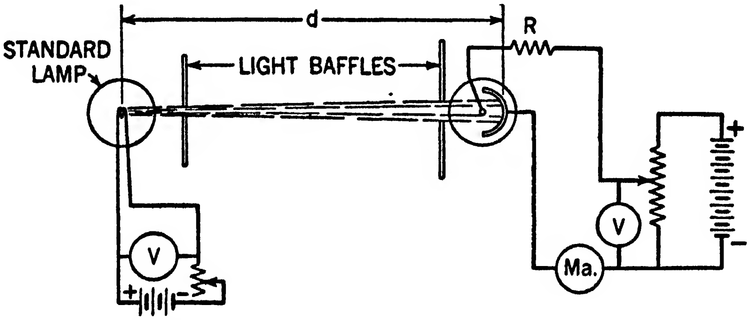


FIG. 12c.—Circuit arrangement for determining the static characteristics of a phototube.

The light flux in lumens falling on the cathode may be determined as follows:

$$F = \frac{IA}{d^2}$$

where F = light flux, lumens
I = luminous intensity of light source expressed, candles
A = area of cathode window, sq. in.
d = distance between lamp and phototube expressed, in.

The circuit connections employed in connection with the phototube are rather common. The protective resistance R should be 1 megohm or greater, and the plate potential should not be increased above the value specified by the manufacturer.

The first tube to be tested is an RCA 917 high-vacuum phototube. This tube has a maximum current rating of 30 μa. and a maximum voltage rating of 500 volts (direct current or peak alternating current). The window area is 1.0 sq. in.

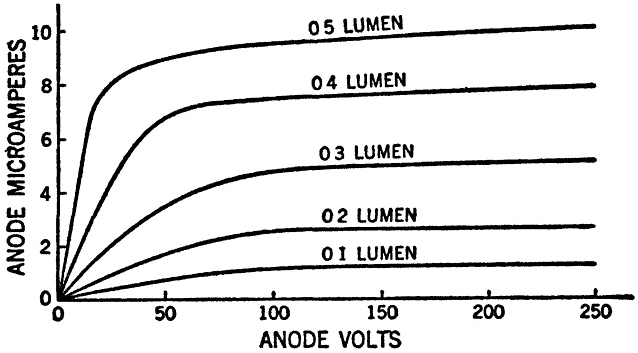


Fig. 12*d*.—Static characteristics of a high-vacuum phototube.

Typical characteristics for a high-vacuum phototube are shown in Fig. 12*d*.

The second tube to be considered is a RCA 918 gas phototube. This tube has a maximum current rating of 20 μa. and a maximum voltage rating of 90 volts (direct current or peak alternating current). The window area is 1.0 sq. in.

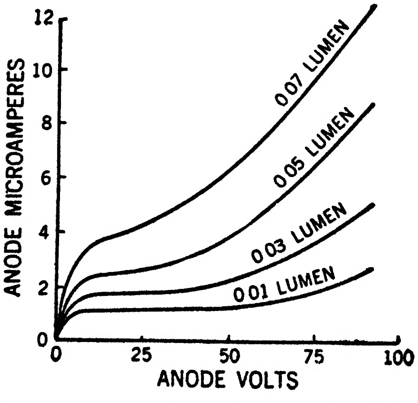


Fig. 12*e*.—Static characteristics of a gas phototube.

Typical characteristics for a gas phototube are shown in Fig. 12*e*.

Exercises

1. Obtain data for and plot curves of anode current vs. anode voltage for a type 917 high-vacuum phototube for the following values of light flux: 0.1, 0.2, 0.3, 0.4, and 0.5 lumen.

2. Obtain data for and plot curves for anode current vs. anode voltage for a type 918 gas phototube for the following values of light flux: 0.02, 0.04, 0.06, 0.08, and 0.1 lumen.

3. Plot a curve of microamperes per lumen vs. lumens for the 917. These values should be taken from the curves of Exercise 1 for an anode voltage of 200 volts.

4. Plot a curve of microamperes per lumen vs. lumens for the 918. These values should be taken from the curves of Exercise 2 for an anode voltage of 70 volts.

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