HIGH-POWER RECTIFIERS FOR RADIO TRANSMITTERS

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STUDY SCHEDULE NO. 29

For each study step, read the assigned pages first at your usual speed, then reread slowly one or more times. Finish with one quick reading to fix the important facts firmly in your mind, then answer the Lesson Question for that step. Study each other step in this same way.

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High-Power Rectifiers for Radio Transmitters

Introduction

THE power demand of a large broadcast transmitter may be equal to that of a small town, with the added complication that unusually high d. c. voltages are required for the plates and grids of the transmitting tubes. The approximate maximum d.c. plate voltages required in typical radio transmitters of various carrier output powers are indicated in Table *I*.

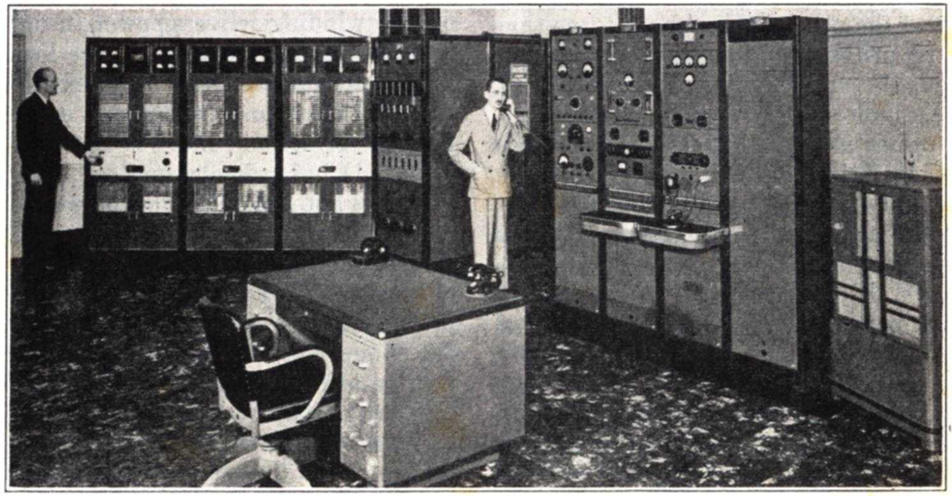
The common sources for obtaining high d.c. voltages include rectifiers operating from an a.c. supply line, motor-generator sets, gasoline engine-driven generators, dynamotors operating from low-voltage storage batteries and, in a very few cases, high-voltage storage batteries. In this lesson, we shall deal only with rectifier systems, these being most commonly used because of their economy and convenience.

A rectifier system is made up of three component units: *1.* A transformer system for changing the a.c. supply voltage to a desired high a.c. voltage or voltages; *2.* Rectifier tubes

CARRIER POWER OUTPUT	APPROXIMATE PLATE VOLTAGE
10 Watts	350 Volts
20 "	550 "
50 "	760 "
100 "	1,050 "
250 "	1,250 "
500 "	1,750 "
1,000 "	2,200 "
2,500 "	3,000 "
5,000 "	10,000 "
10,000 "	10,000 "
25,000 "	10,000 "
50,000 "	20,000 "
100,000 "	25,000 "
500,000 "	30,000 "

TABLE I. Approximate maximum d.c. plate voltages required in various sizes of radio transmitters.

for converting each resultant a.c. voltage into a pulsating d.c. voltage; *3.* A filter system for smoothing out the pulsations in order to obtain a continuous d.c. voltage.



Courtesy RCA Mfg. Co., Inc.

This RCA type 5-D 5,000-watt transmitter at station WFBR in Baltimore, Maryland is a typical example of modern transmitter design. From his centrally-located desk, the radio operator on duty can see all meters on the rack panels. Tubes in the left bank of racks, including the air-cooled high-power rectifier tubes, are accessible from the front through doors protected by interlock switches. All rear panels of dangerous high-voltage sections have the same arrangement, to protect the operator from accidental shock.

Transformers

Single- and Multiple-Phase Transformers. The transformer is normally the most efficient of all electrical devices. Where an efficiency of 80% to 90% is considered excellent for a generator or a motor, large transformers attain efficiencies of 98% to 99%.

Transformers serve to change the available a.c. voltage to a desired higher or lower value. They may be used in single-phase or multiple-phase circuits. In general, the single-phase transformer (or one phase of a polyphase transformer system) consists of two windings; the available voltage is applied to the *primary winding,* while the desired voltage is delivered by the *secondary winding.* When the secondary voltage is higher than the primary voltage, the transformer is called a *step-up* transformer. When the secondary voltage is lower than the primary, the device is referred to as *step-down* transformer.

In low-power rectifiers, it is customary to have two secondary windings, one having fewer turns than the primary and furnishing the a.c. filament voltage for the rectifier tubes, and the other having more turns than the primary and furnishing the plate supply voltages (after rectification). An important advantage of the transformer as used in rectifier circuits is that it isolates the high-voltage d.c. supply for the transmitter from the power line and from other transmitter power supply circuits.

Multiple-phase (polyphase) transformers may be two-phase, three-phase, six-phase, etc. In two-phase circuits, the transformer consists essentially of two single-phase transformers, the primaries of which are connected to the two-phase supply and the secondaries of which furnish a two-phase supply having either a higher or lower voltage value. In three-phase circuits, three separate single-phase transformers may be used or, as is more common, a single three-phase transformer having three primary and three secondary windings all on a single magnetic structure may be employed. The primary windings may be connected either in Y or delta, and the secondary windings also either in Y or delta, depending on the type of load and the voltage requirements.

A particularly valuable characteristic of the transformer, frequently applied in rectifier circuits, is its ability to change the number of phases in the supply voltage. Thus, a two-phase supply may be converted to a four-phase, a three-phase supply to a six-phase, a three-phase supply to a two-phase, a six-phase supply to a three-phase, etc. Typical phase conversion connections for transformers, as used in rectifier circuits, will be discussed later in this lesson.

Theory and Construction of the Single-Phase Transformer. The single-phase transformer consists of two electric circuits or windings, linked with the same magnetic circuit or core. The *primary* winding receives power from the single-phase a.c. supply, and the *secondary* winding delivers power (usually at a different voltage) to the load.

Typical magnetic circuit designs for single-phase transformers are shown in Figs. *1A*, *1B* and *1C*. The *core type* (Fig. *1A*) has primary and secondary windings both on one leg of the core, or has each winding divided into two series-connected coils, one on each leg of the core. The *shell type* (Fig. *1B*) has primary and secondary coils both on the same central core, and the return portion of the magnetic circuit is split into two parts. The *cruciform type* (Fig. *1C*) has the two coils on the same central core, and the return portion of the magnetic circuit is split into four parts.

In each case the iron core is laminated. to minimize eddy currents induced by the alternating flux. The

three types are alike in principle, and differ only in the relative proportions of the electric and magnetic circuits, method of construction, cooling, insulation and connection. The cruciform type is the most economical in that it requires the least copper and magnetic material.

The higher the voltages involved, the more important becomes the problem of securing adequate insulation between the primary windings, the secondary windings and the iron core. To reduce insulation requirements, the primary and secondary windings are often divided into a number of pancake-shaped coils arranged alternately (inter-leaved) on the core, with all primary coils connected together in series to the power line and all secondary coils connected in series to the rectifier system; cylindrical-shaped coils each of different diameter, placed over each other on the core in such a way that adjacent coils belong to different windings, give the same result.

From an operating viewpoint, the relationships between current and voltage in both the primary and secondary play an important part. To obtain a better understanding of the operation of a transformer, let us consider the circuit action along with phase conditions, using the basic transformer circuit shown in Fig. *1D*.

We will first assume that *the load circuit is open.* Voltage V_1 applied to the primary winding will produce a.c. current I_N, the primary no-load current. Because the primary coil is highly inductive, this current will lag the applied voltage by *nearly 90°*. Let us represent this fact by means of vectors, as with vectors V_1 and I_N in Fig. *2A*. The no-load current may be resolved into two components, I_H in phase with V_1, and I_M lagging V_1 by 90°. Component I_H supplies the no-load losses, including hysteresis and eddy current losses in the core and a very small copper loss in the primary winding. Component I_M is the magnetizing current; it sets up a flux (Φ_M, in phase with I_M) which flows through the core of the transformer. This flux links both the primary and secondary windings and, since an alternating flux through both coils will cause changes in flux linkage, induces voltage E_1 in the primary winding and voltage E_2 in the secondary winding (the voltage induced in the primary is, of course, a back e.m.f.).

The voltages induced in the two windings, being produced by the same alternating flux, will be proportional to the number of turns in the respective windings. Thus, the induced voltage E_2 in the secondary will be equal to N_2/N_1 (the turns ratio) times the

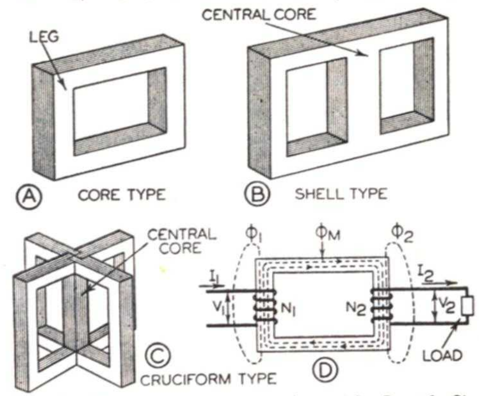


FIG. 1. Typical core constructions (*A*, *B* and *C*) and basic circuit (*D*) for a single phase transformer. ϕ_1 is the primary leakage flux, ϕ_2 is the secondary leakage flux, and ϕ_M is the magnetizing flux.

induced voltage E_1 in the primary, where N_2 is the number of turns in the secondary and N_1 the number of turns in the primary.* (From now on in this lesson, we will designate the ratio of secondary to primary turns as T_R.) Since the a.c. flux Φ_M changes most rapidly when passing through zero value, and least rapidly when passing through maximum value, the induced voltages will be maximum when the flux is zero and zero when the flux is

*This is true only if the primary leakage flux ϕ_1 is neglected or is negligibly small.

maximum. This signifies that the induced voltages E_1 and E_2 will lag the flux Φ_M by 90°, as shown in Fig. *2A*.

Note that the induced voltages E_1 and E_2 in Fig. *2A* are 180° out of phase with the applied voltage V_1. This checks with Lenz's law of induced e.m.f., which states that the induced voltage must be in such a direction as to tend to oppose the change of flux (and hence the applied voltage) producing the induced voltage.

Since the no-load current is very small (usually less than 5% of the full-load current), the *IR* drop in the primary winding is negligible, and E_1 must be practically equal (and opposite) to V_1. For this reason, vector

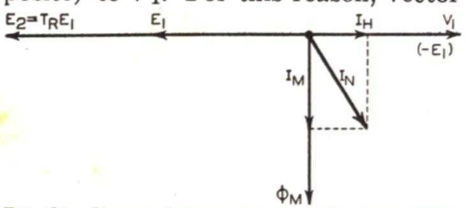


Fig. 2A. Vector diagram for a single-phase transformer when there is no secondary load. Although T_R is assumed equal to 2 in this diagram, it is more customary to assume a value of 1 for T_R when drawing a vector diagram, in order to simplify the presentation.

$-E_1$ in Fig. *2A* is drawn as coincident with vector V_1. We now have the complete no-load vector diagram for a single-phase transformer.

