VACUUM TUBE
RECTIFIERS

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ELECTRONIC TECHNOLOGY SERIES

* *In Preparation*

VACUUM TUBE

RECTIFIERS

by

Alexander Schure Ph.D., Ed.D.

PREFACE

A large proportion of electronic equipment operates from an alternating current supply. Most of the circuits within such equipment require direct current and/or voltages for best results. An integral part of the design, therefore, often consists of a vacuum tube rectifier and its associated components. The function of the rectifier is to convert a portion of the alternating voltage input into the direct current sources required for the particular apparatus. When the requirements of the electronic equipment are critical, the rectifying system must be designed and protected against undesired fluctuations of voltage.

The purpose of this book is to provide the fundamental concepts of vacuum tube rectifier theory. A minimum of mathematical treatment has been employed, but the analyses are sufficiently extensive to permit the interested technician, practicing engineer, or advanced student to develop a full comprehension of the important facets of such theory. Specific attention is given to the basic principles of rectification; rectifiers; design ratings; needs, limitations, uses and characteristics of many rectifiers and circuits; and, the theory and calculations pertinent to rectifier and filter design data.

Educators agree that a thorough knowledge of fundamental theory is essential for the continued development of a sincere student. VACUUM TUBE RECTIFIERS content was selected with this philosophy as a guide—it *is* the thorough foundation, for both theoretical and practical applications.

Grateful acknowledgment is made to the staff of the New York Institute of Technology for its assistance in the preparation of the manuscript of this book.

New York, N.Y.
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A. S.

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Chapter

PHYSICAL CHARACTERISTICS OF RECTIFIERS

1. The Need for Rectification

Most power sources supply alternating current (ac) because of the numerous advantages connected with its generation and transmission. Practically all electron tube circuits and many industrial processes, however, require dc supply voltages and currents, and thus the need arises to convert alternating current to direct current. A rectifier is capable of changing alternating current into pulsating direct current; to obtain smooth dc power a filter system must be added. A complete rectifier system usually also contains a voltage divider for providing direct currents at various desired potentials, and a voltage regulator to minimize the effect of load and supply voltage variations on the dc output voltages.

2. Basic Principle of Rectification

Rectifiers change ac into pulsating dc by eliminating the negative half-cycles or alternating the ac voltage. Only a series of sinewave pulsations of positive polarity remain. An ideal rectifier may be thought of as a switch that closes a load circuit whenever the polarity of the alternating voltage is positive, and opens the circuit whenever the alternating voltage is of negative polarity. A switch operating with such synchronism would have effectively zero resistance for that half of the time when the circuit is closed during positive half-cycles and infinite resistance for the other

half of the time when the circuit is open during negative half-cycles. Practical rectifiers do not attain this goal, but come close to it. Some vacuum tube rectifiers may have almost infinite resistance during the nonconducting interval (back resistance), but the resistance during the conducting interval (forward re-

WHEN $E_b > 0$, $R_f = 0$
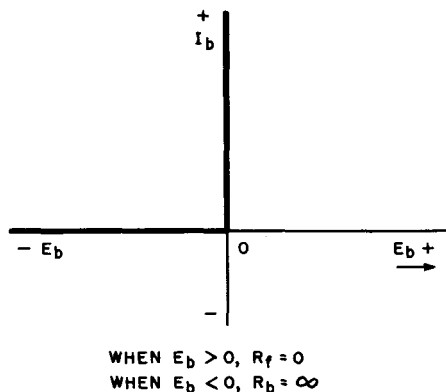WHEN $E_b < 0$, $R_b = \infty$

Fig. 1. The functioning of a diode which is ideal for rectification.

sistance) is never zero or even constant. Regardless of their approach to the ideal, all rectifiers must provide a one-way path for electric current; that is, conduction must take place primarily in one direction only. This is called *unilateral conduction,* or a *unidirectional* characteristic.

3. The Diode as Rectifier

A *diode* is a *device consisting of two elements* or electrodes: one is an electron emitter (cathode), the other an electron collector (anode or plate). Since electrons in a diode can flow only from emitter to collector, the diode provides unilateral conduction and hence, rectification. The voltage-current characteristics of an ideal diode and of three practical diodes are illustrated in Figs. 1 through 4.

Ideal Diode. For comparison, Fig. 1 illustrates the characteristic of an ideal diode. It acts like the synchronous switch discussed above. When the voltage (E_b) at the electron collector is negative, the back resistance (R_b) of the device is infinite and no current (I_b) can flow. When E_b is positive, however, the device conducts, the forward resistance (R_f) is zero and the current (I_b) is effectively infinite. In

practice, the current magnitude is limited, of course, by the internal resistance of the power source and the resistance of the load circuit.

Thermionic Vacuum Diode. The I_b-E_b characteristic of a thermionic vacuum diode is shown in Fig. 2. Such a diode consists
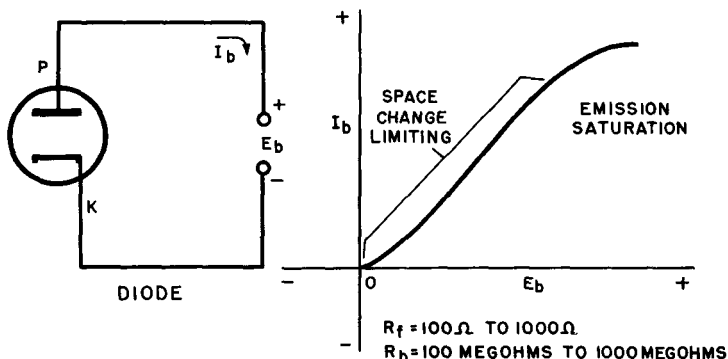

Fig. 2. Thermionic vacuum diode schematic and operation.

of a directly heated cathode (emitter) and a plate or anode (collector), both enclosed in a highly evacuated glass or metal envelope. When the cathode is heated to its proper operating temperature it emits from its surface a copious supply of electrons which form a negative space charge between cathode and plate. When a potential (E_b) is placed on the plate that is positive with respect to the cathode, electrons are attracted away from the space charge and travel toward the plate as a plate current (I_b). The higher the value of the positive plate voltage, the greater is the flow of plate current through the tube. At each plate voltage value, the total plate current that flows is limited by the amount of the negative space charge present. When the positive plate potential is made very high, however, a point is reached where the entire space charge is attracted toward the plate and electrons reach the plate in the same proportion as when they were emitted. The plate current then levels off and *emission saturation* takes place. Further increases in the positive plate voltage cannot cause an increase in the plate current since the entire supply emitted by the cathode is already being drawn to the plate. In practice, thermionic diodes are always operated in the space charge-limiting region to avoid damage to the cathode and to keep tube voltage drop (E_b) at a reasonable value.

When the plate voltage of a diode is made negative with respect to the cathode, the electrons in the space charge are strongly repelled from the negatively charged plate and some are actually driven back into the cathode. Since no electrons reach the plate, no plate current flows, and the tube acts essentially as an open circuit. From the above it may be concluded that electron flow within a diode is always from cathode to plate, provided the plate is made positive with respect to the cathode.

Since the plate current is limited when the diode conducts, the tube exhibits a certain forward resistance (R_f) defined as E_b/I_b for $E_b>0$. This forward resistance varies from about 100 to 1000 ohms for practical vacuum diodes. The back resistance (R_b) defined as E_b/I_b for $E_b<0$, has a range from about 100 to 1000 megohms, or about a million times as high as the forward resistance. Vacuum diodes have practically perfect unilateral conduction and effectively present an open circuit to negative plate voltages

Thermionic Gas Diode. The construction of a thermionic gas diode is similar to that of vacuum diodes, except that a certain amount of gas is purposely introduced into the tube envelope. Ordinarily mercury vapor in equilibrium with liquid mercury is used, but occasionally an inert gas such as helium, neon, or argon may be employed. The presence of a gas radically affects the behavior of the tube.

The I_b-E_b characteristic of a typical gas diode is illustrated in Fig. 3. Note that plate current (I_b) increases gradually at first with increasing (positive) plate voltage, as in a vacuum diode. At a certain critical plate voltage, known variously as ionization potential, striking potential, or firing point, the plate current suddenly increases to a very large value, almost equal to the total electron emission of the cathode. What happens is essentially this: at a certain value of the plate voltage (striking potential), electrons colliding with gas molecules in their journey to the plate attain enough speed and energy to strip off one or more electrons from the outer shell of the molecules. This leaves the affected molecules with a net positive charge and they are then known as positive ions. The electrons freed from the gas molecules join the original electron stream and liberate still more electrons by colliding with other gas molecules. This process, called ionization, is cumulative and results in the sudden, dramatic increase in the plate current, evident in the I_b-E_b characteristic.

Although full electron emission is reached almost at once with the onset of ionization, the large emission current cannot be

utilized in practice because of the presence of the positive gas ions. These positive ions drift toward the negative cathode, where they combine with electrons to re-form neutral gas molecules. If the voltage across the tube is too high (more than about 22 volts), the heavy, positive gas ions strike the cathode with force which
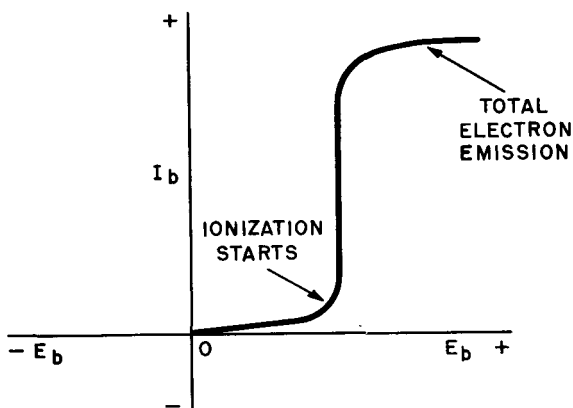

Fig. 3. Graph showing interaction of electrons and gas in a thermionic gas diode.

$R_f = 1.5\,\Omega$ TO $100\,\Omega$
R_b ABOVE 100 MEGOHMS

eventually destroys it. For this reason the external circuit of a gas rectifier is always arranged to keep the tube voltage drop at about 15 volts and the plate current safely below the total cathode emission.

Once ionization has started, the action maintains itself at plate-to-cathode voltage considerably lower than the ionization potential. There is a minimum voltage called the de-ionizing or extinction potential, below which ionization cannot be maintained. The gas then de-ionizes and conduction stops. The tube acts as an electronic switch which closes at the striking potential, permitting a large current to flow, and opens at the extinction potential blocking the current flow.

When a negative potential is applied at the plate of a gas diode, ionization cannot take place and the electrons in the space charge are repelled from the plate, just as in a vacuum diode. Then the tube has the unidirectional characteristic required for rectification. Caution must be exercised when placing gas tubes in ac circuits where the polarity of the plate voltage continually reverses. If the negative (or inverse) plate voltage is too high, or the frequency of the ac supply is too great, the positive gas ions may not have

sufficient time to combine with free electrons and stop ionization before reaching the plate. The gas ions will then strike the nega-tive plate, constituting an inverse current flow, or *arcback*. The tube carries a heavy current on *both* ac half-cycles, which might destroy it. It is important to know the *inverse-voltage rating* of the tube at the operating frequency.

Arcback is also affected by the *ambient temperature* (and cor-responding mercury-vapor pressure) of the tube. If the tempera-ture (and pressure) is too high, the inverse voltage at which arcback occurs becomes abnormally low. If the temperature (and pressure) is too low, the intensity of ionization is reduced to a point where the space charge is not completely neutralized and the plate current is low. Moreover, the voltage drop across the tube becomes excessive at low temperatures, and cathode disin-tegration may occur. Normally, the voltage drop across the tube is low (between 12 and 20 volts) and remains constant for large variations of the plate current. This means that most of the available supply voltage will appear as rectified output voltage and little will be wasted across the tube. The low internal tube drop is one of the big advantages of gas diodes.

Among the disadvantages of gas diodes, besides the somewhat erratic behavior and arcback, is the *preheating time*. The cathodes of mercury-vapor tubes must be brought to normal operating temperatures for one to two minutes before the plate voltage is applied to permit the mercury to be completely vaporized and electron emission to reach its full value. Otherwise, the tube cannot carry its rated plate current and may be damaged.

Because of the relatively heavy plate currents and low voltage drop of gas-filled diodes their forward resistance (R_f) is low, about 1.5 to 100 ohms for representative commercial types. The back resistance (R_b) in the absence of arcback is several hundred megohms. With the exception of the disadvantages stated, there-fore, gas-filled diodes make excellent rectifiers.

Crystal Diode. Another important category of diode rectifiers is the crystal or semiconductor diodes. Current conduction is attained in certain semiconductor crystals such as germanium and silicon by a process too complex to be covered here; suffice it to say that definite amounts of impurities (doping) introduced into these crystals will permit an electron current to flow from emitter to collector, but *not* in the opposite direction. When low positive voltages (forward bias) are applied to the collector, relatively large forward currents flow from emitter to collector, as shown in Fig. 4. The forward resistance of crystal diodes therefore is low, from about 1 to 500 ohms.

When a voltage of opposite polarity (reverse bias) is applied to the crystal diode, a small reverse current (I_s) flows. This reverse current is merely a few microamperes as long as the reverse bias is not made too high. The corresponding back resistance (R_b) varies from about 100 kilohms to several megohms. When the reverse voltage is made very high a breakdown occurs and the reverse current suddenly increases to relatively large values.
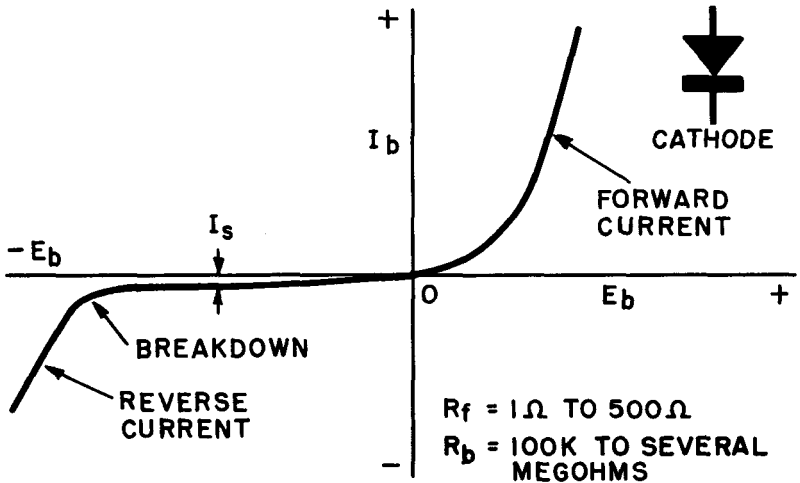

Fig. 4. Characteristics of a crystal, or semiconductor, diode.

This is shown in Fig. 4, where for the purposes of clarity the magnitude of the reverse current has been greatly exaggerated. When the excessive negative voltage is removed, conditions return to normal.

While the circuits of crystal diode rectifiers are similar to those of vacuum diodes, a considerable number of changes must be made in practice to take care of different voltage and current requirements.

4. Triode Rectifiers

Grid-controlled tubes, or triodes, are sometimes used as rectifiers. The use of the grid permits regulating the power delivered to the load by controlling the time during which the current flows

during each cycle. The tubes used for this purpose are almost exclusively gas-filled types called thyratrons. Since this volume is primarily concerned with vacuum tubes, thyratron rectifiers will not be covered here.

5. Design Ratings of Thermionic Diodes

The important design ratings that determine the performance of hot-cathode (thermionic) diode rectifiers and hence influence the selection of tubes for a specific type of service and circuit, are:

(a) The maximum allowable peak plate current (the maximum current which may be allowed to flow at any time) which is determined by the maximum usable cathode emission over the life of the tube. The cathode must at all times maintain a full space charge, hence, the peak plate current is always less than the total emission of the cathode during the useful life of the tube. .

(b) The maximum allowable average plate current (the maximum value of average plate current which may be carried continuously without overheating), or dc output current. This can never exceed one-half of the peak plate current, since current flows through the rectifier tube only half the time, during positive ac half-cycles. The maximum allowable value of the average plate current depends on the permissible plate dissipation (heating of the plate) of the tube. Its value usually turns out to be considerably less than one-half of the peak plate current.

' (c) The maximum allowable inverse plate voltage (the largest voltage which may occur at the negative peak of the cycle without breakdown). It is also the largest negative voltage that may be applied safely to this tube. Its value also determines the maximum positive plate voltage that may be applied to the tube, and thus to the dc output voltage. The exact dc output voltage obtained from the tube depends on the rectifier circuit (as we shall see later), but it is generally less than the allowable inverse plate voltage.

(d) For high-vacuum diodes the voltage drop across the tube (the voltage across the tube during the conduction interval) is determined by the permissible plate current; for mercury-vapor diodes it is more or less constant, as explained before. The product of the tube voltage drop and the allowable plate current is the amount of *plate dissipation* that must be designed into the tube if it is to handle the rated current.* The tube voltage drop is also an important factor in determining the *regulation*† of the

dc output voltage, that is, the value of the dc output voltage for varying load currents. As we have seen, the low, constant tube drop of mercury-vapor tubes provides the advantage of wasting little voltage across the tube, and of keeping the regulation for varying load currents to a minimum change.

Actual design ratings and other data useful for various representative types of high-vacuum and gas-filled diodes are listed in Chap. 5, Table I.

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† $\text{Regulation} = \dfrac{\text{no-load voltage} - \text{full-load voltage}}{\text{full-load voltage}} \times 100$

* This statement is not *strictly* correct. The determination of actual plate dissipation in a tube is fairly complicated and depends on the type of rectifier and the type of output filter used. For capacitor input filters, the dissipation per plate is:

$$W_p = K \; e_d \; I_b$$

where W_p = watts dissipation per plate

e_d = peak voltage drops across the diode with peak current flowing

I_b = dc per plate.

K = a constant having the value 0.84 for vacuum diodes, 0.90 for semiconductor diodes and 1.00 for gas diodes.

For a rectifier with a choke input filter the dissipation is:

$$W_p = \frac{K}{N} \, I_o \; e_d$$

where N = 2 for single-phase full-wave and 1ϕ bridge circuits

N = 3 for three-phase half-wave and 3ϕ bridge

N = 6 for three-phase full-wave

I_o = dc output

e_d = diode drop at current I_o

K = a constant whose value depends upon the ratio of peak ripple current to dc. Curves showing the value of this constant are available if desired.

Thus a diode must be designed for the dissipation which would result in the *worst case—with a capacitor input filter. For vacuum diodes the formula then would be:*

$$W_p = 0.84 \; e_d \; I_b$$

6. Diode Rectifier Circuits

The type of circuit in which diode rectifier tubes are used determines the attainable dc output and voltages, the smoothness of the dc, the amount of filtering required, and other important factors. Rectifier circuits may be classified as either single-phase or polyphase, depending on whether the ac power has one or more phases.

Single-phase circuits are used primarily for the relatively small plate-power requirements of various electronic devices; radio and television sets, public address systems. In contrast, polyphase rectifier circuits are used for high-power requirements demanding economical operation. The capabilities of power transformers and tubes are more fully utilized in polyphase circuits. They have the additional advantage of delivering a dc output that is smoother and requires less filtering than the dc of single-phase circuits.

7. Review Questions

(1) Explain the basic function of a rectifier and the operation of an ideal rectifier.

(2) What is a diode? Distinguish between various types and describe their physical characteristics.

(3) How does the I_b-E_b characteristic of a gas diode differ from that of a vacuum diode, and why? How do both differ from the characteristic of an ideal diode? What are the advantages of each?

(4) What is meant by the breakdown of a crystal diode and how will the reverse current affect rectifier operation?

(5) Define forward resistance and back resistance and state the approximate range of values for each type of diode. What is their significance for rectifier operation?

(6) Define maximum allowable peak plate current, average plate current, peak inverse voltage and tube voltage drop; explain the significance of these tube design ratings.

(7) Distinguish between single-phase and polyphase rectifiers and describe the major uses and advantages of each.

Chapter 2

SINGLE-PHASE RECTIFIERS

8. The Half-Wave Rectifier

A single diode is known as a half-wave rectifier since it permits current to pass only during the positive half-cycle of an applied ac voltage. A half-wave rectifier circuit with its input and output waveforms is shown in Fig. 5. An ac input voltage, usually derived from a power transformer, is applied in series with the diode rectifier and a load resistance. Plate current (I_b) flows through the tube and load every other half-cycle during positive alternations of the input voltage, and is blocked during the negative half-cycles. Although unidirectional, the load current is *not* dc because of its pulsations in amplitude. It can be shown mathematically that these pulsations contain both a dc component and an ac component, known as *ripple*. The current can be converted into a steady dc by filtering out the ac ripple with suitable smoothing filters. (See Chap. 4.)

It is evident from Fig. 5 that during the time that plate current flows, its instantaneous magnitude follows exactly the changes in the applied voltage. The shape of the plate-current waveform, therefore, is an exact replica of the ac input voltage waveform during positive half-cycles. The plate current develops a dc output voltage across the load resistance as it flows through it. The waveform (not shown) is exactly the same as that of the ac input voltage, except that only the positive half-cycles are reproduced. Since one-half of the input voltage is lost, the efficiency of the half-wave rectifier is low.

When the *plate-current waveform* of the half-wave rectifier (Fig. 5) is averaged out over one complete cycle, it is found that the average current flowing through the tube is only 0.318 times

the peak amplitude of the current. This means that a line drawn at 0.318 times the height of the peak current amplitude represents the average or steady direct current flowing through the tube. Exactly the same is true for the dc output voltage. The average value of the pulsating dc output voltage is again only 0.318 times the value of the peak voltage appearing across the transformer secondary winding. (This theoretical value neglects the voltage drop in the transformer secondary and the voltage drop lost across the tube.) If the load draws a considerable current, the output voltage drops to an even lower value because of the increased drops across the tube and the transformer secondary.

Example: As a practical example, let us consider the half-wave rectifier circuit shown in Fig. 6, which employs a type 6W4-GT vacuum diode and a step-up power transformer with a 350-volt secondary plate winding. Another secondary, called the filament winding, supplies 6.3 volts ac to the heater of the rectifier tube.

The root-mean-square (rms) value of the applied plate voltage across the transformer secondary must be multiplied by 1.414 to obtain the peak value of the applied ac voltage. We thus obtain 1.414 x 350, or 495 volts peak ac voltage. The average or dc output voltage, however, is only 0.318 times the peak value, or 0.318 x 495=156 volts. If we multiply the two factors together right away, we would see that the dc output voltage is only 0.45 times the rms value of the applied ac voltage (i.e., 1.414 x 0.318=0.45). Equivalently, the rms value of the applied ac voltage must be 1/0.45, or 2.22 times the value of the desired dc output voltage. The dc output voltage of 156 volts in Fig. 6 represents a theoretical or maximum value. In practice, the voltage will be considerably lower because of the tube voltage drop and the voltage lost in the transformer secondary winding which we have neglected. Moreover, when considerable load current is drawn, these voltage drops will increase and subtract still more from the available dc output voltage. However, the no-load dc output voltage of the circuit in Fig. 6 may actually rise above the rms value of the applied ac voltage when a suitable filter is connected across the output of the rectifier. This is because most filters employ capacitors that charge up to the peak value of the output-voltage pulsations and substantially maintain this value when the plate current drops to zero during negative half-cycles. The poor regulation of the circuit will not maintain a high output voltage when large load currents are drawn through the tube.

Limitations and Uses. We have already seen that a half-wave rectifier makes poor use of the ac supply, since it delivers power only half the time, during positive alternations of the supply voltage. As a result the ratio of the peak currents and voltages to the average current is high, the efficiency low, and the regulation poor. Half-wave rectifiers are not used, therefore, when more than a few-milliamperes load current is required. They are suitable
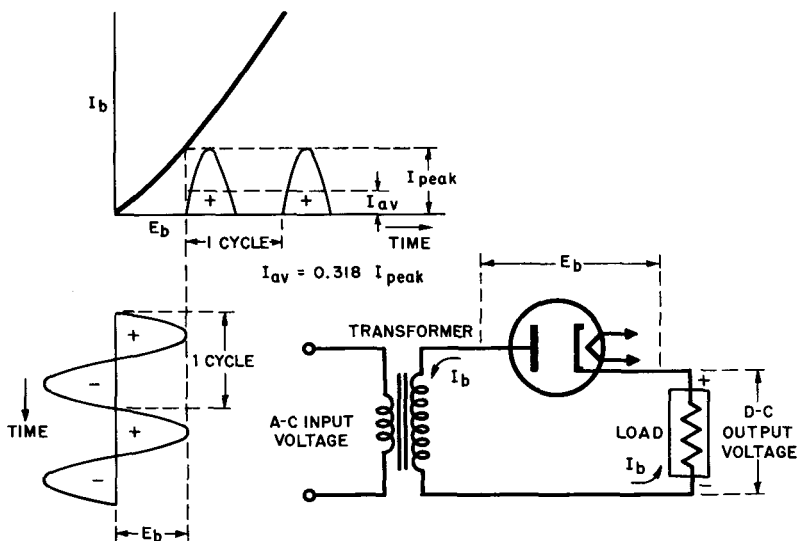
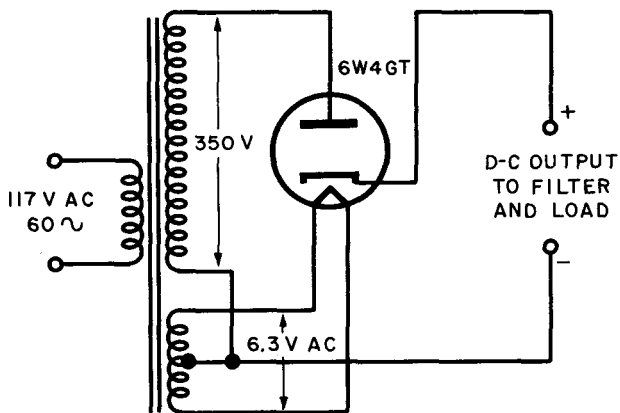Fig. 5. Basic circuit and load current waveform of half-wave rectifier.

Fig. 6. Practical half-wave rectifier circuit.

for applications requiring a small current drain, such as accelerating anode (ultor voltage) supply of oscilloscopes and TV picture tubes.

Perhaps the largest application of half-wave rectifiers is for the power supplies of ac-dc radios. Probably better than 90% of the radios made today use half-wave rectifiers because the current drain is relatively low and the 60-cycle response is very poor. Therefore, the 60-cycle hum voltage is not very troublesome.

Another disadvantage of half-wave rectifiers is that the output current pulsates at the same frequency as the ac power line. Elaborate filter circuits are required to eliminate this low-frequency ripple and produce smooth direct current. Finally, note in Figs. 5 and 6 that the rectified output current flows through the secondary winding of the power transformer. This results in a dc magnetization which saturates the core of the power transformer. The efficiency of the transformer is considerably reduced and its expense goes up. The full-wave and other rectifier circuits, to be discussed next, avoid saturating the core of the power transformer by balancing out the dc magnetization with opposing currents.

9. The Full-Wave Rectifier

Plate current can be made to flow during the full cycle of the ac supply voltage by the use of two diode half-wave rectifiers in a full-wave rectifier circuit (Fig. 7). The tubes alternately supply rectified current to the load during both halves of the ac input voltage in such a way that the load current always flows in the same direction.

Note in Fig. 7 that the cathodes of the two rectifier tubes are tied together and the common junction is connected to one side of the load resistor. The other end of the load is connected to the centertap (C) of the secondary winding of the power transformer. (Two separate windings can be used instead of a single center-tapped winding.) Only one-half of the transformer secondary voltage appears between plate and cathode of each rectifier tube since each tube is connected between one end of the winding and a point midway in voltage (the centertap). This means that the transformer secondary winding must supply a plate-to-plate voltage that is twice the value of the plate voltage required for each tube. To provide sufficient plate and output voltage, the transformer usually has a considerable step-up ratio between primary and secondary winding.

When an ac voltage is applied to the primary winding of the transformer, a voltage of the same shape (shown in Fig. 7), but enlarged in amplitude appears across the secondary winding. This secondary voltage is split in half, one-half appearing across V1 in series with the load, the other half appearing across V2 in series with the load. Assume that the polarities cause the top of the transformer secondary to be initially positive during the first
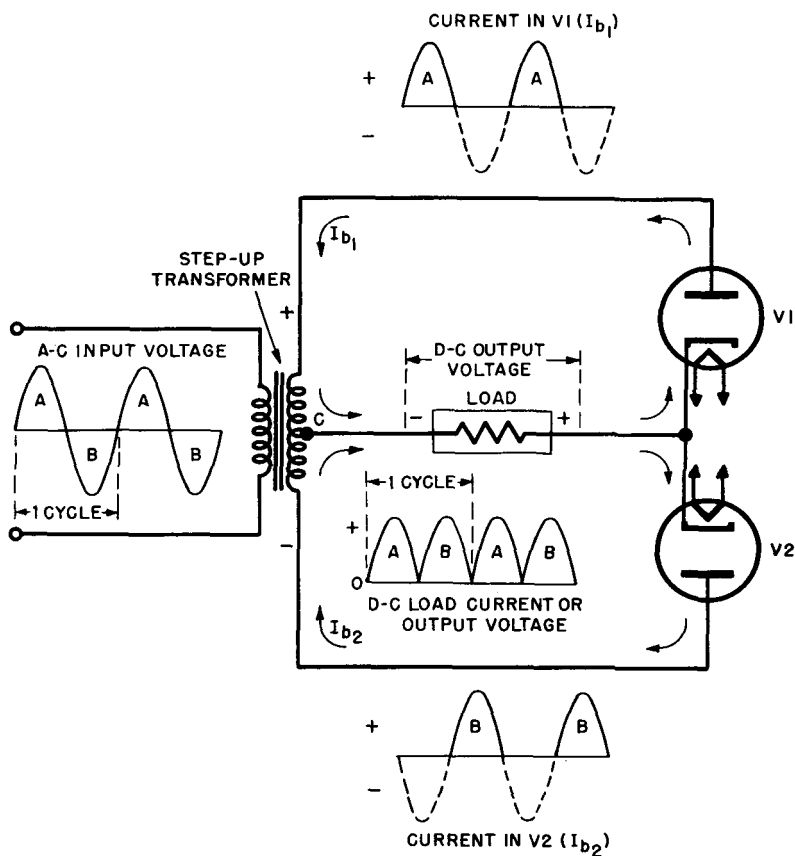
CURRENT IN VI (I_{b_1})

STEP-UP
TRANSFORMER

A-C INPUT VOLTAGE

D-C OUTPUT
VOLTAGE

LOAD

VI

V2

1 CYCLE

1 CYCLE

D-C LOAD CURRENT OR
OUTPUT VOLTAGE

I_{b_2}

CURRENT IN V2 (I_{b_2})

Fig. 7. Basic circuit and waveforms of full-wave rectifier.

half-cycle, (A), of the ac supply voltage. The plate of VI is therefore positive with respect to the cathode junction. A plate current (I_{b1}) flows from the cathode to the plate of VI, through the top half of the transformer secondary, and through the load, in the direction indicated by the top arrows. This current develops a voltage across the load, indicated by the half-cycle (A) in the output voltage waveform (Fig. 7). The direction of the current makes the cathode-end of the load positive. (Electron current flows from minus to plus.)

Note that during this first half-cycle (A) of the input voltage, the bottom of the transformer secondary is negative with respect

to the centertap, hence the plate of V2 is negative. No plate current flows through V2 during this half-cycle.

During the second half-cycle (B) of the ac input voltage the top of the transformer secondary will be negative with respect to the centertap. The plate of V1 is negative with respect to its cathode and no plate current flows. This is indicated by the dotted line for the negative half-cycle of I_{b1}. During this same half-cycle, the bottom of the secondary winding is positive as is the plate of V2 with respect to the cathode junction. Consequently a plate current (I_{b2}) flows from the cathode to the plate of V2, then through the bottom half of the transformer secondary and through the load, in the direction indicated by the bottom arrows. It is evident that the current flows in the same direction through the load as it did during the previous half-cycle. Thus two positive half-cycles (A and B) appear across the load during one ac cycle of the input voltage.

During succeeding half-cycles (A and B) of the input voltage, V1 and V2 continue to conduct alternately, each permitting current to flow during the half-cycle where its plate is positive with respect to the cathode junction. Since there are two output pulses for each complete cycle of the input voltage, the current through the load is a series of unidirectional pulses which have a frequency twice that of the ac supply frequency. With the ripple frequency twice that of the ac input voltage and the current much less discontinuous than that of the half-wave rectifier, the pulsations are easily smoothed out by a suitable filter circuit. Furthermore, the efficiency of the full-wave rectifier is far greater than that of the half-wave type.

Since there are two output pulses for each ac cycle, compared to only one in the half-wave rectifier, the average current value of the full-wave rectifier is twice that of the half-wave rectifier, or 0.636 times the peak current value. Similarly, the average of the output voltage is twice that of the half-wave rectifier for the same input, or 0.636 times the peak voltage value. Since the peak voltage is 1.414 times the rms voltage across the transformer secondary, the average output voltage is 1.414 x 0.636, or 0.9 times the rms value of the secondary voltage (across one-half of the winding). Equivalently, the rms voltage across one-half of the transformer secondary must be 1/0.9 or 1.1 times the desired average value of the output voltage, or only one-half that required for a half-wave rectifier. (Across the entire secondary the value is the same as for a half-wave rectifier.)

Note in Fig. 7 that when V1 is conducting, its cathode is at a

positive potential almost equal to the peak value of the transformer secondary voltage (except for the tube drop). The cathode of (nonconducting) V2, therefore, is at the same high positive potential, while at the same time its plate is at a high negative potential equal to the peak value of the transformer secondary
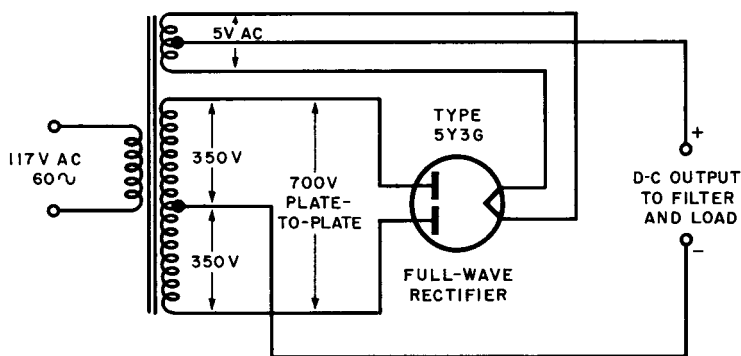

Fig. 8. Practical full-wave rectifier circuit.

voltage. The same is .true when V2 is conducting and V1 is nonconducting. The rectifier tube used in a full-wave circuit must therefore be able to withstand an inverse voltage of almost twice the peak of the secondary voltage applied to each tube separately.