Assume now that the load circuit of Fig. *1D* is closed, with the values of the load voltage V_2, the load current I_2 and their phase relation θ_2 being known. These basic vectors are drawn in Fig. *2B*, with V_2 serving as reference vector. We have assumed an inductive load, so I_2 *lags* V_2 by the angle θ_2. By inducing a voltage E_2 into the secondary, the primary supplies power for the load. This induced voltage does not equal the load voltage V_2, however, for the secondary has resistance, R_2, and inductive leakage reactance, X_2. (From Fig. *1D*, Φ_2 is the flux produced by the flow of secondary current; since this flux does not react on the main flux, it merely serves to add reactance to the secondary circuit.) The induced voltage E_2 must be the vector sum of V_2, the secondary I_2R_2 drop which is in phase with I_2, and the secondary I_2X_2 drop which is 90° ahead of I_2. Note in Fig. *2B* how V_2 plus I_2R_2 plus I_2X_2 gives E_2, the secondary induced voltage.

In order for E_2 and I_2 to exist, we must have a corresponding voltage and current in the primary. The primary must have a back e.m.f. $-E_1$, which is 180° out of phase with E_2, and there must be a current I_1' which is the useful primary load current and is 180° out of phase with I_2 (see vectors $-E_1$ and I_1' in Fig. *2B*). In addition to I_1', the primary source is required to furnish the core magnetizing flux Φ_M, at right angles to E_2; this will be in phase with current I_M which produces this flux. Finally, core losses must be supplied by a small current which is in phase with V_1; when this current vector is added to vector I_M, we get vector I_{M+L} in Fig. *2B*, which is less than 90° away from V_1 and represents the current required for both core losses and magnetizing flux. The total primary current is the vector sum of I_1' and I_{M+L}, and is shown as I_1.

We must not overlook the fact that the primary has resistance R_1, and leakage reactance X_1, each producing a voltage drop which must be supplied by the source. We take these into account in Fig. *2B* by adding voltage vector I_1R_1 (in phase with I_1) and voltage vector I_1X_1 (90° ahead of I_1) to $-E_1$, thereby getting the applied primary voltage V_1. I_1 lags V_1 by the angle θ_1, showing that the transformer and its load are inductive in this example.

Summary of Important Facts Pertaining to Transformers. The vector diagram in Fig. *2B* was developed by assuming definite load current and voltage conditions. Actually, however, a definite supply voltage value is present in a practical case, a given load is to be fed, and the main problem is to determine what the values of load voltage and current will be.

The no-load secondary voltage is the same as the induced secondary voltage *under no-load conditions*, and can readily be determined by multiplying the primary voltage by the turns ratio; this value is often used as an initial approximation of the full-load voltage. The secondary current can be estimated with the same degree of accuracy by dividing the primary current by the turns ratio. These approximations are based on the assumption that the transformer has no losses, no primary and secondary resistance, and no leakage reactance; this assumption is satisfactory only for initial considerations, to get a general idea of what the load current and voltage will be.

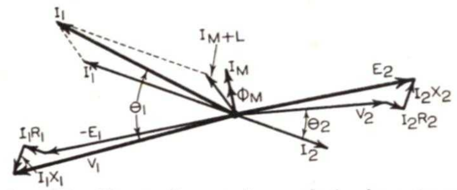


Fig. 2B. Vector diagram for a single-phase transformer having an inductive load connected across its secondary winding. A value of 1 is assumed for the turns ratio. The actual value of voltage E_1 will be $E_2 \div T_R$; the actual value of current I_1' will be $I_2 \times T_R$, where T_R is the true turns ratio.

We have seen that when the secondary of a single-phase transformer is open (a no-load condition), the primary of the transformer draws enough current from the line to produce magnetization of the core, and enough power is drawn to take care of core losses and any I^2R loss which may exist in the primary (the latter loss is usually neglected, because the no-load primary current is quite low). The core loss is due to eddy currents and hysteresis in the core. For a given core lamination material, hysteresis and eddy current losses will increase with frequency and with flux density in the core.

When a load is placed across the secondary of a single-phase transformer, the induced secondary voltage changes from its no-load value chiefly because of the increased primary current through the resistance and reactance of the primary. Figure *2B* shows this; with a definite primary voltage V_1 and an inductive secondary load, the primary back e.m.f. E_1 is considerably different in magnitude from V_1 because of primary resistance drop I_1R_1 and primary reactance drop I_1X_1. The induced secondary voltage E_2 will therefore be correspondingly different from its no-load value. The secondary resistance drop I_2R_2 and secondary reactance drop I_2X_2 will then make load voltage V_2 considerably different from the no-load secondary voltage. For resistive and inductive loads, the load voltage *will be less* than the no-load secondary voltage; for capacitive loads, the load voltage *may be higher* than the no-load secondary voltage.

Voltage Regulation. The difference between the no-load voltage and the load voltage, divided by the load voltage, is the voltage regulation factor; multiply by 100 to get the per cent voltage regulation. For small low-voltage output transformers and for resistive loads, the per cent regulation is about 2.5, with this value increasing somewhat for high-voltage secondaries. The regulation of power supplies depends partially upon the ability of the power transformer to maintain constant voltage during varying load requirements. A good power transformer has negligible core losses, low coil resistance and little leakage flux. The following formula, summarizing the above data on voltage regulation in a power transformer, is worth remembering.

$$\text{Per cent voltage regulation} = \frac{\text{no-load voltage} - \text{load voltage}}{\text{load voltage}} \times 100$$

Auto-Transformers. A transformer having a single winding, *part of which* *is common to both primary and secondary circuits,* is called an auto-transformer. The schematic circuit diagram for an auto-transformer is shown in Fig. *3;* observe that it is simply a single tapped coil wound on an iron core. The core used is generally similar to one of those shown in Fig. *1.* An advantage of the auto-transformer is that *the current in the common portion of the winding is equal to the difference between the primary and secondary currents,* allowing the permissible loading of the transformer to be increased. A disadvantage is that the primary and secondary circuits are not insulated from each other.

A Typical Power Transformer. In connection with the discussion of the elementary single-phase alternator,

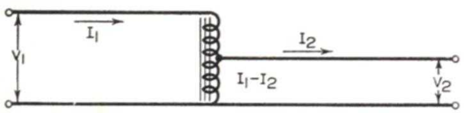


FIG. 3. Schematic circuit diagram of a voltage step-down auto-transformer.

we showed that the polarity of one brush may be considered to be 180° out of phase with the polarity of the second brush. Let us apply this thought to the single-phase transformer.

In Fig. *4A* is shown a diagram of the power transformer used in a typical 75-watt transmitter for amateur communication purposes. The primary winding is connected to the 110-volt a.c. supply. Three secondary windings are provided, one supplying 2.5 volts for the filaments of the rectifier tubes, the second supplying 7.5 volts for heating the filaments of the tubes in the transmitter, and the third supplying a high voltage (1,250 volts) which is rectified to provide a pulsating d.c. voltage. This pulsating d.c. voltage is then filtered so that a pure d.c. voltage is developed across a voltage-dividing resistance. The various d.c. voltages required by the grids and plates of the transmitter are obtained by tapping across portions of this resistance. (The details of the filtering arrangements used will be treated later.) We are here concerned with the manner in which the pulsations in the rectified voltage are minimized so that the amount of filtering required will also be minimized, thereby reducing the cost of the chokes and condensers needed.

Note that all three secondary windings in Fig. *4A* are center-tapped. The filament windings in a transmitter are center-tapped in order to give more uniform emission from all parts of the filament, to give further reduction in ripple voltage in the case of a rectifier tube, and to reduce hum modulation in the case of r.f. amplifier tubes. (Symmetry of the rectified filament circuit is also advantageous.) In the high-voltage circuit, the center tap is provided so that the two halves of the winding may be used as *two sources of single-phase voltage, these being of opposite polarity.* Thus, windings *oa* and *ob* supply voltages each equal to one-half the voltage developed in the complete secondary winding *ab,* but their polarities are 180° out of phase. This is shown in Fig. *4B.*

Now referring to Fig. *4A,* you will observe that a rectifier tube is connected into each of the high-voltage secondary leads. Each tube passes current only when its plate is positive with respect to the filament (only during the positive half-cycle of the a.c. voltage). Thus, circuit or phase *oa* delivers the pulsating voltage shown in Fig. *4C* to the filter circuit. Similarly, circuit or phase *ob* delivers the pulsating voltage shown in Fig. *4D* to the filter circuit. Either of these pulsating voltages would be quite difficult to smooth out so as to give a continuous d.c. voltage. However, when the two voltages are connected in parallel across the filter circuit input, the combined voltage is that shown in Fig. *4E,* and this is very much easier to smooth out.

The circuit shown in Fig. *4A* is known as a *full-wave* rectifier circuit.

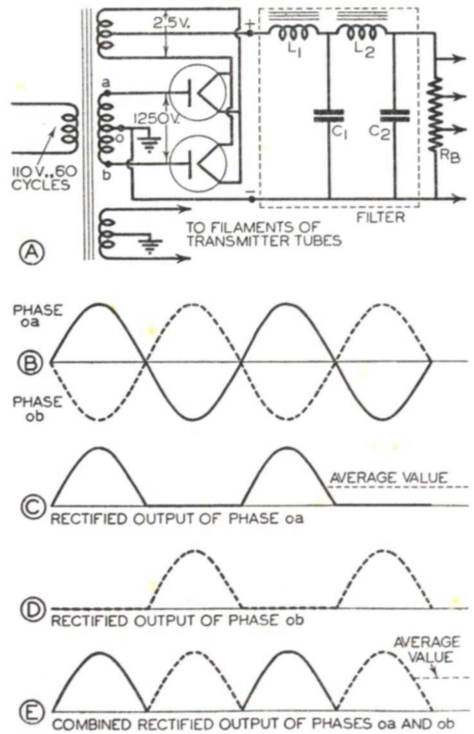


FIG. 4. Full-wave rectifier system, and wave forms of voltages present in various parts of the circuit.

It may be considered as utilizing a single-phase supply to give the equivalent of two separate phases 180° apart. It exemplifies a principle widely used in increasing the available number of phases; this same principle makes possible the 3- to 6-phase conversion which is widely used in the rectifier systems of high-power radio transmitters.

The Three-Phase Transformer. Considerable space, wiring and initial cost may be saved by the use of a three-phase transformer in place of three single-phase transformers when a three-phase a.c. supply is employed. With a few minor exceptions, the three-phase transformer is applicable wherever three single-phase transformers may be used. The same transformer connections may be employed: Y-Y, Y-delta, delta-Y, and delta-delta. Three-phase transformers may be of the *core type,* the *shell type,* or the *cruciform type.* The *core-type* construction is illustrated in Fig. *5A.**

The evolution of the transformer in Fig. *5A* from three separate single-phase transformers is shown by Fig. *5B.* Here, three single-phase core-type transformers, each having its primary and secondary windings wound on one outer leg (on *1, 2,* and *3,* respectively), are placed so that the legs opposite the windings butt against each other. The flux flowing through this common leg will be equal to the vector sum of the magnetic fluxes flowing in the core of each transformer; thus, the resultant flux Φ_R is equal to $\Phi_1+\Phi_2+\Phi_3$.

Since the primaries of the three transformers in Fig. *5C* are assumed

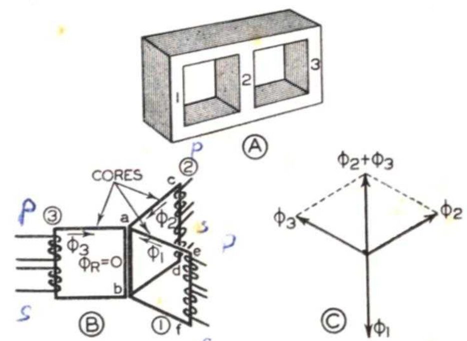


FIG. 5. Three-phase core-type transformer (*A*), its evolution from three single-phase transformers (*B*), and vector diagram (*C*) showing that the fluxes in the three core legs add up to zero.

to be connected to a three-phase supply, the fluxes Φ_1, Φ_2 and Φ_3 are 120° apart in phase. Hence, the sum of the three fluxes is equal to zero, as shown in Fig. *5C* (adding Φ_2 to Φ_3 gives

*A three-phase core-type magnetic circuit appears very much like a single-phase shell-type magnetic circuit. Remember that in the three-phase transformer, there is one primary winding and one secondary winding on each of the three legs.

$\Phi_2+\Phi_3$, and adding $\Phi_2+\Phi_3$ to Φ_1 gives zero). Since no flux flows through the common core *ab*, this core may be eliminated. Moreover, nothing is lost by eliminating sections *a-c* and *b-d* of the core of transformer *2*, moving core element *c-d* up to position *a-b*, and swinging core element *e-f* into line with the other two cores. We then have the core form presented in Fig. *5A*, which is widely used for three-phase transformers.

The different winding connections possible with three-phase transformers are shown diagrammatically in Figs. *6A*, *6B*, *6C*, and *6D*. The ratios of the secondary line voltages to the primary line voltages (assuming that T_R is the ratio of secondary turns to primary turns *for each phase*) are given below the diagrams. Remember that each primary winding is associated with a given secondary winding (wound on the same leg of the core) regardless of whether the primaries form a Y or delta connection with the other two primary windings and regardless of what connection the secondary winding forms with the other two secondary windings. Therefore, the ratio of secondary to primary *phase voltages* is equal to the ratio T_R of secondary to primary turns in each case shown. The ratio of secondary to primary *line voltages* differs from T_R for the connections of Figs. *6C* and *6D* because the line voltage is equal to the phase voltage in a delta connection and to 1.73 times the phase voltage in a Y connection. Thus, a Y-delta connection gives only 58% of the voltage obtainable with a Y-Y connection, while a delta-Y connection gives 1.73 times the Y-Y output voltage. The delta-Y transformer connection is very widely used in three-phase rectifier systems, because it gives the highest output voltage for a given turns ratio.

Three-Phase to Six-Phase Conversion. Consider the transformer connections shown in Fig. *7A*, in which primary windings P_1, P_2 and P_3 are connected in Y. Let the secondary winding for P_1 be *ab*, for P_2 be *cd*, and for P_3 be *ef*. Assume that each secondary winding is center-tapped and that the center-tap connections are all joined together at *o*. Secondary winding *ab* may therefore be considered as

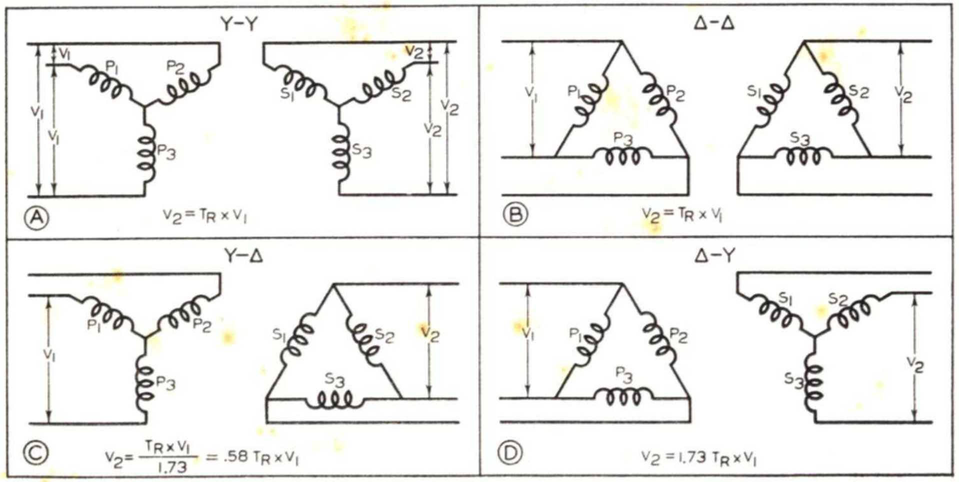


Fig. 6. Typical connections for three-phase transformers. In each case, T_R represents the turns ratio. The secondary voltage is increased or decreased by the turns ratio T_R. The Y connection is so named because of the resemblance of its schematic diagram to the letter Y. Likewise, the delta connection is named after the Greek letter Δ, which resembles the triangular schematic diagram for a delta connection.

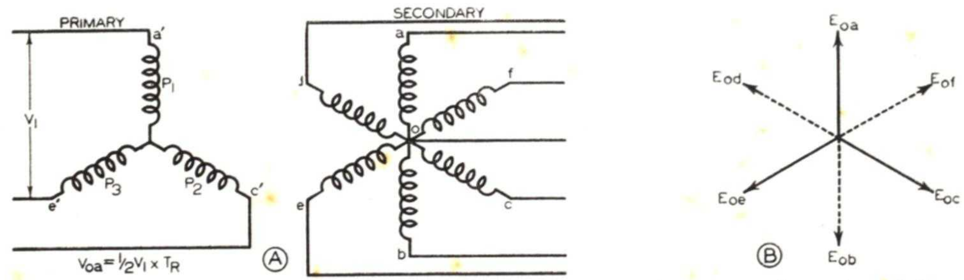


Fig. 7. Conversion of three-phase supply to six-phase supply by means of center-tapped secondary windings.

two separate windings, *oa* and *ob*. Similarly, secondary winding *cd* is made up of two parts, *oc* and *od*, and secondary winding *ef* is made up of *oe* and *of*.

Now consider each secondary winding in turn. The voltage induced in *ob* is 180° out of phase with the voltage induced in *oa;* the voltage induced in *od* is 180° out of phase with the voltage induced in *oc;* the voltage induced in *of* is 180° out of phase with the voltage induced in *oe*. These phase relationships exist because we are tracing through the two halves of each secondary winding in opposite directions.

Now draw the three-phase vector diagram for secondary half-windings *oa*, *oc* and *oe*. These are seen to be connected in Y, exactly like the primary windings, and their vectors must therefore be 120° out of phase, as shown in Fig. *7B*. Voltages E_{oa}, E_{oc} and E_{oe} thus form a three-phase system. Now draw in the vectors E_{ob}, E_{od} and E_{of} (shown in dotted lines in Fig. *7B*). These correspond to the voltages induced in windings *ob*, *od* and *of*, and are in phase opposition to voltages E_{oa}, E_{oc} and E_{oe} respectively, as we have seen. The six vectors, being 60° apart in phase, now form a six-phase system. We thus see how a three-phase Y system may be converted into a six-phase double-Y system.

The secondary coils can be made in the form of six separate windings, as shown in Fig. *8A*. Here, each primary winding has two independent secondary windings. Thus, primary winding P_1 has secondary windings S_1' and S_1''; primary winding P_2 has secondary windings S_2' and S_2''; primary winding P_3 has secondary windings S_3' and S_3''. Let the two sets of secondary windings be connected in two separate Y systems as shown, with secondaries S_1'', S_2'' and S_3'' reversed in polarity with respect to secondaries S_1', S_2' and S_3', respectively. The two sets of secondaries will then form two separate three-phase systems, as shown by the vector diagrams in Fig. *8B*.

Now connect the common or neutral connections of the two Y systems together with the separate iron-core choke coil labeled *balance coil* in Fig. *8A*, and let the center tap *O* of this coil

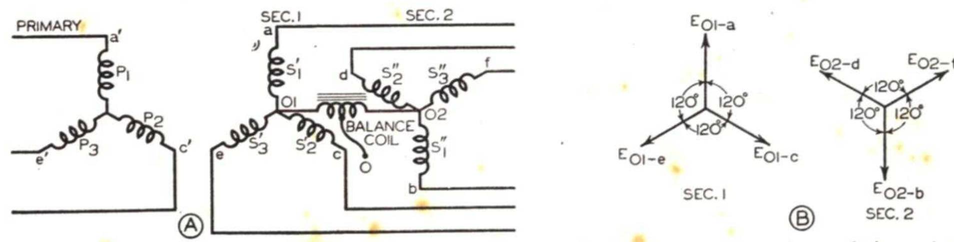
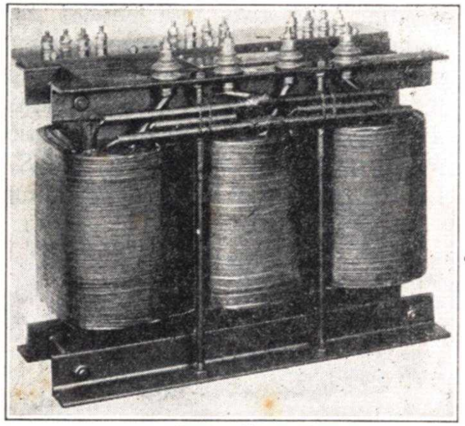


Fig. 8. Conversion of a three-phase supply to a six-phase supply by using two sets of secondaries and a balance coil.

be the common neutral for the complete secondary connection. The two Y systems now form a single system having voltage vectors like those shown in Fig. *7B* (60° apart in phase). If the connection is made without the balance coil, we obtain a six-phase system; using the balance coil to isolate the two Y secondaries really gives a double three-phase system in which all six voltages are 60° apart.

Both six-phase systems just described (Figs. *7* and *8*) are widely used in radio rectifier circuits where the power required exceeds one kilowatt. The *balance coil* arrangement in Fig. *8* is generally preferred, for this coil greatly minimizes ripples in the resultant rectified output voltage.



Courtesy Kenyon Transformer Co., Inc.
Typical three-phase transformer for the high-voltage plate supply of a high-power radio transmitter. The entire unit is housed in a metal tank. This is a core-type transformer since it is designed for three-phase use.

Rectifier Tubes

There are three important types of rectifier tubes; the hot-cathode vacuum tube, the hot-cathode gas tube (usually mercury vapor), and the cold-cathode mercury-vapor tube with an ignition pool.

Hot Cathode Vacuum Tube Rectifier. The hot-cathode vacuum rectifier tube is a vacuum tube containing a heated cathode surrounded by a plate or anode. Such a two-element tube acts as a rectifier because it will pass current only when the plate is positive with respect to the cathode. Thus, when placed in series with an a.c. supply voltage and a load, current to the load can flow only in one direction.

The operation of this type of rectifier is illustrated by characteristic curves *1*, *2* and *3* in Fig. *9*. These are the typical plate current-plate voltage curves of the two-element electron tube. The number of electrons which the cathode is capable of emitting depends upon the temperature of the cathode, and hence, upon the cathode heating power. For high positive plate voltages, all of the electrons emitted from the cathode are attracted by the plate. Once this condition is reached, further increases in plate voltage give no additional change in plate current. The tube is said to be operating at *voltage saturation* under these conditions.