Example: Let us compare the practical full-wave rectifier circuit shown in Fig. 8 with the half-wave rectifier illustrated in Fig. 6. A type 5Y3-G duplex diode (combining two diodes in one envelope) is used in connection with a centertapped step-up transformer. The transformer secondary supplies 350 volts to each plate, or a total of 700 volts, plate-to-plate. A separate 5-volt secondary winding supplies the filament of the tube. The centertapped heater winding is the ideal circuit, but many manufacturers dispense with the centertap (for cost reasons) and B+ is taken directly from one side of the heater.

The (theoretical) average value of the dc output voltage is 0.9 times the rms value of the plate voltage, or 0.9 x 350=315 volts. This is about twice the average dc voltage obtained in the half-wave rectifier for the same rms plate voltage. (For two tubes the plate-to-plate voltage is 700 volts, or double the value required for the half-wave rectifier circuit.) The theoretical value of 315 volts is not realized in practice because of the voltage drops across the tube and transformer secondary. Tube manuals list an actual value of 270 volts average dc output voltage (into a choke-input filter) for a load current of 75 ma. When the load current is increased to its maximum value of 150 ma, the regulation of the

circuit (additional tube and transformer drops) *reduces the* available output voltage by another 25 volts, or to about 245 volts. This is still higher than the output voltage obtained for the half-wave rectifier circuit. Also, the current drain permissible for the full-wave circuit is far higher than that of the equivalent half-wave circuit.

Advantages and Uses. Although we have neglected to mention it thus far, you may have noted in Fig. 7 that the individual tube currents of the full-wave rectifier flow in opposite directions through the secondary winding of the power transformer. This avoids the dc magnetization and resultant saturation of the transformer core, one of the serious defects of the half-wave circuit. This advantage, combined with the high-efficiency high-
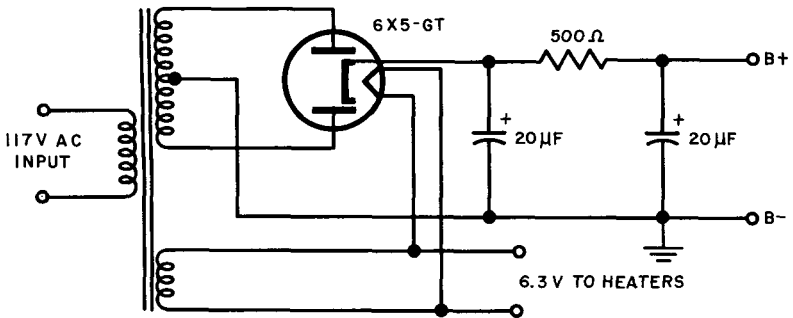
Fig. 9. Rectifier tube with indirectly heated cathode.

permissible current drain, less ripple (at twice the ac frequency), and relatively high dc output voltage, makes the full-wave rectifier circuit suitable for a wide variety of applications in electronics. It is the standard circuit for low-power applications.

A slight variation (Fig. 9) in conventional rectifier circuits is found in the use of rectifier tubes having an indirectly heated cathode. When using such a tube as the 6X5-GT, it is unnecessary to have a separate filament or heater winding. The heater of this tube is supplied directly from the same heater winding that feeds *the other tubes in the associated circuitry.*

10. The Full-Wave Bridge Rectifier

The need for a centertapped power transformer is eliminated by the bridge rectifier, in which four diodes are used (Fig. 10). As illustrated, the input to the bridge circuit is applied to diag-

onally opposite corners of the network, while the output to the load is taken from the remaining two corners. The circuit is a full-wave type, since both halves of the ac input cycle are utilized. Two tubes in series carry the load current on alternate half-cycles. The bridge circuit now makes maximum use of the power supply.

Operation. Assume that the polarities are such that the top of *the transformer secondary winding is initially positive during the* first half-cycle (A) of the ac supply voltage. During this half-cycle
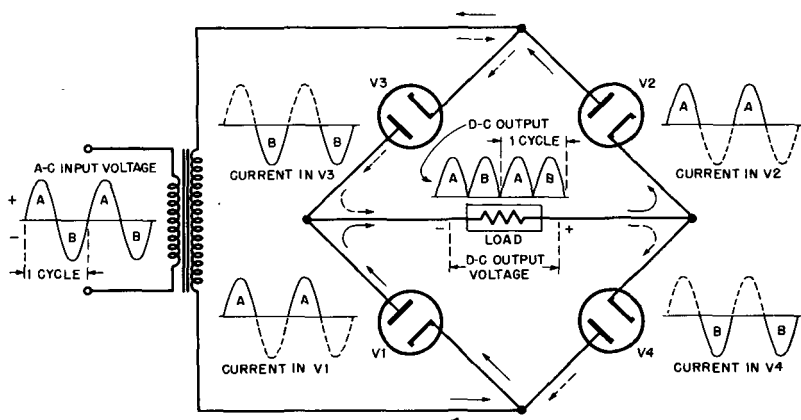
Fig. 10. Basic circuit and waveforms of full-wave bridge rectifier.

the transformer secondary voltage may be considered to be applied across a series circuit, consisting of rectifier tube V1, the load resistor, and tube V2. Since the cathode of V1 is at maximum negative potential and the plate of V2 at maximum positive potential, an electron current flows through V1, the load resistor V2, and the transformer secondary, in the direction indicated by the solid arrows. During this first half-cycle the plates of tubes V3 and V4 are more negative than their cathodes and, hence, these do not conduct. Thus, the half-cycle (A) is reproduced by the conducting tubes V1 and V2 and across the load resistor, as illustrated by the waveforms (A) in Fig. 10.

One half-cycle (B) later, the top of the transformer secondary is negative and the bottom is positive, so that tubes V1 and V2 cannot conduct. However, the plates of V3 and V4 are now positive with respect to their cathodes and an electron current flows through V3, the load resistor, and the transformer secondary,

in the direction indicated by the dotted arrows. Thus, the second half-cycle (B) of the supply voltage is reproduced by conducting tubes V3 and V4 and across the load resistor, as shown by the waveforms (N) in Fig. 10. Note that the current pulses (A and B) flow through the load resistor in the same direction during both half-cycles, each pulse flowing from the V1-V3 plate junction toward the V2-V4 cathode junction of the load resistor. This makes the plate-end of the load resistor negative and the cathode-end positive, since electron current flows from minus to plus. The current pulses thus are unidirectional and their ripple frequency is twice that of the ac supply frequency, just as for the conventional full-wave rectifier circuit.

Advantages and Limitations. One advantage of the bridge rectifier over the conventional full-wave rectifier is that the bridge circuit produces a voltage output nearly twice that of the full-wave circuit for a given power transformer. In the full-wave rectifier the transformer secondary voltage is split and only one-half of the total is applied to the conducting tube. In the bridge circuit, however, the full voltage of the secondary winding is applied across the two conducting tubes during each half-cycle. Therefore, the voltage developed across the load resistor is twice that of a conventional full-wave circuit less the voltage drop wasted across the two conducting tubes. The average dc output voltage of the bridge rectifier is 0.9 times the rms value of the full transformer secondary voltage, compared to 0.9 times the rms value of half the secondary voltage (one side of centertap) for the ordinary full-wave rectifier. It is clear that the bridge rectifier makes better use of the transformer than the full-wave rectifier circuit.

A second advantage of the bridge circuit is that the inverse voltage impressed across each (nonconducting) tube is only half that applied across each tube of a full-wave rectifier. This is evident from the circuit diagram (Fig. 10) inasmuch as two tubes in series divide the transformer secondary voltage between them. The inverse voltage rating of tubes used in bridge rectifiers need be only half of that required for conventional full-wave rectifier tubes. Hence the bridge rectifier is popular for high-voltage work.

One disadvantage of the bridge circuit is that four tubes are required, which makes the operation somewhat uneconomical. (As we shall see in a moment, two tubes cannot be combined in one envelope because the cathodes are not at the same potential and therefore cannot be connected in parallel.)

More detrimental to the utility of bridge rectifiers is the fact that the cathodes (or filaments) of the tubes are not at the same

potential. An analysis of Fig. 10 shows that the cathodes of V2 and V4 are at the same voltage, since they are connected together, but the cathodes of V1 and V3 are at different potentials, both with respect to each other and also to the cathode of V2 or V4. The bridge circuit requires three separate filament transformers (or secondary windings) which must be well insulated from each other and from the ground connection. This makes use of the circuit a rarely exercised luxury. This is true in tubes with directly heated cathodes, but the obstacle is overcome in tubes with indirectly heated cathodes such as used with the 6X4.

The last disadvantage cited does not apply to diodes not requiring cathode heating power, such as metallic-oxide rectifiers and crystal diodes. The bridge circuit is therefore widely used with selenium, copper-oxide, and crystal rectifiers.

11. Voltage-Multiplying Circuits

Diode rectifiers can be made to deliver dc voltages that are twice or several times the peak amplitude of the alternating voltage supplied to the tubes. This is generally done by charging capacitors (through rectifiers on alternate ac half-cycles) with polarities that cause the dc voltages developed to add in series. Voltage multipliers are especially useful in high-voltage circuits where it is inconvenient to employ a transformer with a sufficiently high secondary voltage, and in transformerless receiver circuits operated directly from the 117-volt ac source. The following paragraphs describe several circuits frequently used for such purposes.

12. Full-Wave Voltage Doubler

The full-wave voltage doubler shown in Fig. 11 is capable of delivering a dc output voltage that is twice the peak voltage of the applied alternating voltage. Basically, the circuit is so arranged that the output voltages of the two half-wave rectifiers (V1 and V2) are in series. It is a full-wave doubler because the rectifier tubes pass current to the load on each half of the input ac cycle.

The action of the full-wave doubler is as follows. When the top of the transformer secondary winding is instantaneously positive [during positive half-cycle (A)], diode V1 passes a current in the direction of the solid arrows, which charges up capacitor C1 so that its upper plate becomes positive. (You can see that the upper plate becomes positively charged since electrons flow out from

it to the cathode of V1 leaving an excessive positive charge, while electrons from the plate of V1 and the transformer secondary flow into the lower plate of C1 giving it an excess negative charge.) Capacitor C1 becomes positively charged to the peak value (+E) of the transformer secondary voltage. This is shown in Fig. 11 by the brief charging pulse (A) flowing through rectifier V1 during the first half-cycle.

During the next ac half-cycle (B) the top of the transformer secondary is negative and tube V1 does not conduct. Since the tube is an open circuit, the charge and voltage on capacitor C1
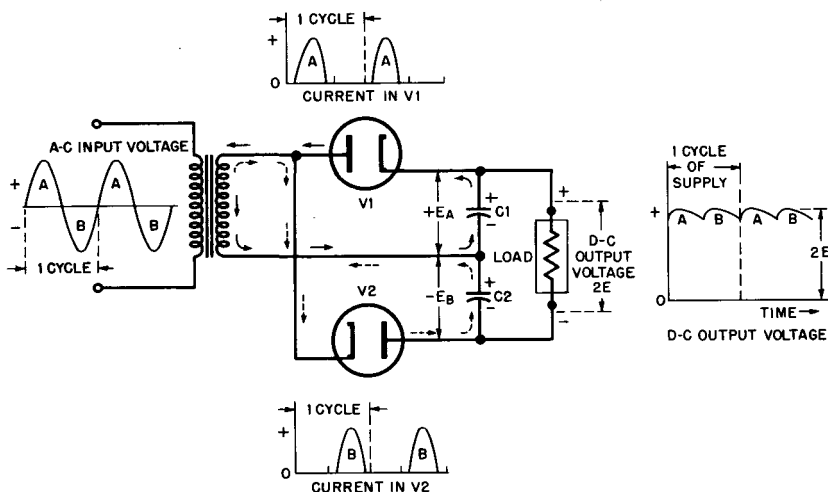
Fig. 11. Circuit and waveforms of full-wave voltage doubler.

remains essentially constant, except for a small amount that leaks through the load resistance. This is shown in Fig. 11 by the slow dropping off of the dc output voltage. During half-cycle (B) the cathode of V2 becomes negative with respect to its plate. Diode V2 passes a current in the direction of the dotted arrows, which charges up capacitor C2 negatively to the peak value ($-E$) of the transformer secondary voltage. The brief charging pulse flowing through V2 is shown by current waveform (B) in Fig. 11.

With a peak voltage (E_A) on capacitor C1 and a peak voltage (E_B) on capacitor C2, the total dc output voltage taken across the two capacitors is 2E. Thus the full-wave doubler supplies a no-load dc output voltage twice the peak of the transformer sec-

ondary voltage. This theoretical value is attained only when no load current is drawn from the output of the circuit.

When a dc load current is drawn, the output voltage drops below 2E by an amount that depends on the magnitude of the load current and the value of the capacitors. It is evident that the energy delivered to the load must come from discharging capacitors C1 and C2 during the time that the diodes are not replenishing the charge (i.e., during alternate half-cycles). If a large load current is drawn, the diodes cannot replenish the charge as fast as it is used and the voltage across C1 and C2 falls greatly. If the capacitors are made sufficiently large (more than 10 microfarads) a fairly large load current can be supplied for short intervals with reasonably good regulation. Large capacitors draw very high peak currents that may damage the diodes, unless protective resistors are placed in series with the tubes.

In general, the poor voltage regulation of the voltage doubler limits it to applications where the average load-current drain is small. This does not mean that relatively large currents cannot be drawn for a few microseconds, as in pulse-circuit applications.

13. Half-Wave (Cascade) Voltage Doubler

Figure 12 illustrates the half-wave voltage doubler, which operates in a slightly different fashion. Because of its configuration, this circuit is also known as the cascade voltage doubler. One immediately apparent advantage of the circuit is that one side of the supply is common with the negative output terminal, permitting both to be grounded. This is especially of advantage in transformerless circuits operated directly from the ac supply line.

Assume initially that diode V2 is disconnected from the circuit. When the top of the transformer secondary is instantaneously negative (during negative half-cycles), an electron current flows through diode V1 in the direction indicated by the dotted arrows, and charges up capacitor C1 to the peak value (E) of the transformer secondary voltage. It is evident that the top plate of C1 becomes positively charged.

Consider the voltage at point X in Fig. 12, which is the junction of the upper plate of C and the cathode of V1. The voltage across the transformer secondary fluctuates between peak values of +E, as shown by the upper waveform in Fig. 12, right. After a few cycles capacitor C1 charges up to the positive peak value of the supply voltage (+E) and holds this charge. Since the capacitor is in series with the transformer secondary the

voltage across the capacitor-transformer combination (between point X and ground) fluctuates around its steady value of $+E$ by the amount of the secondary voltage variations. On positive half-cycles the voltage at X becomes $+2E$ [the capacitor voltage $(+E)$ plus the peak ac voltage $(+E)$], while on negative half-cycles the secondary peak voltage $(-E)$ subtracts from the capacitor voltage $(+E)$, and the resultant voltage at point X becomes zero. This is shown by the lower waveform in Fig. 12.

If diode V2 is now connected in the circuit, the voltage between point X and ground will tend to charge capacitor C2 to the peak voltage existing at point X, or 2E. This takes place during alter-
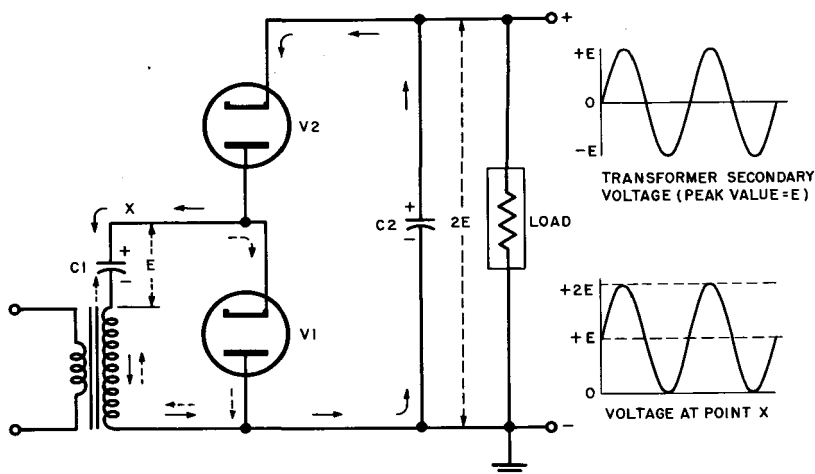
Fig. 12. Circuit and waveforms of half-wave (cascade) voltage doubler.

nate half-cycles, when the top of the transformer secondary is positive and a current flows through diode V2 in the direction indicated by the solid arrows. During these cycles capacitor C2 charges up to twice the ac supply voltage across the transformer secondary or 2E. The circuit is a half-wave doubler because rectified current flows to the load only on alternate halves of the ac input cycle. The regulation of the half-wave doubler is even poorer than that of the full-wave type.

14. Transformerless Voltage Doublers

Two transformerless circuits, utilizing the half-wave and full-wave voltage doublers, are illustrated in Fig. 13. Note that these

are essentially the same circuits as those shown in Figs. 11 and 12 respectively, except that the transformer has been omitted.