At low plate voltages, the number of electrons attracted to the plate depends upon the difference between the attractive force of the plate on electrons leaving the cathode and the repelling force (on the emitted electrons) of the electrons already in the space between the cathode and the plate. The electrons in the inter-electrode space comprise a *negative space charge*. If the plate voltage is zero, this space charge builds up until its repelling force on the cathode electrons is sufficient to prevent further electron emission from the cathode. When a low positive voltage is applied to the plate, electrons are attracted to the plate, thereby tending to reduce the number of electrons in the inter-electrode space. This reduction is accompanied by a decrease in the repelling effect of the space charge on the cathode, so that electrons leave the cathode to compensate for those attracted to the plate. The net effect is a flow of electrons from the cathode to the plate at a rate depending upon the

value of the plate voltage; hence, for low plate voltages the plate current is proportional to the plate voltage. This condition corresponds to section *pq* of the curve in Fig. *9*.

Figure *9* shows how plate current varies with plate voltage for low (curve *1*), medium (curve *2*) and high (curve *3*) values of cathode power (filament voltage multiplied by filament current gives cathode power). Assuming a fixed cathode power corresponding to curve *1*, let us apply an a.c. voltage between the plate and cathode (in series with a load resistance *R*). The diagram at the upper left in Fig. *9* shows the circuit arrangement, and curve *a-o-b-o′-c* shows the wave form of the applied sine-wave voltage. During the positive half-cycle of the applied voltage, the plate-cathode voltage (indicated by dash-dash curve *a-x-b* in Fig. *9*) is less than the applied voltage by the *IR* drop in load resistor *R*. This plate-cathode voltage sends through the tube a current having the wave form of curve *a-m-n-b* at the right in Fig. *9*. Saturation current flows during interval *m-n*, for the plate-cathode voltage is swinging beyond the knee (bend) of E_p-I_p curve *1* during this interval.

During the negative half-cycle of the applied voltage, the plate is negative with respect to the cathode and no current can flow in the circuit. With no current through load resistor *R*, the full applied voltage appears between the plate and cathode. Portion *b-o′-c* of the output current curve in Fig. *9* corresponds to this condition.

The instantaneous output voltage appearing across the load resistor is equal to the instantaneous load current multiplied by the value of the resistance. The output voltage thus has the same wave shape as the plate current, and is pulsating in nature.

All of the important properties of a rectifier tube may be deduced from Fig. *9*. Let us consider these properties.

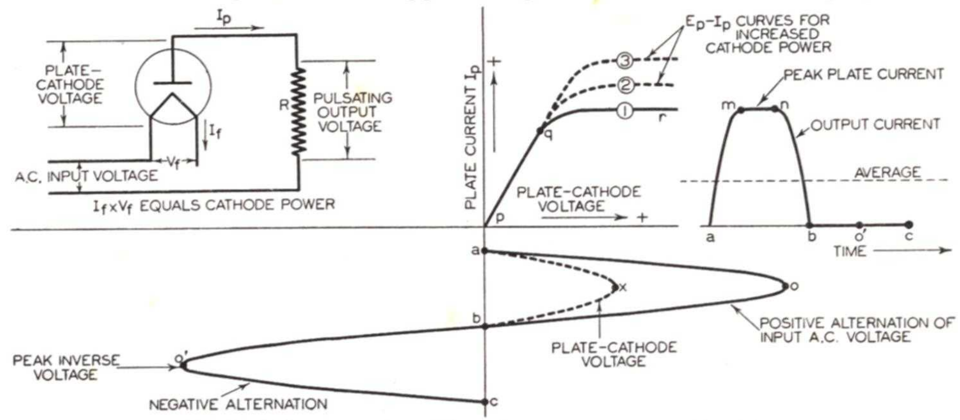


Fig. 9. Voltage-current conditions in a vacuum-type rectifier tube.

Maximum Allowable Peak Inverse Voltage. The peak inverse voltage of a rectifier tube is *the maximum instantaneous plate-cathode voltage in the direction opposite to that in which the tube is designed to pass current.* The maximum peak inverse voltage rating of a rectifier tube is, therefore, *the maximum instantaneous plate-cathode voltage which can safely be applied to the tube in the direction opposite to that in which the tube is designed to pass current.*

The insulating resistance between the plate and cathode is the factor which limits the maximum peak inverse voltage rating, and this in turn limits the value of the applied voltage and the value of the rectified voltage which the tube can deliver. The exact relationship between the d.c. output voltage of a rectifier and the inverse peak voltage depends upon the type of rectifier circuit employed; the inverse voltage will always be greater than the d.c. output voltage, and may be as much as 3.14 times the output voltage in some rectifier circuits.

The inverse peak voltage present in a rectifier circuit will be equal to the peak value of the a.c. secondary voltage per phase plus the peak value of the filter input voltage. In a simple single-phase, full-wave rectifier circuit, the peak filter input voltage is equal to the peak a.c. secondary voltage, hence the inverse peak voltage is twice the peak value of the a.c. secondary voltage. In polyphase rectifier circuits the phase relationships of the a.c. secondary voltages must be taken into account when determining the inverse peak voltage. Exact inverse peak values are given in Table *III*, which is taken up later in this lesson. Vacuum tube rectifiers have been built to withstand peak inverse voltages in excess of 100,000 volts.

Allowable Peak Plate Current. The peak plate current is indicated in Fig. *9*. The maximum allowable peak plate current depends upon the maximum electron emission which the cathode can safely supply for the rated life of the tube. Vacuum tube rectifiers have been built to handle up to 7.5 amperes peak plate current.

Average Plate Current. The average value of the plate current during a complete cycle of the applied voltage is somewhat less than one-half of the peak plate current, as can be seen in Fig. *9*.

Rectified Output Voltage. The d.c. output voltage is equal to the product of the load resistance and the average load current.

In general, the exact relation between the d.c. output voltage and the peak applied voltage depends upon the rectifier circuit employed, upon the position of the operating point of the rectifier tube on its E_p-I_p characteristic (which determines the tube voltage drop), upon the load current being drawn, and upon the filter circuit used. The d.c. output voltage may be equal to from 30% to 165% of the value of the peak applied voltage, depending upon what the above factors are.

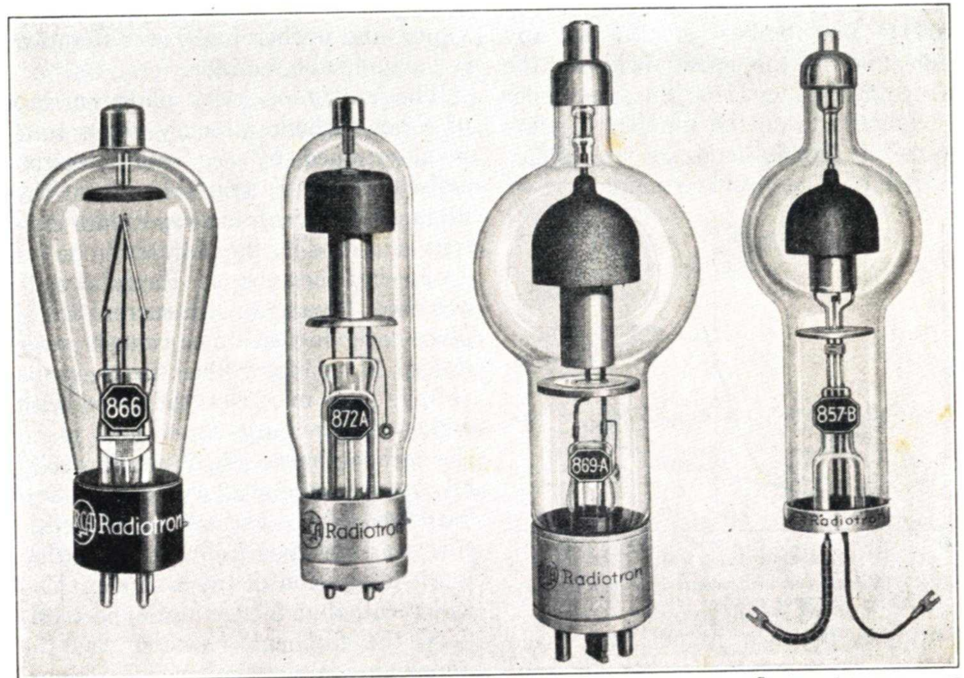
Tubes. Vacuum tube rectifiers are, in general, similar in construction to standard filament-type three-element power tubes with the grid element omitted. Large rectifiers employ tungsten filaments, and are usually cooled by forcing air past the tube with a fan or blower located below the tube. Should the flow of air stop for any reason, a relay opens the rectifier supply circuit.

Small rectifiers depend on the surrounding air for cooling, and use either oxide-coated or thoriated tungsten filaments. The size of the filament is determined by the maximum peak plate current required. The spacing between the filament and plate and the degree of vacuum used determine the insulating resistance between plate and cathode, and hence determine the maximum peak inverse voltage rating of the tube. The tube losses include the filament heating power and the plate dissipation power (the power lost as heat in the tube due to passage of current through the tube). Plate dissipation in a rectifier tube is less than the corresponding loss for a power amplifier tube using the same structure, for in a rectifier there is no grid to shield the plate from the cathode; without a grid, full space current is obtained with a relatively low plate-filament voltage. (Plate dissipation power = E^2/R_p, where E is the tube voltage drop [the plate-filament voltage of the tube] and R_p is the plate-to-filament resistance.

The d.c. tube voltage drop times the d.c. plate current also gives the plate dissipation.) Because of the low d.c. voltage drop, the efficiency of the vacuum tube rectifier is very high, and special water-cooling jackets or fin-type heat radiators are not necessary. Forced air provides sufficient cooling.

The Hot-Cathode Mercury-Vapor Rectifier. This type of rectifier tube contains mercury vapor in equilibrium with liquid mercury. The vapor pressure is very low, and is dependent on the temperature of the liquid mercury. The range of vapor pressures generally employed is from 1/100,000 to 4/100,000 of normal atmospheric pressure.* Only a small quantity of mercury, usually not more than a few drops, is sufficient to supply ample vapor.

The presence of the mercury vapor introduces an important operating feature in the tube. Mercury vapor has an *ionization potential* of 10.4 volts. This means that when a positive voltage of 10.4 volts is applied between the plate and the filament of a mercury-vapor rectifier, some of the electrons flowing from the cathode to the plate will collide with the mercury-vapor molecules and knock electrons out of them (ionize them). When the plate voltage is increased to about 15 volts positive, these ionizing collisions become relatively numerous.



Courtesy RCA Mfg. Co., Inc.

Typical RCA Radiotron half-wave mercury-vapor rectifier tubes, designed for high-voltage operation in radio transmitters. Characteristics of these tubes are given in Table *II*. The type 866 tube shown here has the same characteristics as the 866A, with the exception of a lower maximum inverse peak voltage (7,500 volts).

The electrons thus produced are attracted to the plate, where they add to the normal flow of electrons from the cathode. The increase in plate current

*When a tube is evacuated completely (only theoretically possible), the air in the atmosphere presses on the outside of the bulb; there is no air or vapor inside to resist the pressure. Atmospheric pressure is about 15 pounds per square inch. When air or vapor is present inside the tube, it exerts a back pressure which can be expressed in pounds per square inch or in some fraction of the normal atmosphere pressure, as is the usual practice.

due to the formation of negative ions by collision is not important, however, for the gas pressure is so low that the number of electrons produced by ionization is small compared to the cathode stream. The important factor is that the positive mercury-vapor ions (which result from mercury molecules losing electrons) are attracted to the filament. These ions are very heavy, and move much more slowly than the electrons (about 1/600 as fast); the number present at any one time in the space between the plate and filament is of the same order of magnitude as the number of electrons in the cathode stream (space current). The positive mercury ions

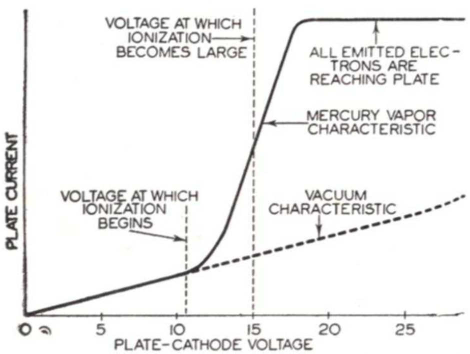


Fig. 10. Voltage-current characteristic of a mercury-vapor rectifier tube.

therefore produce a positive space charge *which neutralizes the normal negative space charge due to electrons*, and the resultant space charge is practically zero. The entire electron emission from the filament can thus flow to the plate even though a positive plate voltage of only 15 to 20 volts is applied. Figure *10* presents a graphical picture of how the plate current varies when mercury vapor is present in a rectifier tube.

Because of its low, practically constant voltage drop, the mercury-vapor rectifier is more efficient and provides better voltage regulation than the vacuum tube rectifier. For a tube of given size and given filament power, the mercury-vapor rectifier will pass a higher current than the vacuum tube rectifier.

The mercury-vapor rectifier is rated in terms of the same operating factors as the vacuum tube rectifier: maximum allowable peak inverse voltage, allowable peak plate current, and safe average plate current. The maximum allowable peak inverse plate voltage is limited by the voltage which will spark across the low-pressure mercury vapor, and is therefore lower than for a vacuum tube rectifier.

The *maximum peak* plate current of a hot-cathode mercury-vapor tube is determined by the total electron emission safely available from the filament. The *safe average* plate current is limited by the plate-cathode resistance of the tube, for the tube voltage drop (average plate current times plate-cathode resistance) must never exceed about 22 volts. As the tube voltage drop increases, the speed with which the mercury-vapor ions reach the cathode increases. When the voltage exceeds about 22 volts, the bombardment of the cathode by the positive ions becomes injurious, resulting in disintegration of the cathode. (You will recall that in vacuum-type rectifiers, the filament emission was the important factor limiting plate current.) Mercury-vapor rectifier tubes are available for peak inverse voltages up to about 25,000 volts, and for peak plate currents up to 450 amperes (average plate currents up to 75 amperes).

One operating requirement of the mercury-vapor rectifier which is not present in the vacuum tube rectifier is the need for close control of the bulb temperature. The bulb temperature determines the value of the vapor pressure within the tube, and this pressure increases with bulb temperature. If the vapor pressure is too high, the tube will spark over at a lower

peak inverse plate voltage. If the vapor pressure is too low, there will be insufficient positive mercury-vapor ions in the space around the cathode. The negative space charge will therefore not be entirely neutralized, and the tube voltage drop corresponding to a given plate current may be increased beyond the safe value of about 22 volts.

It is essential to turn the filament on first in mercury-vapor rectifiers and allow it to heat up for a specified period before closing the plate circuit, in order to prevent this excessive bombardment of the cathode by positive mercury-vapor ions. A time-delay relay in series with the plate circuit is usually employed for taking care of this precaution automatically. The brief warming-up period allows the bulb to reach its normal operating temperature, and insures correct mercury-vapor pressure when plate voltage is applied.

A second operating requirement of the mercury-vapor rectifier is that the plate current of the tube must not be allowed to exceed the allowable peak plate current even momentarily. *Enough plate circuit resistance must be used to limit possible current surges to a safe value.* Not only does such an overload draw more electrons from the filament than is permissible for normal rated life, but *more important still,* the tube voltage drop increases and reaches the 22-volt value which produces disintegration of the cathode by positive ion bombardment.

One type of construction used in high-power mercury-vapor rectifier tubes is shown in Fig. *11*. The cathode is of the heater type, as is common practice for high-power tubes, and is constructed in the form of a cylinder containing vertical vanes. The heater is located within a small cylindrical cathode sleeve, while a highly polished heat-reflecting cylinder surrounds the entire cathode. All the surfaces of the cathode, including the vanes and the central sleeve, are oxide-coated. The plate takes the form of a cup fitting over the cathode assembly.

This form of construction is made possible by the presence of the positive mercury-vapor ions throughout the inter-electrode space, penetrating even into the remote pockets of the cathode. All portions of the cathode may therefore emit electrons. This accounts for the much greater current-handling capacity of a mercury-vapor

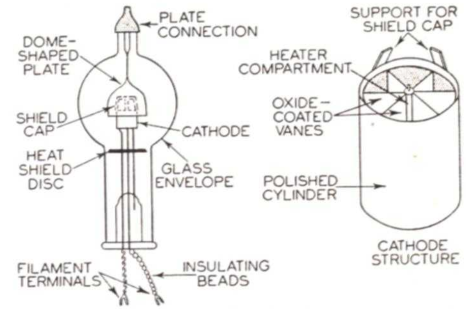


Fig. 11. Structural details of a high-power mercury-vapor rectifier tube. Many other forms of cathode structures are employed, but in each case a large oxide-coated surface is provided. The insulating beads are needed on only one filament lead, for that is sufficient to prevent the two filament leads from touching.

tube for a given filament power. The polished cylinder surrounding the cathode reduces heat radiation, conserving the heat generated by the filament power without in any way affecting the area of emission. The extra discs or caps above and below the cathode also concentrate the heat on the oxide surfaces. The lower heat shield disc prevents condensation of mercury on the leads, while the upper shield cap concentrates the ionization near the cathode surfaces. Because of the penetrating properties of the positive ions, it is essential even for a cathode-type tube that the filament voltage does not exceed 5 volts. In this way, the voltage between the different parts of the filament and the plate ranges from 15 to 20 volts and does not reach the danger point, 22 volts, at which disintegration by cathode bombardment begins.

The shape of the plate is such as to minimize sharp points at which inverse spark-over may begin. Since the tube voltage drop rather than the plate dissipation power is usually the factor which limits the current-handling capacity of the mercury-vapor rectifier, the plate is quite small even in the highest-power tubes.

The Cold-Cathode Mercury-Arc Rectifier. The fundamental difference between the cold-cathode and hot-cathode mercury-vapor rectifier tubes lies in the method of obtaining electron emission at the cathode. In the cold-cathode type, the cathode consists of a mercury pool, with a *hot spot* on this pool serving as the emitter of electrons. An auxiliary electrode called the igniter, partly immersed in the mercury pool, is used for developing the hot spot. When a high positive voltage is applied to the igniter electrode, tiny arcs are formed between the igniter and the mercury, and these develop almost instantly into an emitting or hot spot on the surface of the mercury pool. The tube then functions exactly like the hot-cathode mercury-vapor rectifier.

Mercury-pool rectifiers have been used for many years, first in glass envelopes, later in metal tanks which were continuously evacuated, and finally, in small sizes, in sealed metal envelopes. Rectifiers of this type are much more rugged than the hot-cathode type, and can be designed for types of services requiring very heavy currents. The operating cost with the cold-cathode type of tube is considerably lower, since the tube has an indefinitely long life (there is no filament to burn out and no oxide-coated cathode to weaken). The peak current is not limited by the emission capabilities of a filament, so that besides greater capacity, there is less danger of the tube being ruined by momentary overloads. However, the maximum allowable peak inverse voltage has, in the past, been lower than for the hot-cathode tube.

The construction shown in Fig. *12A* for a cold-cathode rectifier tube serves to increase the rated peak inverse voltage, largely by cooling the main body of the cathode. As a consequence of these factors, the cold-cathode mercury-vapor rectifier tube (also called an *ignitron* tube by Westinghouse and

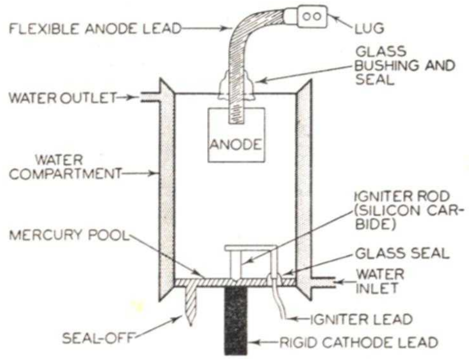


FIG. 12A. Constructional details of a WL-651 water-cooled metal-jacket Westinghouse ignitron (cold-cathode mercury-vapor rectifier tube).

General Electric). This rectifier tube competes advantageously with the hot-cathode tube in transmitter installations of 50 kilowatts or higher.

Referring to Fig. *12A*, the water-cooling jacket is at the same potential as the mercury pool. The igniter and anode leads are insulated from the metal jacket by means of glass bushings. The igniter rod is a crystalline material which is not made wet by mercury, such as silicon carbide. As a result, contact with the mercury is made at a large number of small points on the igniter rod. When voltage is applied between the igniter and the mercury, breakdown occurs first at these sharp points, and tiny arcs are formed. The currents in these minute arcs rise rapidly at the surface of the mercury pool, resulting in sufficient electron emission to initiate and sustain the cathode-to-anode flow.

In order to prevent any reversal of current through the tube when the plate is driven negative, it is necessary to extinguish the arc in the pool. This is done by supplying the igniter with current furnished through a small half-wave rectifier, as shown in Fig.

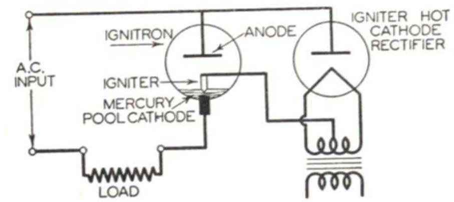


FIG. 12B. Half-wave ignitron rectifier circuit.

12B. As the a.c. voltage applied to both tubes increases in the direction which makes the anodes of both tubes positive, the small igniter rectifier is the first to pass current. Its current flows, igniting the pool, and the ignitron conducts current. When the a.c. supply reverses in polarity, the igniter rectifier stops conducting, the mercury arc is extinguished, and no current can flow through the ignitron in the reverse direction.

Choice of Rectifier Tubes. On the basis of the foregoing discussion of the three types of rectifier tubes, it is possible to decide which type of tube should be used for a given application. Prior to the advent of the hot-cathode mercury-vapor rectifier, the high-vacuum rectifier was in widespread use. However, the advantages of the hot-cathode mercury-vapor tube early became apparent. Its chief limitation, that of lower peak inverse voltage, was soon offset by the design of radio power amplifier tubes which operated on voltages sufficiently low (see Table *I*) that they could be furnished by the mercury-vapor tube. Today, practically all transmitters up to 50 kilowatts employ hot-cathode mercury-vapor rectifiers, while larger sizes of transmitters usually employ the cold-cathode type. The use of the high-vacuum rectifier is limited to applications requiring very high d.c. voltages (above 35,000 volts) and to low-power, low-voltage applications, as in receivers, where the superior ruggedness and freedom from transients* of the high-vacuum type of tube is an advantage. Table *II* gives the characteristics of a number of typical hot-cathode rectifier tubes.