The two diodes have been combined in one envelope as duplex-diodes. Representative types are the 25Z6 and the 117Z6-GT, which are designed to operate directly from the 117-volt ac line. In transformerless receivers, the heaters of all tubes are connected in series with a voltage-dropping resistor (R) connected across the line. Note that the dc load circuit of the full-wave doubler (Fig. 13 left) cannot be connected to ground or to one side of the ac supply. This may cause hum because of the high ac voltage between the heaters and cathodes of the series-connected tubes. In addition, the full-wave doubler places the heater string at a positive potential of one-half the dc output voltage. This polarity of dc

R = HEATERS OF OTHER TUBES IN SERIES
WITH VOLTAGE-DROPPING RESISTOR
R_1 = PROTECTIVE RESISTOR
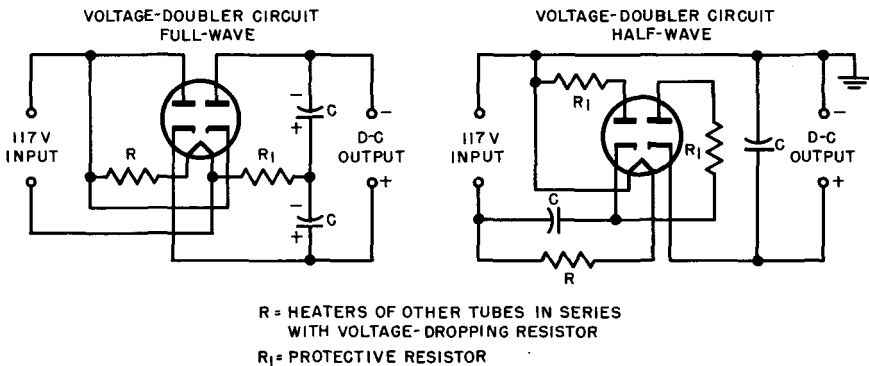
Courtesy RCA Receiving Tube Manual

Fig. 13. Transformerless voltage doubler.

voltage between heater and cathode is in the worst direction for tube reliability and is not recommended by manufacturers. The half-wave doubler (Fig. 13, right) overcomes this difficulty by making the negative terminal common with one side of the ac line.

15. Voltage-Tripler Circuit

The cascade voltage doubler can be combined in series with a half-wave rectifier to provide a dc output voltage that is three times the peak of the ac input voltage. A cascade voltage tripler is shown in Fig. 14. The input voltage may be supplied from a transformer or directly from the ac supply line.

Diodes V1 and V2 evidently comprise a half-wave voltage doubler which delivers an output voltage across C2 equal to 2E or twice

the peak value (E) of the applied ac input voltage. In addition, half-wave rectifier V3 produces across C3 a voltage equal to the peak value (E) of the applied ac input voltage. The voltages
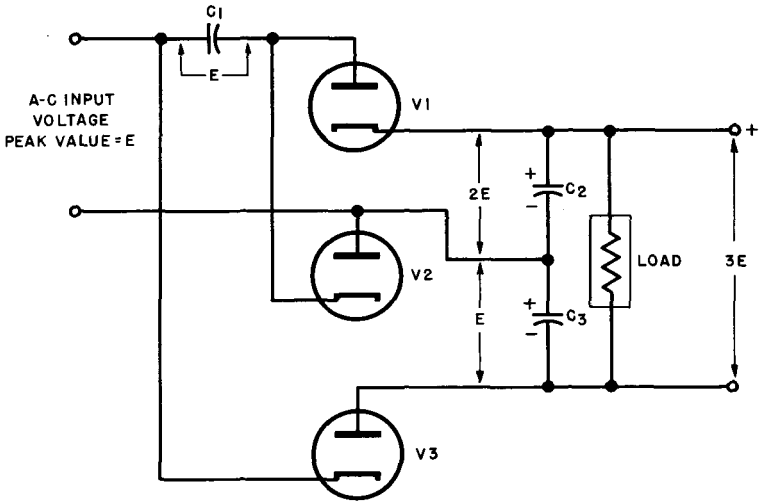
Fig. 14. Schematic of a cascade voltage-tripler circuit.

across capacitors C2 and C3 are added in series, and the no-load dc output voltage is three times the peak input voltage. The voltage drops off rapidly when load current is drawn.

16. Voltage-Quadrupler Circuit

By combining two cascade voltage doublers in series, a voltage-quadrupler circuit is obtained, as is illustrated in Fig. 15. Here two half-wave (cascade) doublers are fed from a common source (either a transformer or the ac line) so that their output voltages add in series. Note that the voltage across C1 equals the peak of the input voltage (E) while the voltage across C2 is equal to twice the peak voltage, or 2E. The voltage across C3 and C4 in series (or across the load) thus approaches four times the peak value of the ac supply voltage, when no load current is drawn.

In theory, cascade voltage doublers may be added in series indefinitely to produce progressively higher output voltages. Since a voltage quadrupler will deliver a no-load dc output voltage of
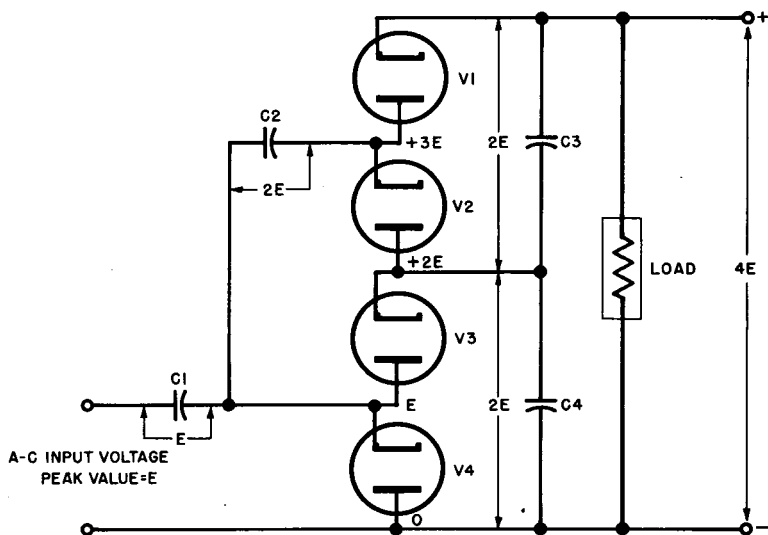
Fig. 15. Two voltage doublers shown as a cascade voltage quadrupler.

4 x 1.414 or about 5.65 times the rms value of the ac source voltage, two quadruplers in series should produce an output voltage approximately 11 times the rms value of the ac input voltage. For a 117-volt ac line, this would result in a dc output voltage of about 1,300 volts, which would be nice work if you could get it.

In practice, however, it is found that the quadrupler presents a technical and economical limit of attainable voltage multiplication. As it attempts to increase the multiplication, the regulation of the system becomes progressively poorer, so that the attained output voltage drops off rapidly with even small load-current increases. The voltage stress across the series capacitors becomes increasingly great, requiring expensive units with high voltage ratings. Also, since the peak current through the rectifier must be limited to the rated values, the possible load current that can be supplied by the tubes becomes less with increasing multiplication. Finally, the cathodes of the tubes must be well isolated from each other, since they are at different potentials with respect to each other. This becomes increasingly difficult as the number of tubes is made larger. Despite these objections, voltage-multiplying circuits using metallic-oxide rectifiers and crystal diodes are quite popular for low-current applications, such as TV power supplies.

17. Review Questions

(1) Draw the circuit of a half-wave rectifier and explain its operation. Assign a typical value to the ac input voltage and compute the dc output voltage.

(2) Explain the advantages of a full-wave rectifier over that of the half-wave type. What is the ratio of the average to the peak current or voltage? The rms voltage to the dc output voltage?

(3) Define the following terms: regulation; ripple frequency; dc magnetization of core; step-up ratio; rms , peak , and average values of voltage and current; no-load current.

(4) Using a tube manual, select a full-wave rectifier tube, assign a value to the transformer secondary voltage and compute the no-load dc output voltage.

(5) Explain the operation of a bridge-type rectifier and state its advantages and disadvantages.

(6) What is the ratio of the average dc output voltage to the rms value of the transformer secondary voltage in a bridge rectifier circuit?

(7) Why are bridge circuits using metallic-oxide rectifiers and crystal diodes popular?

(8) What is the basic principle of voltage-multiplying circuits?

(9) Draw the circuit of a full-wave voltage doubler and explain its operation.

(10) Compare the operation of a half-wave doubler with that of a full-wave type; compare their regulation and other features.

(11) Explain the operation and features of triplers and quadruplers.

(12) Draw a voltage multiplier that will have an output voltage equal to seven times the peak value of the ac input voltage.

POLYPHASE RECTIFIERS

18. The Need for Polyphase Circuits

Practically all alternating-current power is transmitted over three wires in a three-phase circuit. In such a circuit the voltage appearing between any two wires is 120° out of phase with the voltages appearing across the other two pairs. Each wire serves to some extent as a return wire for the other two, permitting a considerable saving in copper. This and other advantages increase the efficiency and power utilization of three-phase systems to such an extent over a single-phase supply that practically all large-scale industrial power consumers utilize three-phase power. (The ordinary house current uses one phase of a three-phase system.) Since many industrial processes require dc power, however, polyphase rectifier circuits are needed. Because of the heavy current requirements, gas-filled diodes, such as mercury-vapor tubes and ignitrons, are frequently employed in polyphase rectifiers.

When a three-phase power supply is available, advantage is taken of its high efficiency by connecting the rectifier tubes in 3-, 6-, and 12-phase circuits. All are derived from the basic three-phase supply. Two-phase power supplies and their associated rectifiers are of little interest because of their relatively low efficiency. Despite the multiplicity of possible rectifier circuits for polyphase systems, only a few of importance in electronics will be discussed.

19. Three-Phase Half-Wave Delta-Wye Rectifier

The simplest of the three-phase rectifiers is the half-wave delta-wye circuit, shown in Fig. 16. The terms "delta" (Δ) and "wye" (Y) refer to the configuration of the primary and secondary coils, respectively, of the three-phase transformer.

Note in Fig. 16 that the three-phase line is connected to the junctions of three delta-connected primary coils, so that the full
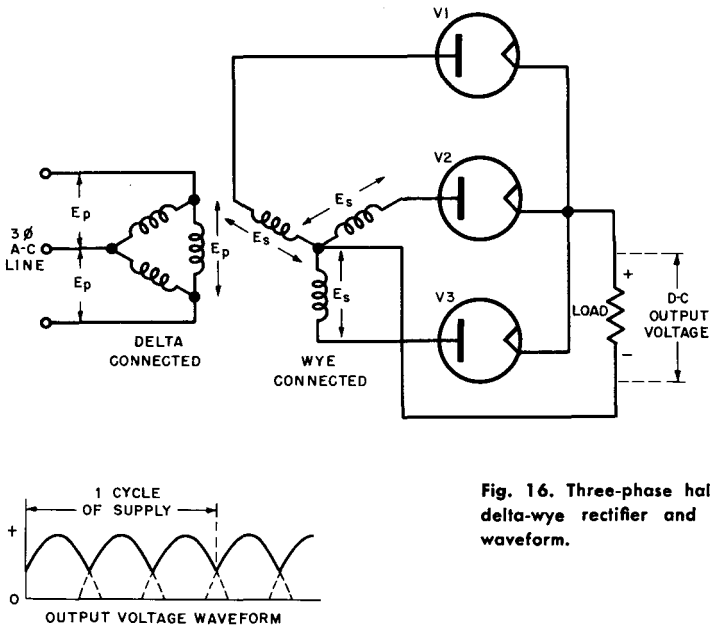
Fig. 16. Three-phase half-wave delta-wye rectifier and output waveform.

primary voltage (E_p) of each phase is developed across each coil. The three secondary coils of the transformer are mounted in the shape of a wye and a secondary voltage (E_s) is developed across each coil or leg. These secondary voltages are 120° out of phase with each other; that is, the output sinewave of each coil is displaced in time by 120°, or one-third of a cycle, with respect to the sinewaves of the other two coils.

The circuit shown in Fig. 16 consists essentially of three separate half-wave rectifiers, one for each leg of the secondary wye, or one for each phase. The operation of each half-wave rectifier is identical to that described for the single-phase half-wave rectifier, illustrated in Fig. 5 and 6. Each tube carries current only during the positive half-cycles of its phase, or only one-third of the time. The output

voltage, therefore, fluctuates at three times the ac supply frequency, as shown in the waveform of Fig. 16. This permits easy filtering of the ripple.

•   Although each of the rectifier tubes is only a half-wave unit, the cathode currents of all the tubes flow through the common load resistance, so the average dc load current is much higher relative to the peak current than in a single-phase rectifier. The average dc current of a three-phase half-wave rectifier is 0.826
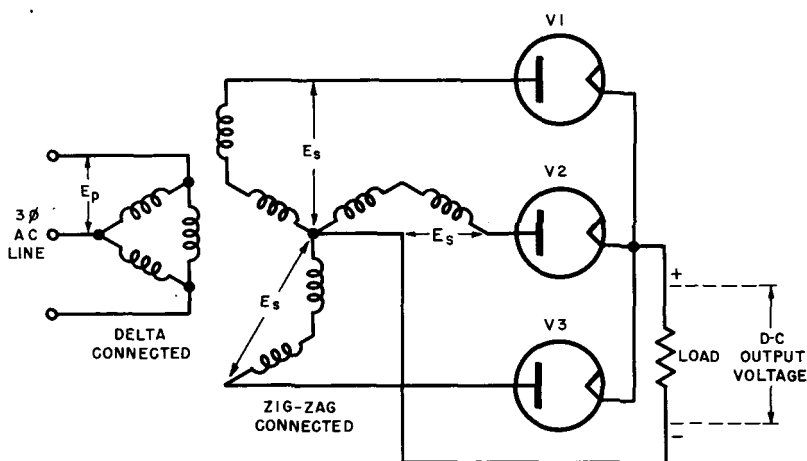
Fig. 17. Three-phase half-wave delta-zig-zag rectifier.

times the peak current, compared to a value of 0.318 for the same ratio in the single-phase, half-wave circuit, and 0.636 for the single-phase, full-wave circuit. Because of this high average current value, the dc output voltage is correspondingly high, and as a matter of fact, it is greater than the ac rms voltage of each secondary leg by a factor of 1.17. (The peak voltage is 1.414 times the rms value; hence the average output voltage is 1.414 x 0.826, or 1.17 times the rms voltage.) Equivalently, the rms voltage across each leg (E_s) of the secondary need only be 1/1.17 or 0.855 times the average desired dc output voltage.

20. Three-Phase Half-Wave Delta-Zig-Zag Rectifier

The circuit shown in Fig. 17, known as a three-phase half-wave delta-zig-zag rectifier, because of its configuration, is identical with the delta-wye rectifier except for the method of installing and

mounting the coils in the three-phase transformer. In the delta-wye circuit (Fig. 16) the rectified current flows through each secondary coil in one direction, which saturates the transformer core and effectively reduces the inductance of the winding, just as in the single-phase half-wave rectifier. This disadvantage is overcome in the delta-zig-zag circuit by supplying each core with two secondary windings operating in phase opposition to each other. As a consequence, each leg is made up of two sections, each operating in a different magnetic circuit. These are connected in successive legs of a zig-zag arrangement to give secondary voltages phased 120° apart. Each secondary phase (E_s) then turns out to be the vector sum of two winding voltages that are effectively 60° out of phase with each other. It may be shown* that E_s equals $\sqrt{3}$ or 1.732 times the voltage developed across each coil winding.

21. Three-Phase Half-Wave Double-Wye (Six-Phase) Rectifier

What essentially amounts to six-phase operation is obtained in the circuit shown in Fig. 18 by connecting two three-phase half-

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* In Fig. A, E_s is the vector sum of two voltages of magnitude e differing in phase by 60°, as shown in Fig. B. The e vectors may be redrawn as in Fig. C. Triangle Ade forms a 30°-60°-90° triangle with sides in the proportions $\sqrt{3}$-1-2. Triangle CBE$_s$ is a similar triangle with sides in the same relative proportions.