Type	Maximum Peak Plate Current	Maximum Average Plate Current	Maximum Inverse Peak Voltage	Filament Voltage	Filament Current	A=Air-cooled FA=Forced air-cooled.	
866-A	1.0 amp.	0.250 amp.	10,000 v.	2.5 v.	5.0 amp.	A	Mercury Vapor
872-A	5 amp.	1.25 amp.	10,000 v.	5.0 v.	6.75 amp.	A	
869-A	10 amp.	2.5 amp.	20,000 v.	5.0 v.	18.00 amp.	A	
857-B	40 amp.	10 amp.	22,000 v.	5.0 v.	30.00 amp.	A	
870	150 amp.	75 amp.	16,000 v.	5.0 v.	70.00 amp.	FA	
217-A	.6 amp.		3,500 v.	10.0 v.	3.25 amp.	A	High Vacuum
217-C	.6 amp.		7,500 v.	10.0 v.	3.25 amp.	A	
836	1.0 amp.	.25 amp.	5,000 v.	2.5 v.	5.00 amp.	A	

TABLE II. Characteristics of typical hot-cathode rectifier tubes.

Two important operating limitations of the hot-cathode mercury-vapor rectifier must be emphasized: *1.* Normal plate current will not flow until the voltage in the circuit containing the rectifier exceeds about 15 volts positive. Since the circuit voltage is generally of sine wave form, there is an abrupt starting and stopping of plate current, with each cycle producing circuit transients. The rectifier circuit must be designed to minimize such transients. *2.* In the

*Erratic changes in current or voltage from normal: the charging or discharging of a condenser or coil through a resistor produces a transient current.

parallel operation of mercury-vapor rectifiers, the plates of the rectifiers must operate independently in order to obtain high output currents. To minimize the possibility of one rectifier taking over the load, isolating inductors are introduced into the plate leads before connection to the common a.c. voltage. This provides equalization of voltage so that the tube having the lower voltage drop will not carry all of the current and become overloaded.

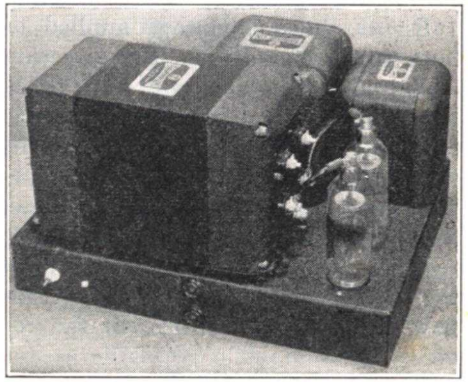
Rectifier Circuits

Per Cent Ripple. Because the output voltage of a rectifier is pulsating, and the voltage used in most tube circuits must be nearly free from pulsations, rectifiers which supply d.c. voltages to tubes must be followed by smoothing filters. A term used to define the degree of departure of the final d.c. voltage from absolute steadiness is the *per cent ripple.* The per cent ripple in the output voltage of a rectifier system is *the ratio of the r.m.s. value of the pulsating voltage* (superimposed on the direct voltage) *to the value of the d.c. voltage.* The object of rectifier circuit design is to reduce the per cent ripple to as low a value as is economically practical.

Single-Phase Half-Wave Rectifier Circuit. The filtering action can be improved by selecting a proper combination of rectifier tubes and transformer connections. Thus, if only one rectifier tube and one high-voltage secondary winding were used in the circuit of Fig. *4A,* we would have the pulsating output voltage shown in either Fig. *4C* or *4D* (depending upon the polarity of the secondary winding). This is a *half-wave rectifier circuit;* it is seldom used in high-power radio equipment, however, because of the high cost of the filter condensers and chokes needed to smooth the output pulses.

In general, single-phase half-wave rectifier circuits are used only for such services as battery charging, where the pulsating nature of the voltage is immaterial, and in receiver supplies where the current drain is low. By using the *full-wave rectifier circuit* shown in Fig. *4A,* the output voltage takes the form shown in Fig. *4E,* and the filter system required is considerably more economical to build.

Obviously, the use of polyphase systems will give still further reduction in the percent ripple, and filters with low-capacity condensers will suffice. Three of the most widely used polyphase circuits are shown in Fig. *13.*



Courtesy Thordarson Electric Mfg. Co.

Modulator power supply for a 1-kw. transmitter employing high-level modulation. Two diode mercury-vapor rectifier tubes are usually connected into a single-phase, full-wave rectifier circuit for applications of this nature.

Note that delta-Y transformers are used, as they give the desired output voltage with a lower turns ratio than is required with Y-Y transformers.

Three-Phase Half-Wave Rectifier Circuit. Figure *13A* shows a three-phase half-wave rectifier circuit. Each phase of the Y-connected secondary is seen to be equivalent to a single-phase half-wave rectifier circuit, and the three circuits have a common load and a common neutral return wire. The voltage output which would be produced across a resistive load by each of the half-wave circuits acting independently is shown by the curves

accompanying Fig. *13A,* and the voltage output of the combined system is represented by the heavy-line curve. Notice particularly that the average d.c. output voltage is nearer the peak value than for the wave shown in Fig. *4E,* which in turn is nearer to the peak value than for the wave shown in Fig. *4C.* The reason for drawing the output voltage of the combined system as shown needs further explanation.

Let us consider the instant of time corresponding to point *a* on the curves in Fig. *13A,* when the voltages induced in transformer windings *1* and *2* are very nearly equal. Let the voltage in winding *1* be +100 volts and the voltage in winding *2* be +99 volts. Since the voltage drop required across each mercury vapor rectifier tube in order that it may pass current is +15 volts (practically independent of the load current), each tube would operate provided it were connected to a separate load. Phase *1* would produce a voltage of 100 — 15 = 85 volts across its resistive load, and phase *2* would produce a voltage of 99 — 15 = 84 volts across its resistive load.

Now, what happens when the load is common to the two circuits, as in Fig. *13A?* The rectifier in the circuit having the higher induced voltage (phase *1*) will operate, of course, and produce a voltage of 85 volts across the load.* Now, since phase *2* is connected to the same load, its 99-volt source must (if it passes current at all) overcome its own tube voltage drop plus the 85-volt drop across the load. Subtracting 85 volts from 99 volts leaves 14 volts for the tube drop, which is not enough to cause it to pass appreciable current.

*Imagine two batteries, one supplying 45 volts and the other 44 volts, connected in parallel to a load. Only the 45-volt battery will supply current to the load; in fact, this battery will force current through the 44-volt battery.

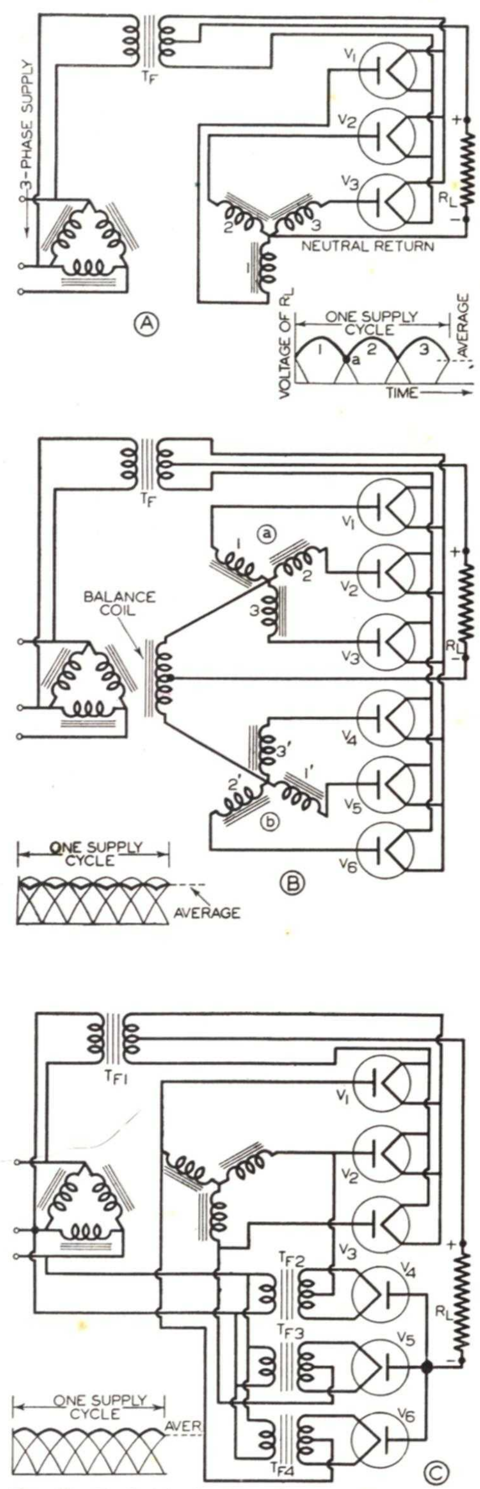


Fig. 13. Typical basic three-phase rectifier systems.

It is thus evident that when two tubes having nearly equal applied voltages are in parallel, *only the tube having the higher applied voltage will supply current to the load.* For the circuit of Fig. *13A*, each tube carries current one-third of the time, and the voltage across the load is shown by the heavy-line envelope of the curves. Note that the per cent ripple is much smaller than for the full-wave single-phase rectifier; the ripple frequency is now three times the supply frequency, or 180 cycles if the supply frequency is 60 cycles.

Strictly speaking, the foregoing analysis applies only to mercury-vapor type rectifiers, and gives only a good first approximation in high-vacuum rectifier systems. However, since practically all transmitters employ mercury-vapor rectifiers exclusively, we will limit our discussion to this type.

Three-Phase Half-Wave Double-Y Rectifier Circuit. Figure *13B* shows a circuit having the same balanced coil secondary connection shown in the six-phase system of Fig. *8A*. The rectifier circuit in Fig. *13B* might be considered a six-phase half-wave rectifier system, but it is more frequently referred to as a *three-phase half-wave double-Y* circuit. The two Y systems are so connected to the load that when the output of one three-phase unit is a minimum, the output of the other three-phase unit is a maximum. This is equivalent to saying that the two three-phase units form a six-phase system. However, there is considerable justification for calling it a double-Y system, as will appear from the following.

The voltage output of the individual phases is shown by the curves accompanying Fig. *13B*, and the voltage output of the combined system is substantially as shown by the heavy-line envelope of the curves. The per cent voltage ripple is very low, the ripple frequency being six times the frequency of the supply voltage, or 360 cycles.

The balance coil of Fig. *13B*, (often called the inter-phase reactor) serves an important function. By referring to Figs. *8A* and *8B*, you will recall that each phase of one of the three-phase systems is sandwiched in between two phases of the other three-phase system insofar as phase voltages are concerned. For convenience in study, let us refer to one of the Y circuits in Fig. *13B* as system *a*, and the second Y as system *b*; likewise, we will refer to the phases in system *a* as *1*, *2*, and *3*, and to the phases in system *b* as *1′*, *2′* and *3′*.

The positive half-cycles of the phase voltages are shown in Fig. *14*, with the solid-line curves referring to system *a* and the dotted-line curves referring to system *b*. If each system alone operated as a three-phase half-wave rectifier system, the voltage which it would deliver to a resistance load would be as shown by the heavy envelopes of the curves, solid for system *a* and with short heavy dashes for system *b*. Each phase of each system would obviously carry current one-third of the time.

Now, if the two systems were combined as in Fig. *13B* but with the balance coil omitted, we would have a six-phase system, with each phase carrying current only one-sixth of the time. The function of the balance coil is *to allow the two systems to operate independently,* so that each phase will draw current one-third of the time even though the two Y systems feed a common load.