A   B   C
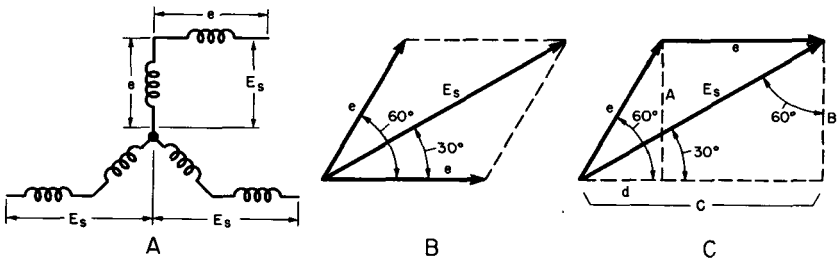
$$A = B = \frac{\sqrt{3}\,e}{2}$$

$$B = \frac{E_s}{2}$$

Therefore: $E_s = 2B$
$$= \frac{2\sqrt{3}\,e}{2}$$
$$= \sqrt{3}\,e$$
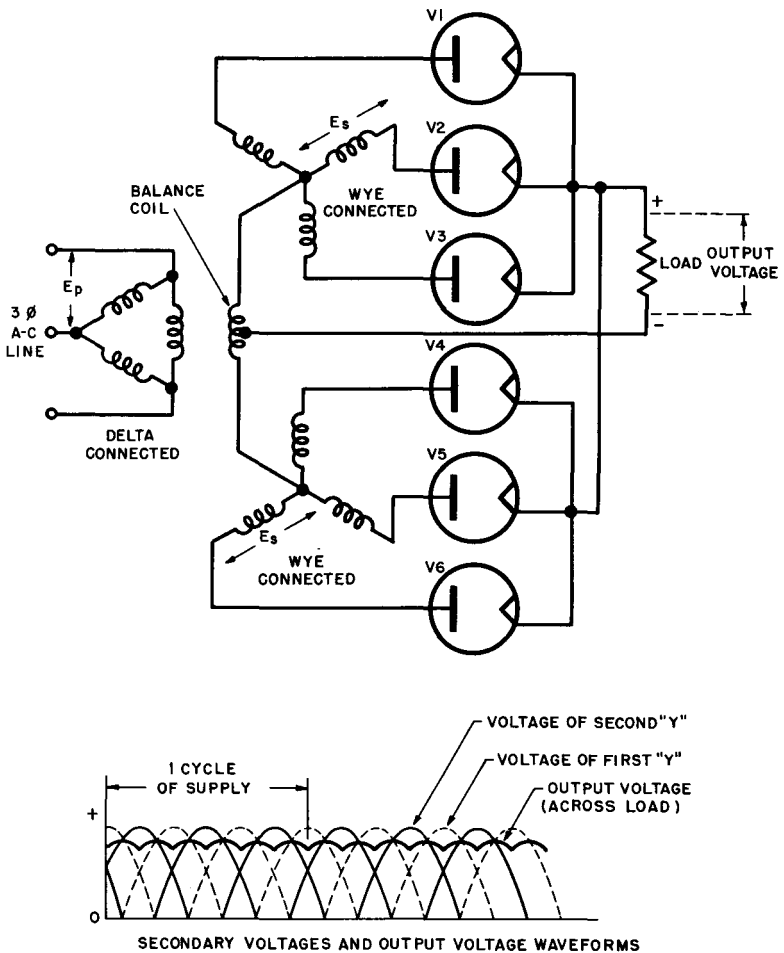
Fig. 18. Three-phase half-wave double-wye (six-phase) rectifier and waveforms.

wave circuits in parallel through a balance coil (also known as interphase reactor). This results in reversing the polarities of corresponding secondary windings in the lower wye with respect to those in the upper wye. Thus, when the secondary voltage (E_s) of one winding in the upper wye is at maximum, the voltage of the corresponding winding in the lower wye will be at a minimum. This effectively adds three extra phases, making a total of six phases.
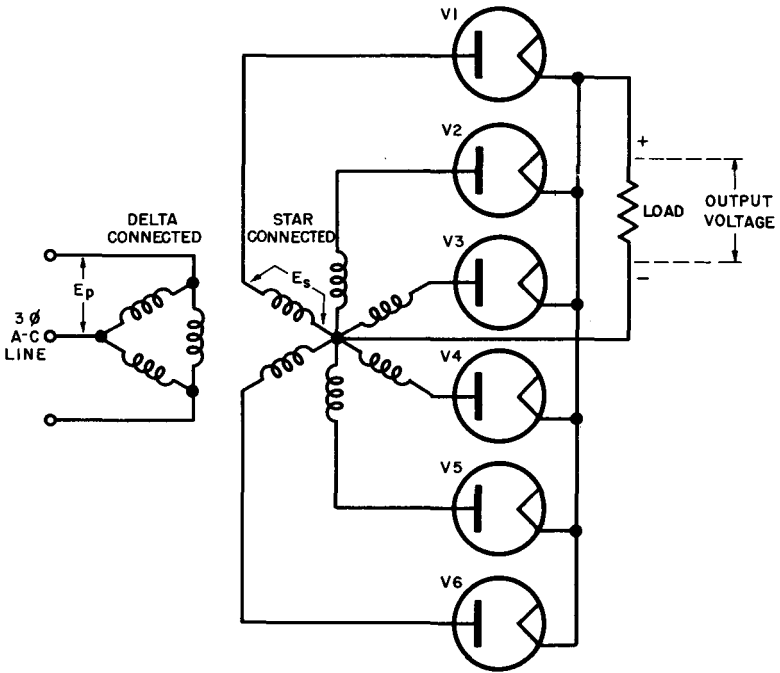
Fig. 19. Three-phase delta-star (six-phase half-wave) rectifier.

Note that the circuit of Fig. 18 requires six rectifier tubes, each acting as a half-wave rectifier for one phase, or one leg of each wye. The central junction of each wye is connected to the other through the interphase balance winding, which compensates for any inequalities in the upper and lower sections. The centertap of this winding becomes the negative terminal of the dc output voltage. The plates of the rectifier tubes are connected to the legs of the two wyes, while their cathodes are connected together. Consequently, the cathode currents of all tubes flow through the common load resistance.

Examine the secondary wye and output voltage waveforms of the double-wye circuit (Fig. 18). As explained before, the secondary voltage of the first wye (dotted line) is at a minimum when the secondary voltage of the second wye (solid line) is at maximum, and vice versa. The same holds true for the rectified output voltages of each wye, since the half-wave rectifiers simply cut off the negative half-cycles, but do not change the relative

amplitudes. There are, therefore, six fluctuations in the output voltages of the wyes for each ac supply cycle and the ripple frequency is six times that of the ac supply.

Because of the action of the balance coil, the actual dc output voltage across the load does not follow the peaks of the wye output voltages, but rather the average of the rectified wye output voltages, as is shown in Fig. 18. The peak current through each tube is only one-half of the average dc load current. The rms voltage required across each leg of the transformer secondary is still 0.855 times the average desired dc output voltage for the delta-wye half-wave rectifier circuit shown in Fig. 16. This somewhat paradoxical situation is due to the requirements of the interphase balance coil, which must insure that the individual three-phase half-wave systems (upper and lower wyes) operate independently with current flowing through each tube one-third of the time. Note that the voltage across the balance coil is the difference between the output voltages of the individual wyes. To assure independent operation, the coil must have enough inductance for the voltage (difference) across it to give rise to a peak alternating current that is less than the direct current flowing through one leg of the coil. To be exact, the peak value of the alternating current in the coil must be less than one-half the dc load current. This is the reason for the low peak-current per tube compared to the average dc load current. Note also that the direct current flows in opposing directions through the two halves of the balance coil, which means no dc saturation is present.

Example: Assume a 230-volt three-phase, 60-cycle ac line is connected to the primary of a 1:1 transformer operating in the double-wye rectifier circuit, shown in Fig. 18. If the average dc drawn by the load is 100 amps, what are the average and peak currents per rectifier tube, the average dc output voltage, the dc power delivered to the load, and the ripple frequency?

Solution: The average current per plate is obviously one-sixth of the dc load current, since there are six tubes. Thus, the average current per tube is $100/6 = 16.7$ amperes. The peak current per tube is one-half the average load current, or $\frac{1}{2} \times 100 = 50$ amperes. Dc output voltage is $1/0.855$ or 1.17 times the rms value across each leg of the transformer secondary. For a 1:1 transformer, the secondary leg voltage must be 230 volts; the dc output voltage (neglecting the transformer and tube drops) is 1.17×230 or 269 volts. In practice this value will be lower because of the voltage drops lost in the tubes and transformer. The dc power delivered to the load is the product of the average dc output voltage and the load current, or $269 \times 100 = 26,900$ watts. Finally, the ripple frequency is six times the supply frequency, or $6 \times 60 = 360$ cycles. This is easily made pure dc with a simple filter circuit. (See Chap. 4.)

22. Three-Phase Delta-Star (Six-Phase Half-Wave) Rectifier

The equivalent of six-phase operation from a three-phase supply can be attained by centertapping the secondary winding of a three-phase transformer more easily than it can be achieved in the double-wye circuit. Refer to the single-phase, centertapped transformer shown for the full-wave circuit in Chap. 2, Fig. 7. Such a star-connected secondary will have voltages of opposing polarities across each half of a winding with respect to centertap, giving effectively a total of six phases (one for each leg of the star.) A typical three-phase delta-star rectifier circuit is shown in Fig. 19.

Note that the delta-star circuit requires six half-wave rectifier tubes, one for each phase or secondary leg, just like the double-wye circuit. The output waveform is similar to that shown for the double-wye circuit (Fig. 18) and also has a ripple frequency equal to six times that of the ac supply.

Because of the absence of the balance coil the limitations with respect to the peak and average currents do not apply to the delta-star circuit and the average dc load current of the latter turns out to be 0.955 times the value of the peak current per tube. The average output voltage is thus also 0.955 times the peak voltage, or 1.414 x 0.955=1.35 times the rms value (E_s) of the secondary voltage across each leg. Equivalently, the rms voltage across each secondary leg must be 1/1.35 or 0.74 times the average desired dc output voltage.

For example, if an output voltage of 300 volts at a load current of 10 amperes is desired in the circuit of Fig. 19, the ac rms voltage across each secondary leg (E_s) must be 300 x 0.74=222 volts, and the peak current per tube is 10/.955 or 10.5 amperes. The average current per tube is, of course, 10/6 or 1.67 amperes for each of the six tubes.

23. Three-Phase Full-Wave Delta-Wye Rectifier

The full-wave delta-wye (sometimes called the three-phase, full-wave bridge circuit) rectifier circuit shown in Fig. 20 is essentially an extension of the single-phase full-wave bridge rectifier, described in the last chapter (Fig. 10). Although this circuit uses double the number of tubes of the three-phase, half-wave, delta-wye rectifier (Fig. 16), it has the advantage of delivering twice the output voltage of the half-wave rectifier for the same total secondary voltage (E_s).

Note in Fig. 20 that each leg of the secondary wye is connected to the junction of two half-wave rectifiers, arranged back-to-back, so

that full-wave rectification of both ac half-cycles is obtained from each phase. The waveform of the output voltage, shown at right in Fig. 20, is essentially the same as that of the double-wye circuit (Fig. 18), where the ripple-frequency of the output is six times that of the three-phase ac supply.

No balance coil is required, but the power transformer must have three secondary windings and the filament transformer must have four separate secondary windings, one for V1, V2, and V3, and one each for V4, V5, and V6. Since the rectified tube currents flow in
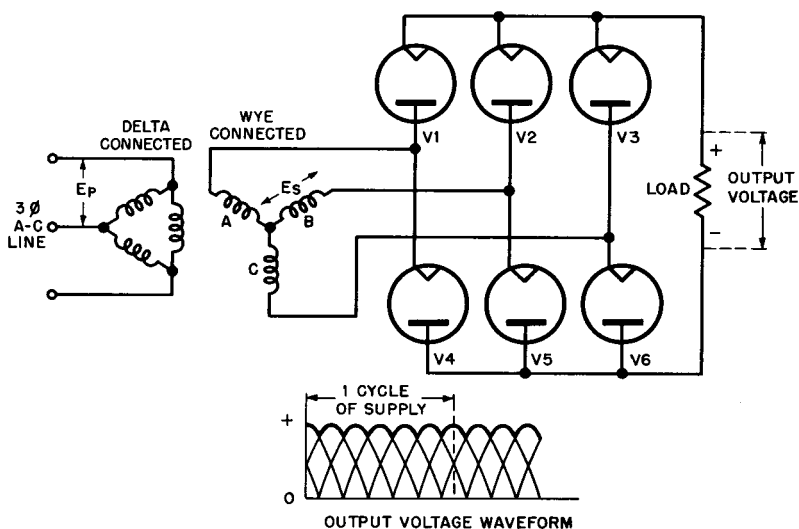
Fig. 20. Three-phase full-wave delta-wye rectifier and output waveform.

opposing directions through the secondaries, no dc magnetization can take place. Three single-phase transformers may be used in place of one three-phase transformer.

As in the delta-star circuit, the average dc load current is 0.955 times the peak current through each tube, but one-third of the dc load current flows through each tube (rather than one-sixth, as in the delta-star circuit), because two tubes are required for each output current pulse. As pointed out before, the average dc output voltage is twice that of the three-phase half-wave rectifier, or 2 x 1.17=2.34 times the rms value of the ac voltage across each secondary leg. Conversely, the rms voltage across each leg need

be only 1/2.34 or 0.428 times the value of the average desired dc output voltage.

Example: The transformer secondary voltage per leg (E$_s$) in a full-wave delta-wye rectifier is 150 volts rms, the load current 2 amperes. What is the average dc output voltage, the peak and average current through each tube, and the average power delivered to the load?

Solution: Since the average dc output voltage is 2.34 times the rms voltage across each leg, the output voltage is 2.34 x 150=351 volts. The peak current through each tube is 1/0.955 or 1.05 times the average load current; the peak current is 1.05 x 2=2.10 amperes per tube. The average current per tube is one-third of the total, or 1/3 x 2=0.667 ampere. Finally, the average power is the product of the average current and the output voltage, or 2 x 351=702 watts.

24. Uses of Polyphase Circuits

Polyphase rectifiers are used only when the efficiency of rectification is more important than the cost of the rectifier itself. This is generally the case when the required dc power exceeds about 1 kilowatt. Many industrial plants, broadcast and television stations requiring up to 20,000 volts dc at peak currents of 10 amperes or more utilize polyphase circuits. The tubes employed are generally the gas-filled (mercury-vapor) type. Polyphase circuits also have the advantage over single-phase types of developing fairly steady output voltages that require little filtering. Finally, the more efficient polyphase circuits give a higher output voltage relative to the peak inverse voltage of the tube and utilize the power transformer more efficiently than do equivalent single-phase circuits.

25. Review Questions

(1) State some of the advantages of three-phase power systems over single-phase supplies.

(2) Draw the circuit and output waveform of a three-phase half-wave delta-wye rectifier and explain its operation.

(3) What is the advantage of the delta-zig-zag connection over the delta-wye circuit? Is there any difference in the output waveform of the circuit; in the average and peak currents; in the ripple frequency?

(4) Why is the half-wave double-wye circuit sometimes called a six-phase rectifier? What is the ripple frequency of the output?

(5) Explain the function of the interphase balance coil in the double-wye circuit and how it affects the ratio of the peak current per tube to the average load current. Compare ratio with that of the half-wave delta-wye rectifier.

(6) Compare the operation of a double-wye circuit with that of the delta-star rectifier connection. How would you convert one into the other?

(7) A broadcast station requires a dc voltage of 2000 volts at a load current of 10 amperes. For both the delta-star rectifier (Fig. 19) and the double-wye circuit (Fig. 18) compute the required rms voltage across each secondary winding of the transformer, the peak and average current per tube, the dc power delivered to the load and the ripple frequency. (Neglect the tube and transformer voltage drops.) Which circuit would you choose?

(8) Draw the circuit of a three-phase full-wave delta-wye rectifier and compare its operation with that of a single-phase, full-wave bridge rectifier. Compute the same data as for the review question (7) and compare all three circuits. If you had three single-phase transformers of the proper ratings available, would you change your selection in question (7)?

(9) Remembering the delta connection, draw the circuit of a three-phase full-wave delta-delta rectifier.

Chapter 4

OUTPUT FILTER CIRCUITS

26. The Need for Filtering Out the Ripple

Although rectifier systems deliver an output voltage that always has the same polarity, the voltage is not suitable as dc supply for vacuum tubes because of the pulsations in the amplitude, or ripple. The ripple voltage may be thought of as an alternating voltage that fluctuates around the average value of the dc output voltage.

The ripple voltage is not of a single frequency, as was previously assumed, but actually a fundamental frequency and a number of frequencies that are multiples of the fundamental frequency, called *harmonics*. Thus, the second harmonic is twice the fundamental frequency, the third harmonic is three times the fundamental, and so on. The fundamental ripple frequency may be the same as the supply frequency (for the single-phase half-wave rectifier) or as high as six times the supply frequency (for the full-wave three-phase rectifier), depending on the rectifier circuit used. The amplitude (magnitude) of the fundamental component of the ripple voltage is always larger than that of any harmonic. When the value of the ripple voltage for a particular rectifier is stated, as in Chap. 5 (Table II), it usually takes into account the amplitudes of all the major harmonics and is expressed either as the percentage of the average dc output voltage or as the ratio of the rms ripple voltage to the average dc output voltage.

Depending on the application, varying amounts of ripple may be tolerated, but it must always be a relatively low percentage of the dc output voltage. Devices for reducing the ripple voltage are

known as filters. Filter circuits generally consist of capacitors, inductors, and sometimes resistors. The capacitors are always connected in parallel with the load, while the inductors or resistors are connected in series with the load.

27. Capacitance Filter

Consider first the action of a shunt capacitor across the load and rectifier output (Fig. 21). This is the simplest possible type of filter.

It will be remembered that a capacitor opposes any change in voltage across its terminals (the load, in this case) by storing up
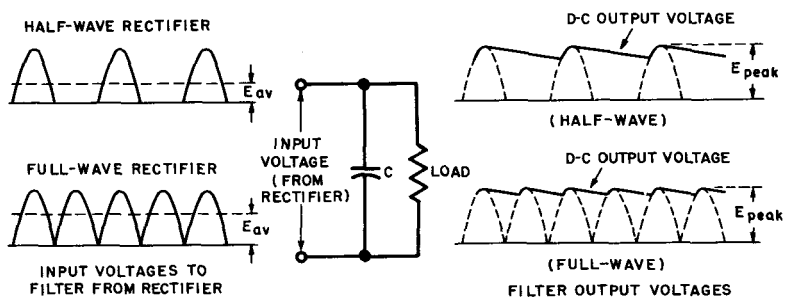
Fig. 21. Capacitor-filter waveforms with rectifier voltages applied.

energy in its electrostatic field whenever the voltage tends to rise, and converting this stored energy back into current flow whenever the voltage across its terminals tends to fall. Some of the energy of the rectifier output pulses is stored in the field of a capacitor, and the capacitor discharges between the rectifier current pulses, considerably reducing the fluctuations in the output voltage (ripple).

Figure 21 shows the action of the capacitor filter when either half-wave or full-wave rectifier output voltages are applied to the filter. In either case the capacitor charges up to the peak voltage of the rectifier output during the time that current pulses are delivered to the filter and load. When the rectifier output drops off to zero, the capacitor cannot discharge instantaneously; its voltage falls off slowly as it discharges through the load. During the next rectifier current pulse, the capacitor is charged again to the peak voltage, and the cycle is repeated. The only difference

between the half-wave and full-wave action is that the capacitor discharges more between current pulses of the half-wave rectifier, so the dc output voltage of the latter averages less than that of the full-wave rectifier, which almost equals the peak voltage. The actual value of the average dc output voltage relative to the peak value depends on the capacitance and the amount of load current drawn. If the capacitance is large, more energy is stored during current pulses and the capacitor output voltage remains relatively high during discharge. In contrast, if the load current is large, the capacitor discharges rapidly between current pulses and the average dc output voltage falls to a low value.

Because of its poor regulation (large output voltage drops for small load current increases) the simple capacitor filter is not used with rectifiers that supply a substantial load current. Also, the amount of ripple remaining is greater than can be tolerated in the plate supply of most electronic circuits. Finally, the capacitor filter draws large charging currents that may damage some rectifier tubes. The filter is used sometimes in the output of voltage multipliers where input chokes cannot be employed.

28. Inductance Filter

The action of a single inductor (choke coil), placed in series with the rectifier output, is illustrated in Fig. 22. This filter is usually used in combination with shunt capacitors, as we shall see later.

Essentially, any inductor opposes a change in the magnitude of the current flowing through it by storing up energy in its magnetic field when the current tends to increase, and by taking energy away from the field to maintain current flow when the voltage across the inductor tends to decrease. Hence, by placing a choke coil in series with the rectifier and load, abrupt changes in the magnitude of the rectifier output current and the load voltage are minimized. Another way of looking at the action of the series inductor is to consider that the coil offers a very low resistance (only that of the winding) to the passage of dc, while offering at the same time a high impedance to the passage of fluctuating or alternating currents. The dc passes through, and the ripple is largely reduced.

As shown by the output waveform in Fig. 22, the load current through the filter (and hence the load voltage) lags 90° behind the rectifier output voltage and never reaches its peak value. The average dc output voltage from a single inductor is less than that from the capacitor filter, but the voltage does not fall off as rapidly with increases in load current as with a capacitor filter.
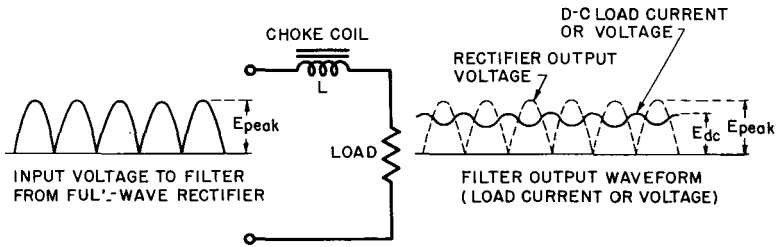
Fig. 22. Waveforms and diagram of inductance filter action.

29. Capacitor-Input Filter

More effective filtering action can be attained by combining the actions of a shunt capacitor and a series inductor in capacitance-inductance filters. Various combinations of such filters exist, but in all of them the action of the capacitors is to resist changes in output voltage by charging and discharging, as required, while the inductors oppose any changes in the magnitude of the load current through the action of their associated magnetic field. Equivalently, the shunt capacitors may be considered to form a low impedance path to minus, and ground for the ripple voltage,
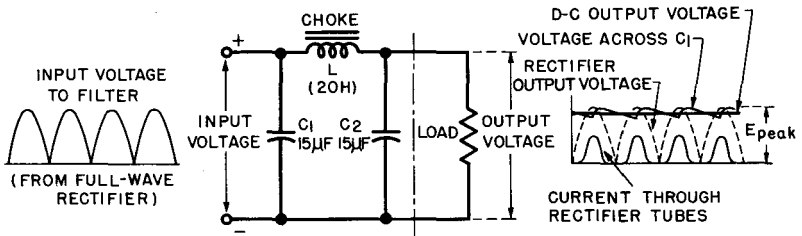
Fig. 23. Capacitor-input filter diagram and waveforms.

and an essentially infinite impedance to dc. The series inductors (choke coils) can be considered to offer a low impedance to the passage of dc and a very high impedance to the ripple current.

Figure 23 illustrates a capacitor-input filter (also known as a π-filter) with typical component values. This circuit is characterized by a high output voltage at low current drain, the voltage being almost equal to the peak value of the transformer secondary voltage applied to each tube. (The peak value is 1.414 times the

rms value.) As the load current increases the output voltage falls off rapidly (because of the capacitor discharge) and may become less than the rms value of the applied ac voltage. In other words, the regulation of a capacitor-input filter is poor.

The waveforms of Fig. 23 show the basic action of the filter. The current pulses flowing through the rectifier tubes and filter charge up input capacitor C1 to the peak voltage of the transformer secondary. The filter input capacitor must have a rating high enough to withstand the instantaneous peak value (1.414 times the rms value of the ac) if breakdowns are to be avoided. Between current pulses, the voltage across C1 falls off somewhat, but never reaches zero, just as in the case of the simple capacitor filter (Fig. 21). Because of the action of the choke coil (L), the voltage peaks across C1 lag behind the peaks of the rectifier output voltage (obtained without a filter). With the additional filtering provided by the coil and capacitor C2, the dc output voltage becomes essentially constant, as indicated (in exaggerated form) by the solid line in Fig. 23. Actually, a small ripple is still present in the output of the filter, which may be eliminated by adding another filter section.

By increasing the value of the filter capacitors above those shown in Fig. 23 (especially that of input capacitor C1) the ripple voltage may be decreased further and the average dc output voltage will be increased slightly. Increasing the dc output (load) current, however, increases the ripple voltage and reduces the available dc output voltage.

Bleeder. Some resistance must always be connected across the output of the capacitor input filter, even when the normal load is absent. This maximum resistance is called the bleeder resistor, and as its name implies, its chief purpose is to discharge the capacitors when the equipment is turned off. To improve voltage regulation, the bleeder resistor is usually made smaller than this maximum value, as will be explained later on.

30. Choke-Input Filter

A typical choke-input filter, consisting of a 20-henry series inductor and a 10-microfarad shunt capacitor, is shown in Fig. 24.

When the load draws no current, the dc output voltage of the choke-input filter is nearly equal to the peak value of the ac voltage applied to the rectifier, just as in the case of a capacitor-input filter. This is so because in the absence of a load current no voltage drop is developed across the choke coil (L), and hence the

output capacitor (C) charges up to the peak value. However, if even small load current is drawn, the dc output voltage drops rapidly to some lower value and then remains fairly constant over a wide range of load-current values. The initial sharp drop occurs because the series inductor prevents the capacitor from charging to the peak voltage when a load current is drawn. After this initial drop there is good voltage regulation of the choke-input filter.

Bleeder Resistor. A bleeder resistor connected across the filter output is generally designed to draw sufficient current for operation
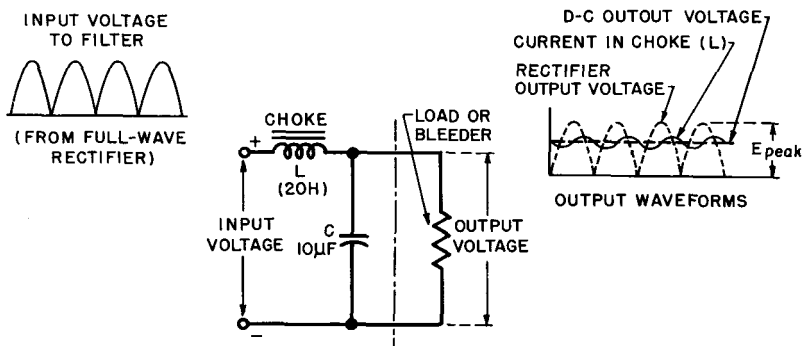
Fig. 24. Choke-input filter waveforms and schematic.

in the beginning of the almost constant portion of the voltage-current curve of the filter output, where the voltage regulation is excellent (Fig. 26A). By placing a load across the output, the bleeder becomes useful also in preventing high-voltage surges through the power supply when the equipment is first turned on. For satisfactory operation, the bleeder should draw about 10% of the rated load current.

Waveforms. The voltage and current relations in a choke-input filter are illustrated by the waveforms in Fig. 24. The load current in the choke coil lags behind the rectifier output voltage, as shown, and has a small ripple. The dc output voltage across C and the load is substantially constant, as indicated by the dotted line, and its value is somewhat less than the peak ac voltage, depending on the load current drawn. The ripple in the dc load current through the choke can be considerably reduced by increasing the value of the inductance. For an infinite inductance (the ideal case) the dc load-current waveform becomes a straight line equal to the average of the fluctuations shown in Fig. 24.

Input Inductance Requirements. For normal choke-input filter operation there must be a continuous flow of current through the choke coil. The peak value of the ac ripple current through the choke must be less than the dc output current, or the current through the choke might fall at times to zero. This condition is approximately realized by choosing the value of the input inductance (L) so that the following relation is satisfied:

$$L = \frac{E_1}{2 \pi f I}$$

where E_1 = fundamental component of the ripple voltage

I = dc output current in amperes

f = fundamental ripple frequency in cycles

π = 3.1416

For the practical case of a 60-cycle, single-phase full-wave rectifier, the fundamental ripple frequency is 120 cycles, the ripple voltage E_1=0.667 E (where É is the dc output voltage) and hence the above relation becomes

$$L = \frac{E}{1130\ I}$$

where E is the dc output voltage and I is the output current.

Example: What should be the minimum value of the inductance in a choke-input filter if the output voltage from a full-wave 60-cycle rectifier filter system is 350 volts and the dc load current is 100 ma.?

Solution: The minimum inductance

$$L = \frac{E}{1130\ I} \quad = \quad \frac{350}{1130 \times .10} \quad = \quad 3.1 \text{ henrys}$$

Actually to assure good operation at low load currents, a larger value than the minimum inductance should be selected.

The minimum inductance given by the above relation is that value below which the choke-input filter is no longer capable of functioning properly, but at which it acts like a capacitor-input system. Note that the minimum inductance depends inversely on the load current. If the load current fluctuates over a certain range, an inductance corresponding to the lowest load-current value must be chosen to obtain satisfactory operation. Here again, a fixed bleeder resistor, drawing about 10% of the full dc output

current, assures good voltage regulation and eliminates the need for excessive input inductance values.

In the next chapter we shall consider choke-input filter design in more detail and the minimum inductance values for various rectifier circuits (single- or three-phase) will be given.

Swinging Choke. From the relation given for the minimum input inductance, it is evident that the required inductance may vary over a wide range, depending on the load-current fluctuations. Even with a bleeder present, the required inductance at the minimum (bleeder) current may be excessive compared to the value needed for effective hum suppression at normal load currents. A swinging choke is designed to overcome this disadvantage by varying its inductance according to the load. The inductance of a swinging choke is high at low load currents and drops off with increasing load currents. This is accomplished by making the air-gap of the choke coil very small. At small load currents, the incremental inductance of such a choke will be very high, while at large load currents it will be sufficient to give adequate filtering. (The incremental inductance is the inductance to the alternating ripple current superimposed upon the dc magnetization.)

It is important to realize that the minimum inductance given by the previously stated relation is the incremental inductance, that is, the inductance to the ac ripple superimposed on the dc magnetizing current. As the dc magnetization decreases at low load currents, the incremental inductance of any choke increases. Even without a swinging choke, the relation for minimum inductance at low load currents will generally be satisfied by any well-designed choke coil.

31. Resistance-Capacitance Filter

When the load-current requirements are small and a moderate dc voltage drop across the filter is permissible, the inductance of a capacitor-input filter may be replaced by a series resistance. The resulting resistance-capacitance (R-C) filter is not as effective as an inductive filter, since the series resistor offers as much impedance to dc as to the ripple voltage. Some ripple is always present. The advantage of the R-C filter is that a resistance is much less expensive than an inductance. An R-C filter with typical component values is shown in Fig. 25.

Capacitance C1 in Fig. 25 is made sufficiently large to present a very low impedance to the ripple frequency, while at the same time offering practically infinite impedance to dc. The ripple
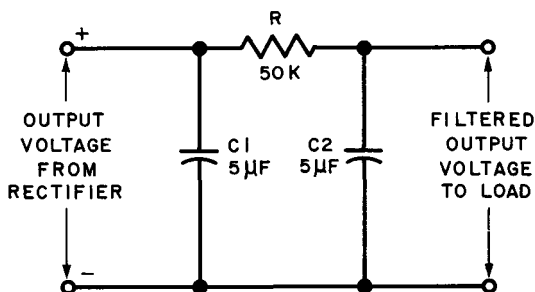
Fig. 25. Schematic of a typical resistance-capacitance filter.

voltage, therefore, prefers the shunt path through C1 to minus (and ground), while the dc is forced through resistor (R) and develops a voltage drop across it. Most of the remaining ripple voltage at the filter output is shunted to ground through the low-impedance path offered by capacitor (C2), while the filtered rectifier voltage is available at the output terminals. The value of the filtered dc output voltage is substantially the rectifier output voltage developed across capacitor (C1) minus the voltage drop developed across series resistor R.

Amount of Filtering. In practical R-C filters, the reactance of the shunting capacitors is always made small compared with the series resistance. Under this condition, each section of an R-C filter reduces the ripple voltage applied to its input by the following (approximate) ratio:

$$\text{Reduction Factor} = \frac{\substack{\text{A-c Ripple Voltage} \\ \text{Across Filter Output}}}{\substack{\text{A-c Ripple Voltage} \\ \text{Applied to Filter Input}}} = \frac{1}{2 \pi f C R}$$

where f = the frequency of the ripple voltage component

R = series resistance of filter

C = the filter output capacitance (C2 in Fig. 25.)

When several filter sections are connected in series (cascade), the total reduction factor is approximately equal to the product of the voltage reduction factors of the individual sections. In polyphase rectifiers, where the ripple frequency (f) is high, a single R-C section is usually adequate.

Example: Compute the ripple voltage reduction factor of the R-C filter shown in Fig. 25, for a 60-cycle single-phase, full-wave rectifier.

Solution: (See Fig. 25.) The fundamental ripple frequency of a full-wave rectifier is 120 cycles. According to the relation above, the reduction

$$\text{factor} = \frac{1}{2\pi \times 120 \times 5 \times 10^{-6} \times 50,000} = 0.0053$$

Hence, the output ripple is only 0.53% of the input ripple.

Uses of R-C Filters. Because of their relatively low expense R-C filters are popular in a wide variety of low-current drain applications including oscilloscope power supplies, and decoupling networks in resistance-coupled amplifiers. In these applications, some voltage drop in the filter is permissible and the current drain is sufficiently low to prevent the voltage drop from becoming excessive. Whenever large load currents are required, however, the high voltage drop developed across the resistance of an R-C filter cannot be tolerated.

32. Comparison and Design of Capacitor-Input and Choke-Input Filters

The main electrical difference between choke-input and capacitor-input filters is that current flows continuously from the rectifier to the filter in choke-input circuits, while current flow is an intermittent series of charging pulses in capacitor-input circuits. The consequences of this basic difference are a higher dc output voltage, lower ripple voltage and poorer voltage regulation for a capacitor-input filter than for the choke-input type, when both are used with the same circuit and load. Furthermore, in a capacitor-input filter the ripple voltage increases with increasing load current (i.e., the filtering becomes poorer), while for choke-input filters the ripple voltage is independent of the load current. Finally, the ratio of the peak current to the average dc flowing through the rectifier tubes is higher for a capacitor-input filter than for the corresponding choke-input circuit. This results in poor utilization of rectifier tubes and the transformer for capacitor-input filters.

Applications. In general, capacitor-input filters are employed when the amount of required dc power is small. This is the case in most electronic home appliances, radio sets, television receivers, and small public-address systems. Choke-input filters, on the other hand, are used whenever the amount of dc power required is large, because of the savings in tubes and transformer costs resulting from the lower peak currents. For this reason, choke-input filter circuits are exclusively used in polyphase rectifiers and wherever

good regulation of the dc voltage is more important than a small increase in its value. Voltage-multiplying circuits always use capacitor-input filters, since the input capacitor is essential to their operation.

Regulation of the D-C Voltage. The regulation of a rectifier-filter system is the decrease in available dc output voltage from no-load current to full-load current. Figure 26 graphically compares the variation in output voltage with load current of a choke-input filter (solid line) with that of a capacitor-input filter (dotted line) in a typical single-phase, full-wave circuit.