Note that the two ends of the balance coil in Fig. *13B* are connected to the neutral points of the two Y systems, while the center tap is connected to one end of the load. The two Y systems may be considered as each supplying *one-half the load current,* since the balance coil prevents one section from being directly in shunt with the other section. The return current to each Y neutral is equal to *one-half the load current,* and each return current passes through that half of the balance coil associated with its own Y system.

Remember that the current supplied to the load by each Y system has a ripple in it (just as in the output voltage of the system). The ripple current of each Y system produces a ripple voltage drop in its half of the balance coil, and the total ripple voltage across the terminals of the coil is equal to the *mean* or *average* of the two ripple voltages in the outputs of the two Y systems, as shown by the heavy long-dash curve in Fig. *14*.

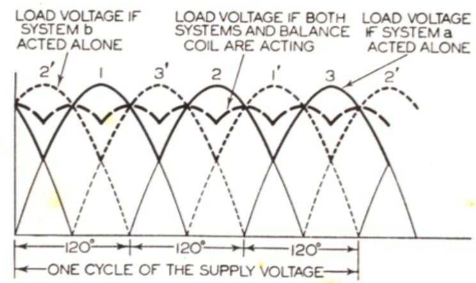


Fig. 14. Voltages in the three-phase half-wave double-Y rectifier system of Fig. *13B*, in which a balance coil is employed.

This is the value of the ripple voltage which will be present in the d.c. output of the combined double-Y system; as will be seen from Fig. *14*, it has a frequency six times that of the supply frequency, or 360 cycles per second (c.p.s.).

Three-Phase Full-Wave Rectifier Circuit. Figure *13C* shows a three-phase full-wave rectifier circuit. Note that each phase supplies two tubes connected for full-wave rectification. The voltage wave delivered to the load is identical with that which would be obtained if the balance coil were omitted from the circuit of Fig. *13B*, for each tube carries current during only one-sixth of the time (the voltage wave will correspond to the top row of curves in Fig. *14*, numbered *2′-1-3′-2-1′-3-2′*).

Comparison of Three-Phase Rectifier Circuits. Both the three-phase half-wave rectifier circuit (Fig. *13A*) and the three-phase double-Y rectifier circuit (Fig. *13B*) require but a single filament transformer, whereas the three-phase full-wave rectifier circuit (Fig. *13C*) requires four separate filament transformers (one for tubes V_1, V_2 and V_3 and one each for V_4, V_5 and V_6). The latter two circuits both deliver voltage waves having about the same percentage ripple. The double-Y circuit requires a balance coil and two sets of secondaries, which more than offset the cost of the added transformers for the full-wave circuit; however, the double-Y delivers twice the current to the load for the same value of tube peak current. The average value of output voltage is nearer the peak value for the circuits shown in Figs. *13B* and *13C* than for Fig. *13A*. By *increasing the number of phases* in a rectifier system, the *average d.c. output voltage approaches more nearly the peak a.c. voltage supplied by each phase.*

To avoid possible d.c. saturation of the transformer core, it is necessary to employ three-phase transformers for the half-wave circuits, whereas either a three-phase transformer or three single-phase transformers may be used in the full-wave circuit. D.C. saturation of the balance coil is automatically avoided because the d.c. current flow in the two halves of the coil is in opposite directions.

Rectifier Filter Circuits

Elementary Considerations of Filters. Having seen that the per cent ripple in the output voltage wave of a rectifier circuit depends considerably upon the type of circuit used, and is materially reduced in multiple-phase circuits, let us consider filters. Not only must we concern ourselves with the amount of ripple reduction, but also with the effect the filter has on the operation of the rectifier tube. Remember that the transmitter acts essentially as a resistive load on the rectifier system, and that series choke coils and shunt capacitors eliminate or reduce the ripple components.

Filter networks can be divided into two fundamental types: *1. Filters with condenser input,* as shown in Fig. *15A*; *2. Filters with coil input,* as shown in Fig. *15B*. The type of input device determines to a large extent the d.c. output voltage, the voltage regulation and the peak rectifier current.

How a Condenser Input Filter Works. From an elementary viewpoint, the rectifier-filter circuit in Fig. *15A* is fed with an alternating voltage E_{AC} which is to be rectified and smoothed. The input filter condenser will charge and discharge by an amount which depends upon the resistance of the shunting load. If the load is not excessively large, the discharge will be slow and the input condenser voltage will closely approach the peak value of E_{AC} (assuming that there are negligible drops in the rectifier and the series choke coil).

As the load increases, the discharge of the input condenser becomes more rapid; the output voltage not only drops, but it contains more ripple. During the charging process, the input condenser is drawing large currents from the source, and the peak value of this current may be excessive for the rectifier tube used. The voltage developed across X_{C1} will be a pulsating d.c. voltage, but X_L and X_{C2} (acting as a voltage divider for the a.c. component only) will reduce the ripple in proportion to the ratio of the reactance of X_L to the reactance of X_{C2}.

How a Coil Input Filter Works. The filter circuit shown in Fig. *15B* is actually a double voltage divider for the a.c. component of the filter input voltage V (the rectifier a.c. voltage). X_{L1} and X_{C1} reduce the a.c. component by an amount depending on the ratio of the reactance of X_{L1} to that of X_{C1}. The ripple voltage appearing across X_{C1} is further reduced by X_{L2} and X_{C2}. In any case, a high coil reactance (high coil inductance) and a low condenser reactance (high condenser capacity) improve a.c. filtering. In no case should the resonant frequency of the coil and condenser correspond to any ripple frequency; to eliminate this possibility, X_{L1}-X_{C1} and X_{L2}-X_{C2} are usually made to resonate at about one-half the *lowest ripple frequency* of the rectified current.

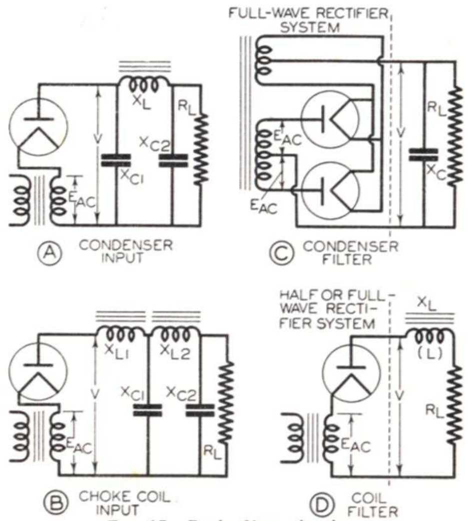


FIG. 15. Basic filter circuits.

A coil input filter is actually a "brute force" filter, for each increase in coil inductance or condenser capacity gives additional reduction in ripple components without affecting the d.c. component. For this reason, the d.c. voltage across load R_L is always equal to the average value of the rectified a.c. voltage V. When a coil input filter is used, this d.c. output voltage is therefore the average value which is indicated in Figs. *4* and *13;* a comparison will show that for a given a.c. voltage input to the rectifier-filter circuit, *the d.c. output voltage increases as we increase the number of phases in the supply.* Compare this with the condenser input filter, where with even a half-wave single-phase rectifier the d.c. output voltage may be close to the peak a.c. voltage if a large input filter condenser and a low d.c. current drain exist.

Filters for Polyphase Rectifiers. With polyphase rectifier systems, the d.c. output voltage approaches or even exceeds the peak a.c. input voltage per phase, hence coil input circuits are equally as good as condenser input filters from this angle. The surge of input current does not exist when coil input is used. The inverse peak voltage applied to the rectifier tubes will be greater for coil input, however; this is due to the need for higher input a.c. voltages for a desired output d.c. voltage, to the d.c. voltage drop in the filter choke, and to the fact that the input choke coil may assume a large a.c. voltage which can increase the instantaneous voltage in the circuit at the time E_{AC} is at its maximum negative peak. By using low-resistance choke coils and low-resistance secondaries in the step-up transformer, the voltage regulation can be made quite good, assuming that the rectifier is of the mercury-vapor type and has a constant voltage drop. For transmitter supplies, it is universal practice to use coil input filters.

In this discussion a number of new factors have been introduced, requiring a more detailed explanation of what effects coil or condenser input filters have on the output wave and on the rectifier tubes. To simplify our study of this subject, we will first consider the basic condenser filter as shown in Fig. *15C*, then take up the basic choke filter as shown in Fig. *15D*.

The Condenser Filter. First let us consider the current and voltage waves in a single-phase full-wave rectifier circuit using the simple condenser filter shown in Fig. *15C*. If the condenser were omitted, the voltage across the load would follow the rectified a.c. voltage V and be as shown by curve *1* in Fig. *16;* the load current would have the same wave form since the load is essentially resistive.

With the condenser across the load, conditions are materially changed. The voltage across the condenser approaches the peak a.c. value as the rectified a.c. voltage rises to a positive peak, after which the condenser voltage decays because of the drain placed on the condenser by load resistor R_L; the condenser voltage is therefore as shown by curve *2* in Fig. *16*. A low value of load resistance causes a large current drain, making the condenser voltage drop markedly. The condenser reaches its maximum voltage at time *a*, corresponding to the positive peak of each rectified pulse, and discharges to a lower voltage value at point *b* on the following pulse.

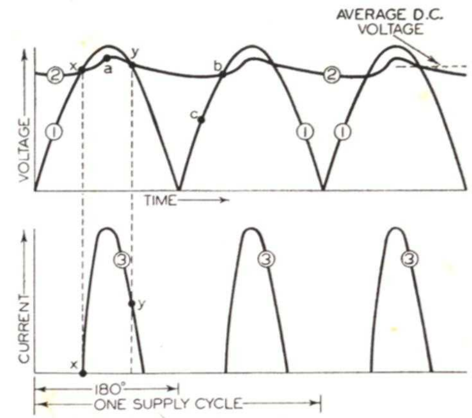


FIG. 16. Voltages and currents in a single-phase full-wave rectifier filter circuit. Curve *1*: Load voltage when filter is omitted (same as rectified a.c. voltage and filter input voltage V); curve *2*: Load voltage when a condenser filter is present (same as condenser voltage); curve *3*: Rectifier tube current (same as filter input current).

In this filter circuit, current can flow through one of the rectifier tubes only when the rectified a.c. voltage V is greater than the condenser voltage (the condenser voltage is greater than the a.c. supply voltage the remainder of the time, so both diode rectifier plates are negative and neither tube can pass current). We see that between points x and y in Fig. *16* the rectified a.c. voltage V (curve *1*) is greater than the condenser voltage (curve *2*); it is during this period that current flows through the rectifier tubes to the condenser. Tube current rises sharply to a peak value, then drops to zero again almost as suddenly, as shown by curves *3* in Fig. *16*. Theoretically, the tube current should be zero at y, but actually it lasts a short while longer because the leakage reactance of the secondary of the transformer tends to hold up the supply voltage. The value of the peak tube current is determined in a complex manner by the difference between circuit voltages and by other circuit factors, particularly by the capacity of the condenser. A large input capacitor can produce excessive peak currents which can readily exceed the maximum permissible peak current for a mercury-vapor tube. A small input condenser causes more ripple, however, hence the design engineer must select a compromise.

Decreasing the load resistance (increasing the load current) will not materially decrease the peak voltage across the condenser, but rather will cause the condenser to discharge more rapidly and more completely; in other words, a load of low ohmic value might make the condenser voltage drop to point c in Fig. *16*. This reduces the average d.c. voltage and increases the ripple amplitude; also, rectifier tube current flows for a longer time period. With a condenser filter, we thus see that increasing the load increases the ripple output and makes the voltage regulation poorer. In a practical condenser input filter circuit like that in Fig. *15A*, however, additional filtering of the ripple voltage would be provided by the coil and the second condenser.