It is evident from Fig. 26 that the no-load dc output voltage of both types of filters is almost equal to the rectifier peak output voltage. In both filters the output voltage drops off with increasing
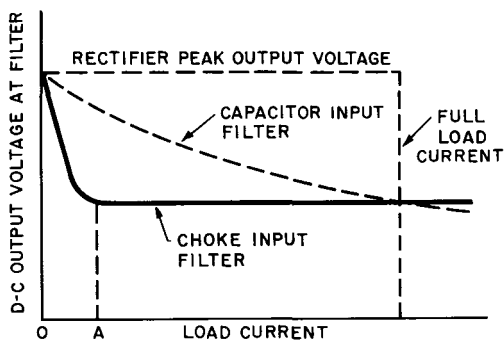
Fig. 26. Effect of load current on dc output voltage for capacitor- and choke-input filters in a full-wave rectifier circuit.

dc load current because of unavoidable voltage drops across the transformer windings, rectifier tubes, and filter components. Note, however, that the output voltage with a capacitor-input filter continues to drop off steadily with increasing loads, while the output voltage with a choke-input filter becomes almost constant after an initial sharp drop. The reason for this difference is as follows. In the capacitor filter, the output voltage continues to fall off because of the more rapid discharge of the filter input capacitor with increasing load currents. In the choke-input filter the output voltage drops off sharply with a small increase in load current because the choke coil prevents the shunt capacitor from charging to the peak voltage. After this drop the output voltage falls off only gradually, due to increasing tube and transformer drops. Choke-input filters are, therefore, always operated in the current-voltage region beyond point A (in Fig. 26) by a suitable bleeder resistor placed across the output of the filter.

Curves of the type shown in Fig. 26 permit determination of

rectifier output voltage of a particular circuit for various loads and filter component values. Such curves are frequently presented in manufacturer's tube manuals, or the information for them may be listed in tabular form under "typical operating conditions."

L-C Filter Design. Figure 27 shows typical examples of choke-input and capacitor-input filters of one or more sections which are placed between the rectifier output and the load to obtain substantially pure dc.

Note in Fig. 27 that for design purposes each filter section is considered to be made up of a series inductance (choke coil) and a shunt capacitor. The input inductance of a choke-input filter is part of the first filter section, but the shunt capacitance (C) of a capacitor-input filter is included not as part of the first filter section, but as an integral part of the rectifier output. With the input capacitor considered as part of the rectifier, the filter sections of choke-input and capacitor-input circuits become identical. Then rectifier output and ripple voltage that feeds into the series induct-ance of a choke-input filter or into the shunt capacitance of a capacitor-input filter must be determined. Now it is possible to compute the reduction in the ripple voltage in the same way for both types of filters. As stated before, the rectifier tube output voltages (for typical operating conditions) into either an input inductance or a shunt capacitor are listed in manufacturers' tube manuals.

When the reactance of the shunt capacitance of an L-C filter section is small at the lowest ripple frequency compared to the load resistance (or the reactance of the inductor that follows), which is always the case in practical filters, the reduction is the ripple voltage for a single section may be computed from the following approximate relation:

$$\text{Reduction Factor} = \frac{\begin{array}{c}\text{A-c Ripple Voltage}\\\text{Across Filter Output}\\\hline\text{A-c Ripple Voltage}\\\text{Applied to Filter Input}\end{array}} = \frac{1}{4\pi^2\ f^2\ LC - 1}$$

where f = frequency of ripple voltage component

   L = series inductance of filter section

   C = shunt capacitance of filter section

  $4\pi^2$ = 39.48

Example: What is the reduction in the fundamental ripple voltage of a 60-cycle, single-phase, full-wave rectifier, if a capacitor-input filter of the type shown in Fig. 27B with 10-μf shunt capacitors and a 20-henry choke is employed?
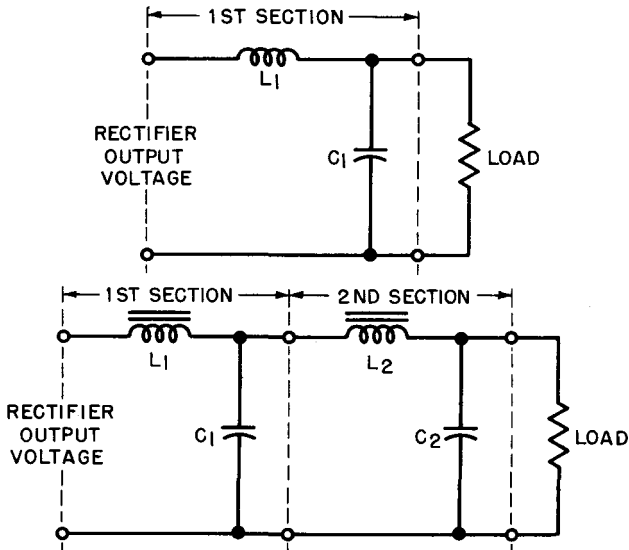
(A) CHOKE-INPUT FILTERS
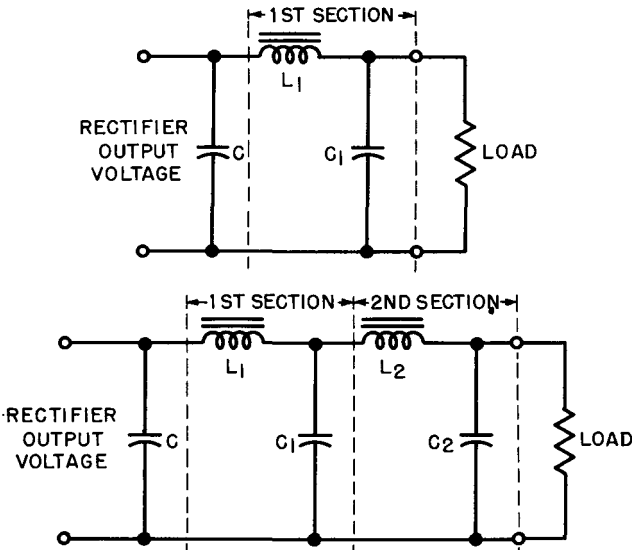
(B) CAPACITOR-INPUT FILTERS

Fig. 27. Schematics of typical filter sections.

Solution: The fundamental ripple frequency (f) is 120 cycles; the reduction

$$\text{factor} = \frac{1}{39.48\,(120)^{\,2} \text{ x } 20 \text{ x } 10 \text{ x } 10^{-6} - 1} = 0.0089$$

The output ripple voltage is only 0.89% of the input ripple voltage applied to the filter.

In the next chapter a number of curves will be presented from which the reduction factor for L-C filters with various rectifier circuits can be determined without elaborate computation.

33. Tuned (Resonant) Filters

By using a resonant circuit as a filter, a particular ripple frequency may be effectively suppressed. As shown in Figs. 28 and 29, either a series-resonant circuit in parallel with the load or a parallel-resonant circuit in series with the load, may be used to suppress the ripple.

In the series-resonant filter circuit (Fig. 28) the reactance of the coil and that of the capacitor cancel out at the resonant (ripple)
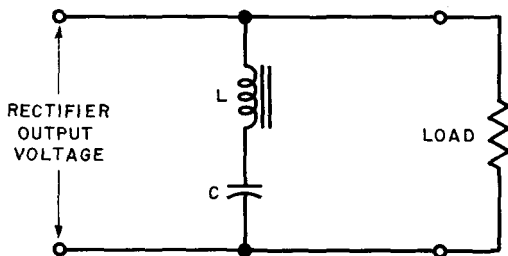
Fig. 28. A series-resonant filter circuit in parallel with the load.

frequency and the opposition to the ripple voltage is thus only the series resistance of the tuned circuit, which is essentially the coil winding resistance. The filter, therefore, acts as a short circuit across the load for the ripple frequency to which it is tuned, while presenting almost infinite impedance to the dc output voltage.

In contrast, the parallel-resonant filter (Fig. 29) presents a very high impedance (Q times the impedance of the coil) to the ripple frequency to which it is tuned, while at the same time presenting only the coil resistance to the flow of direct current. It effectively blocks the passage of the ripple current to the load. Small ripple currents that do get through are further by-passed to ground by shunt capacitors C' and C".
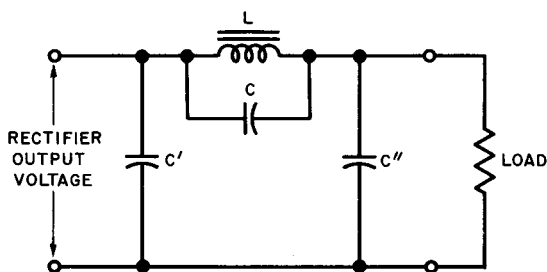
Fig. 29. A parallel-
resonant filter circuit
in series with the load.

Since the resonant frequency (f) of either tuned circuit is approximately $1/2\pi\sqrt{LC}$, the product of inductance and capacitance for a resonant filter must satisfy the relation

$$L\,C = \frac{1}{4\pi^2\ f^2} = \frac{I}{39.48\ f^2}$$

where L = inductance of resonant filter

C = capacitance of resonant filter

f = frequency of ripple voltage component

In the parallel-resonant filter (Fig. 29), the minimum inductance of the choke coil is usually determined by the previously discussed considerations for a capacitor-input filter, so that the value of the capacitance (C) is also fixed.

Example: What value capacitance must be connected across the choke coil of a capacitor-input filter to tune it to resonance for a 60-cycle, single-phase, half-wave rectifier, if the minimum inductance for effective filter operation is 5 henrys?

Solution: The fundamental ripple frequency for a half-wave rectifier is 60 cycles. Hence, by the relation stated above

$$L\,C = \frac{1}{39.48\ (60)^2} = 7.04\text{ x }10^{-6}$$

The capacitance $C = \dfrac{L\,C}{L} = \dfrac{7.04\text{ x }10^{-6}}{5} = 1.41\text{ x }10^{-6} = 1.41\ \mu f$

The disadvantage of resonant filters is that they can suppress only one of the several ripple frequency components present in the output of the rectifier. If they are correctly tuned to the fundamental ripple frequency, they will not effectively suppress the other ripple frequency components, and additional filters must be used. Also, the individual tuning of each resonant circuit is a bothersome procedure. For these reasons tuned filter circuits are

seldom used in rectifier power supplies, although they find considerable application in other types of electronic circuits.

34. Review Questions

(1) What is meant by the fundamental ripple frequency and the harmonics; what is their relationship to each other?

(2) Draw a capacitor-filter circuit, explain its action and describe its advantages and disadvantages.

(3) Explain the action of an inductance filter and compare it with a capacitance filter.

(4) Why is a capacitor-input filter better than a single shunt capacitor? What is the maximum dc output voltage of the filter and how does it vary with increasing load current?

(5) What is a bleeder resistor and why is it necessary in the output of a capacitance-type filter? What are its other advantages in conjunction with any type of filter?

(6) Compare the operation of a choke-input filter with that of a capacitor-input filter. State which filter has better voltage regulation? lower ripple voltage? higher dc output voltage? For which application is each filter best suited?

(7) What is meant by the minimum input inductance of a choke-input filter? Compute the minimum inductance for a three-phase, full-wave, 60-cycle circuit, if the dc output voltage is 400 volts and the load current is 250 ma.

(8) Define incremental inductance. How does the variation in incremental inductance of a swinging choke make it useful for choke-input filters?

(9) When is a resistance-capacitance filter practicable? Compute the ripple reduction factor of an R-C filter, using 25-μf shunt capacitors and a 20,000-ohm series resistor, for a 60-cycle, single-phase, half-wave rectifier circuit.

(10) Design a choke-input filter for a three-phase, full-wave, 60-cycle rectifier, so that the fundamental ripple voltage from the filter output is only 0.1% of the input ripple. The dc voltage of the rectifier is 300 volts, the output current is 500 ma, and the bleeder current is 50 ma. (Hint: Compute first the minimum input inductance of the filter, then the value of the shunt capacitance.)

(11) What value capacitance is required to tune the filter in question (10) to parallel resonance at the fundamental ripple frequency?

RECTIFIER AND FILTER DESIGN DATA

35. Rectifier Tube Characteristics

The choice of a rectifier tube is restricted to two major commercially available categories; high-vacuum thermionic types and hot-cathode gas-filled types. High-vacuum rectifiers, available as half-wave or full-wave diodes, are used primarily for low power applications at plate voltages up to about 500 volts and load currents not exceeding a few hundred milliamperes. Because of their high peak voltages, high-vacuum diodes are also employed in applications requiring very high dc voltages at extremely small currents, such as for cathode-ray tube accelerating potentials.

The hot-cathode gas diodes, ordinarily mercury-vapor types, find their chief application in industry and in transmitting stations, where high dc plate powers are required. Mercury-vapor tubes have low tube voltage drops (about 10 to 15 volts) compared to high-vacuum types, but must be preheated and protected from even momentary overloads. Because of the possibility of arcback, · the peak inverse voltage of mercury-vapor tubes is critical, and dependent to some extent on the tube's ambient temperature. (See Chap. 1.)

The most important design ratings of representative commercial rectifier tubes are listed in Table III. The significance of these

ratings is explained in Chap. 1. For full-wave types (two diodes in one envelope) the maximum plate currents listed apply to the plate of one diode only.

36. Rectifier Circuit Design Data

Table I summarizes the main characteristic and design factors of the various rectifier circuits discussed in Chaps. 2 and 3. The significance of these factors has been described in detail in Chaps. 2 and 3, but it may be well to explain the derivation and use of the table, and in the process recapitulate the meaning of the various design factors.

All numerical factors in Table I are ratios based on a dc output voltage of 1 volt, or a dc output of 1 amp. In the case of the secondary ac voltages and currents, the numbers express the ratio of the rms value of the voltage or current to the dc output voltage or current. The average current per tube expresses the fraction contributed by each tube to the total dc output (taken as 1). The value of the peak current per tube expresses the ratio of the peak value of the output current waveform to its average or dc value, taken as 1. This is the inverse of the average-to-peak current (or voltage) ratio, previously stated in Chaps. 2 and 3 for various circuits. For example, it was stated that the average current of single-phase, full-wave rectifier is 0.636 times the peak current. In Table I the inverse ratio (peak current to average current) is listed as 1.57, which evidently is 1/0.636. Note, however, that the peak-to-average ratios assume that nothing is done to change the output current waveform of the rectifier. In other words, the rectifier must be connected directly to a pure resistance load, so that the full ripple in the output waveform is present. If the rectifier is connected to a filter, the output waveform is changed by suppression of the ripple and the average current or voltage values begin to approach the peak values. The values listed in Table I do *not* apply to filter operation. In the case of an "ideal" choke-input filter (with infinite input inductance), for example, the current ripple is entirely suppressed and the average dc load current becomes equal to the peak current per plate. (The exception is the double-wye, three-phase circuit, where the peak current-per-tube must be held to one-half of the average dc current, as explained in Chap. 3).

Table I also lists the rms ripple voltage as a percentage of the dc output voltage. These values were obtained by taking the root-mean-square value of the sum of the fundamental and har-

monic ripple voltage amplitudes. The values stated represent the combined effect of all ripple components present in the rectifier output. This is useful for filter calculations.

The values listed in Table I for the secondary winding voltages and currents (E_s and I_s, respectively) assume that no voltage is lost in the transformer windings and across the tubes. To obtain actual values for the required secondary voltages and currents in a specific circuit, the voltage drop across the transformer secondary windings and the tube voltage drops must be added to the value obtained from Table I. Manufacturer's component data and tube manuals may be consulted to obtain the tube and transformer drops.

The kva (kilovolt-amperes) values listed in Table I for the transformer primary permit estimating current-handling requirements of the transformer and its required kva rating. Note the excessive kva rating for the single-phase, half-wave circuit; this is caused by the dc saturation of the unbalanced rectified current flowing through the transformer secondary, as was explained in Chap. 2. The kva rating represents the input power including the reactive component. To obtain the true input power the kva value must be multiplied by the power factor of the circuit. Both the kva and the power factor listing assume that there are no losses in the transformer. To obtain true values these losses must be added to the listed values.

As is apparent from Table I, the relation between the peak inverse voltage per tube and the dc output voltage depends on the rectifier circuit. The listings represent minimum values calculated for sinewave conditions. Because of the presence of line surges and other transients a safety factor should be allowed for the peak inverse voltage per tube. Tubes should be selected (from Table II) whose peak inverse voltage rating exceeds the required values listed in Table I for the particular circuit used.

The proper use of Table I will become evident through the examples of rectifier calculations, worked out later on in the chapter. For complete rectifier-filter circuit design all the tables in this chapter must be used in conjunction with each other.

37. Filter Design Data

Some of the critical design factors determining filter operation have been discussed in Chap. 4 and formulas have been given for computing the reduction in ripple voltage for different filter sections. These various factors and relations are summarized in the filter design chart of Table II, which gives the minimum

TABLE I: RECTIFIER CIRCUIT DESIGN DATA

	Half-wave 1 phase	Full-wave 1 phase	Full-wave bridge 1 phase	Half-wave 3 phase (delta-wye)	Half-wave 3 phase Zig-zag	Half-wave 6 phase or 3 phase delta-star	Double Y inter-phase 3 phase	Full-wave 3 phase bridge (delta-wye)
Tubes needed	1	2	4	3	3	6	6	6
Reference Fig. No.	3	5	6	12	13	15	14	16
				Transformer loading values				
Leg voltage								
E_s (RMS) (Secondary Voltage)	2.22	1.11	1.11	0.855	0.855	0.74	0.855	0.43
I_s (RMS) (Secondary Current)	1.42	0.707	1.0	0.58	0.58	0.41	0.29	0.816
Trans. (PRI) KVA	3.49	1.11	1.11	1.21	1.21	1.28	1.05	1.05
Line power factor	0.29	0.90	0.90	0.83	0.83	0.955	0.955	0.955
				Tube loading values (resistance load)				
Peak inverse voltage on tube	3.14	3.14	1.57	2.09	2.09	2.09	2.09	1.05
Current per tube (avg.)	1.0	0.5	0.50	0.33	0.33	0.167	0.167	0.33
Current per tube (peak)	3.14	1.57	1.57	1.21	1.21	1.05	0.50	1.05
(DC load current=1.0)								
				D-C output voltage characteristics				
Ripple frequency predominating	1f	2f	2f	3f	3f	6f	6f	6f
RMS Ripple voltage, per cent of dc output voltage	111.	48.3	48.3	18.3	18.3	4.2	4.2	4.2

inductance for choke-input filters and the L-C product values for both choke-input and capacitor-input filters.

Note that Table II gives L-C values for both 50-cycle and 60-cycle supply sources. The 50-cycle ac supplies are common in many countries. The horizontal axis at the bottom of the chart lists the rms ripple voltage (of both fundamental and harmonic components) as a percentage of the dc output voltage. The horizontal scale at the top of the chart gives the ripple voltage in db (decibels) with reference to the dc output voltage. Decibels are frequently used to express a relative voltage ratio and the db values may be found from the relation db $= 20 \log_{10} E_1/E_0$, where E_1/E_0 is the voltage ratio to be expressed in db.

For example, the value of 10% ripple in the chart corresponds to −20 db, since for a voltage ratio E_1/E_0 of 0.1 (10%),

$$20 \log 1/10 = 20 \times (-1) = -20 \text{ db}$$

Similarly, for a ripple of 0.5%, the voltage ratio E_1/E_0 is 0.005 or 1/200, and hence

$$db = 20 \log 1/200 = 20 (\log 1 - \log 200) = -46 \text{ db}$$

The chart, therefore, shows a value of −46 db corresponding to a ripple of 0.5%. Negative db values are usually spoken of as being so many below the reference voltage. Thus a ripple of 0.5% is referred to as being 46 db below the dc output voltage.

Choke-Input Design Procedure. To design a choke-input filter by means of the chart, assume a plausible minimum value for the input inductance. Then determine from the manufacturer's tube manuals or by calculation, the actual value of the dc output voltage into this input inductance for the particular circuit and desired operating values. A check with the minimum-inductance formula $L = KE/If*$ will then reveal whether the assumed inductance value is adequate, or possibly even excessive. If the load-current requirements of the circuit vary over a range, the minimum load current (or bleeder current) should be substituted for I in the minimum inductance formula. Finally, the L-C product for the desired ripple reduction and circuit is determined from the chart, and the value of the shunt capacitance is computed by dividing it into the L-C product. Depending on requirements, a different order may be followed in the procedure.

---

* Note that E in this case is the dc output voltage, not fundamental component of ripple voltage as shown in the equation on page 46.

TABLE II: L-C FILTER DESIGN CHART

RMS RIPPLE VOLTAGE IN DB WITH REFERENCE TO DC OUTPUT VOLTS

LC (HENRYS × MICROFARADS)

RMS RIPPLE VOLTAGE IN PERCENT OF DC OUTPUT VOLTS

| I SECTION | 2 SECTIONS | 3 SECTIONS |
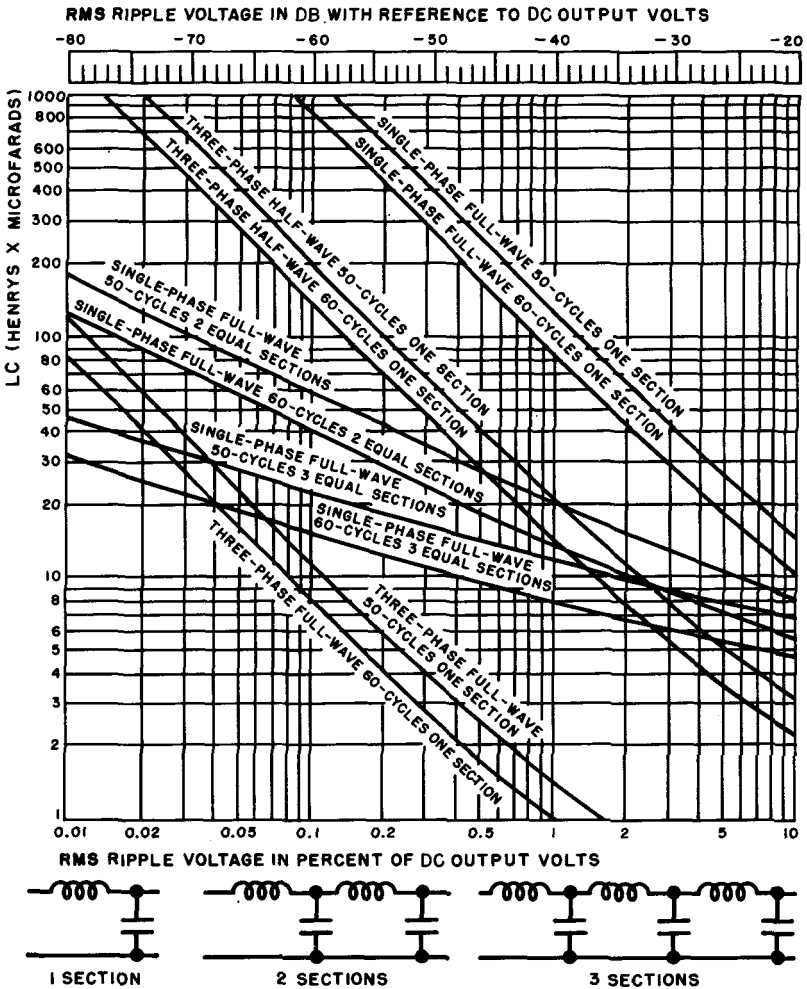
MINIMUM INDUCTANCE FOR A CHOKE-INPUT FILTER IS DETERMINED FROM

$$L = \frac{KE}{If}$$

WHERE

L = MINIMUM INDUCTANCE IN HENRYS K = 0.0527 FOR FULL-WAVE, SINGLE-PHASE
E = d-c OUTPUT IN VOLTS   = 0.0132 FOR HALF-WAVE, THREE-PHASE
I = OUTPUT CURRENT IN AMPERES   = 0.0053 FOR FULL-WAVE, TWO-PHASE
f = SUPPLY FREQUENCY IN CPS   = 0.0016 FOR FULL-WAVE, THREE-PHASE

Courtesy ITT Reference Data for Radio Engineers

Type and Service	Peak Inverse Volts	Maximum Peak Amperes (per plate)	Maximum Aver. Amperes (per plate)	Filament Volts	Amperes
HIGH-VACUUM					
5Y3-GT (full-wave)	1,400	0.40	0.075	5.0	2.0
5U4-G (full-wave)	1,550	0.675	0.135	5.0	3.0
5V4-G (full-wave)	1,400	0.525	0.087	5.0	2.0
5R4-GY (full-wave)	2,800	0.65	0.125	5.0	2.0
6W4-GT (half-wave)	1,250[1]	0.60	0.125	6.3	1.2
1V2 (half-wave)	7,500	0.01	0.0005	0.625	0.3
1X2A (half-wave)	18,000	0.01	0.001	1.25	0.2
1B3GT (half-wave)	30,000	0.017	0.002	1.25	0.2
2X2-A (half-wave)	12,500	0.060	0.0075	2.5	1.75
2V3-G (half-wave)	16,500	0.012	0.002	2.5	5.0
836 (half-wave)	5,000	1.0	0.25	2.5	5.0
878 (half-wave)	20,000	0.02	0.005	2.5	5.0
1616 (half-wave)	6,000	0.80	0.13	2.5	5.0
5825 (half-wave)	60,000	0.04	0.002	1.6	1.25

MERCURY-VAPOR (except as noted)

3B25	(Xenon-filled half-wave type)	4,500	2.0	0.5	2.5	5.0
816	(half-wave)	7,500	0.5	0.125	2.5	2.0
866-A	(half-wave)	10,000	1.0	0.25	2.5	5.0
872-A	(half-wave)	10,000	5.0	1.25	5.0	7.5
575-A	(half-wave)	15,000	6.0	1.5	5.0	10.0
869-B	(half-wave)	20,000	10.0	2.5	5.0	19.0
857-B	(half-wave)	22,000	40.0	10.0	5.0	30.0
5558	(half-wave)	5,000	15.0	2.5	5.0	4.5
5561	(half-wave)	10,000	16.0	4.0	5.0	10.0

[1] In rectifier service, 1250 must be used. A 3500 volt rating is used only in damper service.

Capacitor-Input Design Procedure. For a capacitor-input filter, it is advisable to determine first the required value of the input (shunt) capacitor for the desired rectifier output voltage. This information is usually given in manufacturers' tube manuals, or it may be calculated. The L-C product for the desired minimum ripple voltage is then determined from the chart for the circuit and supply frequency used. Finally, the value of the series inductance is determined by dividing the L-C product by the value of the shunt capacitance (C). If several filter sections are needed, the L-C product is ascertained from the proper curve in the chart. The same values are used for the series inductance and shunt capacitance of each section.

R-C Filters. A simple formula has been given in Chap. 4 for determining the ripple reduction factor of an R-C filter in terms of the component values (R and C) and the ripple frequency (f). This formula is easy to use for one or more R-C sections and makes it unnecessary to provide an additional design chart for R-C filters.

38. Typical Rectifier-Filter Calculations

The two examples below illustrate the procedures to be followed for designing rectifier-filter systems, using the design data provided in this chapter and manufacturer's tube data.

Example 1: A single-phase, 60-cycle, full-wave rectifier is required to supply to the filter and load a dc output voltage of 430 volts at a load current of 225 ma, and should have a ripple not exceeding 1%. Choose tubes, filter, and component values.
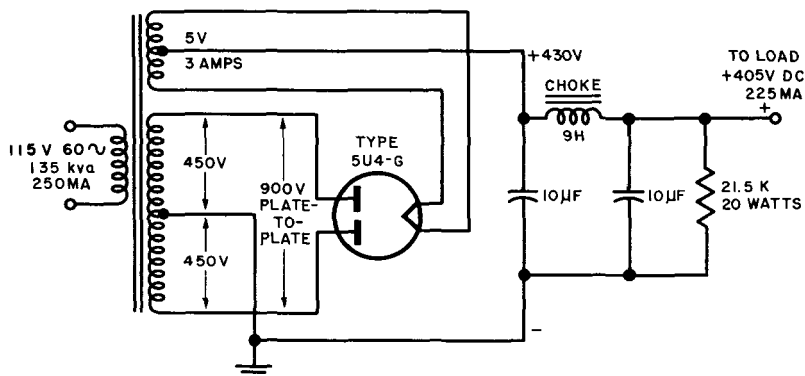
Fig. 30. A rectifier-filter circuit illustrating Example 1.

Solution: (Refer to Fig. 30) From Table I, the peak inverse voltage on the rectifier tube will be 3.14 x 430 = 1,350 volts, and the peak plate current is 1.57 x 225 = 354 ma.

From Table III it is apparent that a 5U4-G full-wave rectifier tube will easily and economically meet these requirements.

Referring to the manufacturer's receiving tube manual, it is seen that either a choke-input or capacitor-input filter will be able to supply the required dc output voltage and current, but a choke-input filter will necessitate a plate-to-plate transformer secondary voltage of 1100 volts (550 volts each leg), while the capacitor-input filter requires only 900 volts secondary plate-to-plate voltage. A capacitor-input filter will thus permit the use of a less expensive power transformer, although its voltage regulation will be poorer than that of the choke-input type. Choosing a capacitor-input filter for economy, we see from the tube manual that an input capacitor of 10 microfarads will give a dc output voltage of 430 volts into the filter at the desired load current of 225 ma (112.5 ma per plate). The tube manual also states that the regulation from half load to full load (112.5 ma to 225 ma) is 80 volts.

To design the filter, refer to Table II, which gives for one section an L-C product of about 83 for a ripple voltage of 1% of the output (or 4.3 volts ac). Since the input capacitor is 10 microfarads; the minimum series inductance of the section should be 83/10 or 8.3 henrys. A practical value of 9 henrys will be more than sufficient. Allowing about a 25-volt drop in the choke, the output voltage from the filter will be 405 volts at full load.

A bleeder resistor drawing about 10% of the load, or about 20 ma, should be connected across the filter output. By Ohms Law its resistance should be 430/.02 = 21,500 ohms and its wattage rating must be more than 430 x .02 = 8.6 watts. For safety, a rating of 15 to 20 watts should be selected.

The dc output power of the rectifier is the product of output voltage and full load current or 430 x 0.225 = 97 watts (approximately). Adding about 15% or 15 watts to take care of bleeder requirements, tube and transformer drops, the total dc power is about 112 watts. The kva rating from Table I is 1.11 times the dc output power or 1.11 x 112 = 125 kilovolt-amperes. In practice, a transformer with a rating of about 135 to 150 kva should be chosen.

Example 2: It is desired to design a 60-cycle, three-phase, half-wave rectifier-filter circuit capable of delivering a dc output of 3,500 volts at 3 amperes maximum load current, and with a ripple not exceeding 0.5% of the output voltage.

Solution: (Refer to Figure 31.) Reference to Table I shows that the peak inverse voltage that each rectifier tube must withstand is 3,500 x 2.09 = 7,320 volts and the peak plate current per tube is 3 x 1.21 = 3.63 amperes; the average plate current is 3 x 0.333 = 1 ampere each tube. Inspection of Table III reveals that the lowest-power tube capable of meeting these requirements is the type 872-A, half-wave mercury-vapor tube. For a three-phase, half-wave rectifier three 872-A's will be needed.
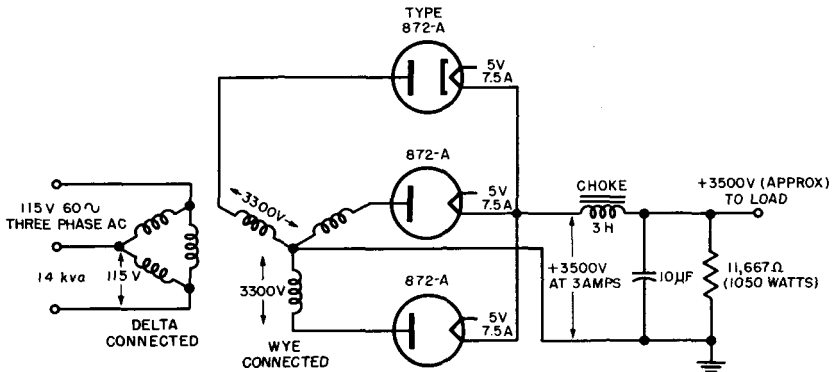
Fig. 31. A rectifier-filter circuit illustrating Example 2.

Neglecting the dc resistance of the filter choke, each secondary leg of the power transformer must develop an rms voltage of 3,500 x 0.855 = 3000 volts (see Table I) and provide a secondary current of 3 x 0.58 = 1.74 amperes. Plus 10% for tube, transformer and filter drops, the secondary voltage per leg should be about 3,300 volts. Since the output power is 3,500 x 3 = 10.5 kw, the kva rating of the transformer primary (from Table I) should be 10.5 x 1.2 = 12.7 kva. Adding again 10% to compensate for losses, the transformer should be rated at 14 kva. In addition, a filament winding must be provided, rated at 5 volts, 22.5 amperes, to supply the 5-volt, 7.5-ampere filaments of the three rectifier tubes.

A choke-input filter must be used, since this is the only type applicable to polyphase circuits. Assuming a minimum load current (bleeder or voltage divider) of 10% of the total, (0.3 ampere), the minimum input inductance (from Table II) becomes

$$L = \frac{k\,E}{I\,f} = \frac{0.0132 \times 3,500}{0.3 \times 60} = 2.57 \text{ henrys}$$

A choke rated 3 henrys at full load should prove adequate. For a permissible ripple of 0.5% of the output, the chart (Table II)

gives an L-C product of about 30 for the three-phase, half-wave circuit. The value of the shunt capacitor, therefore, is

$$\frac{LC}{L} = \frac{30}{3} = 10 \text{ microfarads}$$

The value of the bleeder resistor (if one is provided) to draw 10% of the load current, or 0.3 ampere, should be 3,500/0.3 = 11,667 ohms and its wattage rating must exceed 3,500 x 0.3 = 1050 watts. (The high power rating will probably make it uneconomical to use a bleeder.)

39. Review Questions

(1) What is the chief application of high-vacuum rectifier tubes and at what power level would you begin to use mercury-vapor tubes. What are the relative advantages and disadvantages?

(2) Explain the significance of the rectifier design data in Table 1. Why are the transformer requirements for a single-phase, half-wave circuit excessively high?

(3) Describe the effect of resistive, capacitive, and inductive loading of the rectifier output on the ratio of peak to average current per tube.

(4) What allowance should be made, when using Table I, for voltage drops lost in tubes, transformer windings, filter, etc.

(5) How would you obtain the true power rating of a transformer from its kva rating in a specific circuit, using Table I?

(6) Explain the normal design procedure for a choke-input filter, using Table II. What current would you use to compute the minimum input inductance of the choke?

(7) Design a capacitor-input filter, using Table II, that will give a ripple of 0.1% with a three-phase, 60-cycle, full-wave circuit. If the shunt capacitance is 5 microfarads, what should be the value of the inductance? Express the ripple in db.

(8) Design a single-phase, half-wave rectifier (60 cycles) that will give 250 volts dc output at a load of 125 ma. Choose a filter, select tubes, and state all component values, including a bleeder resistor.

(9) Design a 60-cycle, three-phase, full-wave (delta-wye) rectifier-filter system with a choke-input filter providing an output of 8,000 volts dc at 5 amperes load current. The ripple voltage should not exceed 0.04% of the dc output voltage.

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