The Coil Filter. We will now consider in turn a single-phase half-wave rectifier, a single-phase full-wave rectifier, and a three-phase half-wave rectifier, each feeding a resistance load through a simple coil filter like that shown in Fig. *15D*. It will be assumed that inductive reactance X_L of coil L at the fundamental frequency of the ripple wave is very high compared to the resistance of the load. It will also

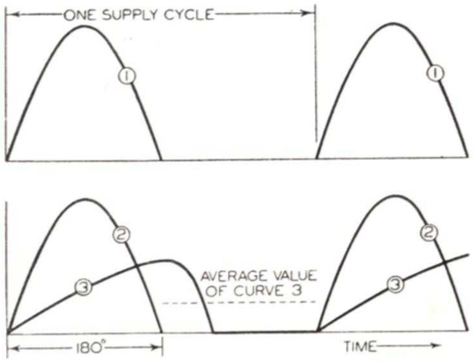


FIG. 17A. Voltages and currents in a single-phase half-wave rectifier employing a coil filter as in Fig. *15D*. Curve *1*: Rectified a.c. voltage (same as filter input voltage); curve *2*: Tube current, load current and load voltage without coil filter; curve *3*: Tube current, load current and load voltage when coil filter is used.

be assumed that the tube voltage drop is negligible compared to the filter input voltage V (with mercury-vapor rectifiers, this assumption is permissible).

Curves for the single-phase half-wave rectifier are shown in Fig. *17A*, where curve *1* represents the rectified a.c. voltage V (the filter input voltage). If the coil filter were removed, the tube current would have this same wave shape, as shown by curve *2*; since all tube current flows through the load resistor, producing across it a voltage drop ($E = IR$), both the load current and load voltage are also represented by curve *2* when the coil filter is omitted.

When the coil filter is used, however, the self-inductance of coil L tends to

prevent *changes* (increases or decreases) in current. Therefore, when the filter input voltage increases from zero, the tube and load currents build up more slowly than for the "no-filter" case; likewise, tube and load currents decay much more slowly than for the "no-filter" case when the filter input voltage decreases from its maximum value. The wave form for the tube and load currents is therefore as shown by curve *3* in Fig. *17A*. Since the load is a resistance, its voltage will have a similar wave form. Note that tube current flows even after the filter input voltage has dropped to zero; the simple filter L thus has a pronounced smoothing effect on the pulsating load current and voltage.

Next, consider the case for a single-phase full-wave rectifier with a simple coil filter. Curves showing voltage and current conditions which exist with and without the coil filter are shown in Fig. *17B*. The load current is at any instant equal to the sum of the currents in the two tubes at that instant, and hence there is only a small ripple when the filter is used; the load voltage has the same wave shape as the load current.

An interesting characteristic shown in Fig. *17B* is the manner in which the load current shifts from one tube to the other; this is called *commutation*. Thus, when the rectified a.c. voltage (corresponding to the positive voltage on the anode of tube *1*) has dropped to zero (time a), the current of tube *1* still has an appreciable value because of the effect of filter coil L. If tube *1* were acting alone, this current would persist for an appreciable time, as was shown in the case for a half-wave rectifier. However, the positive voltage on the anode of tube *2* is increasing from zero at time a, and tube *2* is accordingly beginning to supply current to the load. This tends to build up a voltage in L which in turn tends to *oppose* the flow of current, and thus (insofar as the current in tube *1* is concerned) neutralizes the normal action of the coil. The tendency for the current in tube *1* to persist beyond the zero-voltage point (a) is thus materially decreased, and the current drops to zero in a considerably shorter time. Meanwhile, the current which tube *2*

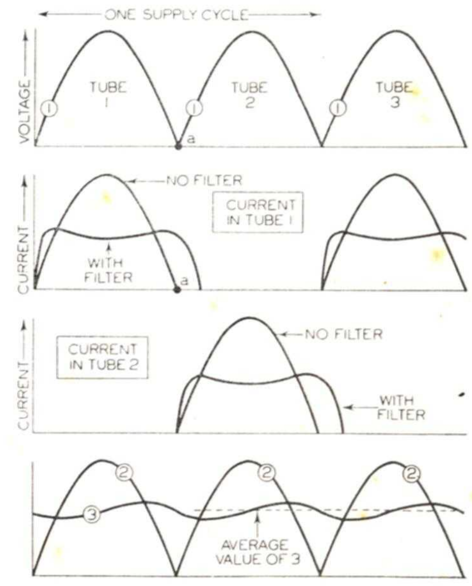


FIG. 17B. Voltages and currents in a single-phase full-wave rectifier employing a coil filter, as in Fig. *15D*. Curve *1*: Rectified a.c. voltage produced by tubes *1* and *2* together; curve *2*: Load voltage and load current without filter; curve *3*: Load voltage and load current when filter is used.

supplies to the load continues to increase, so that by the time the current in tube *1* has decreased to zero, tube *2* is handling the load. This action of the coil filter in providing *commutation* tends to reduce the percentage ripple in the load current.

Refer now to Fig. *17C*, which shows the conditions for a three-phase half-wave rectifier employing a coil filter like that in Fig. *15D*. If filter coil L were not used, the currents in the three tubes would be as shown by the dotted curves, and the wave form of the combined load current would be as in curve *1*. Note that each phase would carry current only during the time when its voltage (shown at the top in Fig. *17C*) exceeded the voltage of the adjacent phases. The load current (and voltage) would thus have an appreciable ripple. When the coil filter is used, however, the action of coil L in providing *commutation* tends to make each current overlap that of the following phase, as shown by the solid-line curves for tube phases *1*, *2*, and *3*.

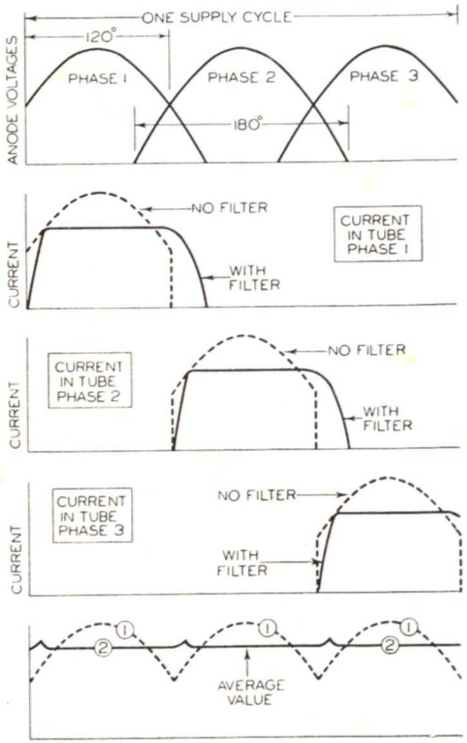


FIG. 17C. Voltages and currents in a three-phase half-wave rectifier circuit employing a coil filter. The top set of curves shows the positive anode voltages for the three phases; the next three sets of curves show the tube currents in the three phases before and after the filter is connected. Curve *1* shows the rectified a.c. voltage at the filter input (this has the same wave form as the load current and voltage without a filter). Curve *2* shows load current and voltage when a filter is used.

As a result, the instantaneous load current, being equal to the sum of the three instantaneous tube currents, has a materially smaller ripple than for the "no-filter" case. The load voltage has the same wave form as the load current.

A comparison of Figs. *17A*, *17B* and *17C* shows that the average load current and voltage increases and the ripple component decreases as more tubes are used in a rectifier circuit employing a coil filter. Increasing the load does not affect the wave form; it merely reduces the output voltage, due primarily to the voltage drops in the choke and the secondary of the power transformer.

Factors Affecting Filter Design

1. Ripple Reduction. In the design of suitable filter circuits, consideration is given to the fact that a series choke is a high-reactance path for ripple currents, while a shunt condenser acts as a low-reactance path for ripple currents. The reactance of a coil in ohms is equal to 6.28 times the ripple frequency in cycles per second times the coil inductance in henrys ($X_L = 6.28 \times f \times L$), while the reactance of a condenser is equal to 1 divided by a number determined by multiplying 6.28 times the ripple frequency in cycles per second times the capacitance in farads ($X_C = 1 \div 6.28 \times f \times C$). The ratio of the coil reactance to condenser reactance is the basic *ripple reduction ratio.*

For effective ripple reduction, *the reactance of the coil in a conventional choke input filter should be much greater than the reactance of the condenser.* To get the final peak ripple voltage value, *divide the peak ripple voltage at the filter input by the ripple reduction ratio.*

For ordinary computations, the ripple reduction ratio can be determined by multiplying .00004 times the square of the ripple frequency in *cycles* times the coil inductance in *henrys* times the condenser capacity in *microfarads* ($R_R = .00004 \times f^2 \times L \times C$).

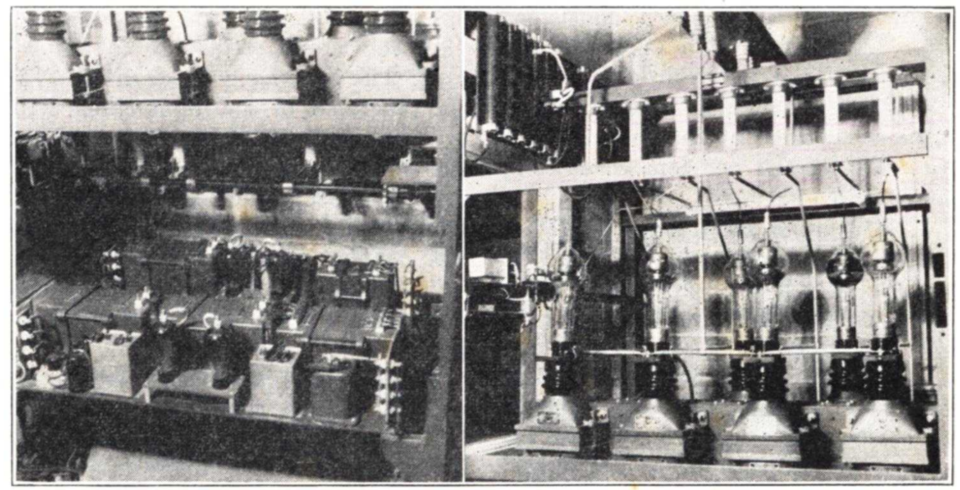
Suppose we were to select a single brute-force filter having a 10-henry choke and a 1-mfd. condenser. What will be the ripple reduction for various

rectifier arrangements? Basing our computations on the fact that the supply frequency is 60 c.p.s., we get the following tabulation of results for this choke input filter in which L is 10 henrys and C is 1 microfarad:

Rectifier Circuit	Ripple Frequency in Cycles	Ripple Reduction Ratio
Single-phase, half-wave	60	1.4
Single-phase, full-wave	120	5.6
Three-phase, half-wave	180	12.9
Three-phase, full-wave	360	51.8

Note that increasing the number of phases increases the fundamental ripple frequency. With each circuit, of course, there will be higher harmonics of less amplitude, and these will naturally be reduced more than the fundamental ripple frequency. Increasing the number of phases gives a marked improvement (increase) in the ripple reduction ratio. In addition, we must not overlook the fact that increasing the phases also reduces the actual ripple value at the filter input. We can therefore see that polyphase rectifier circuits allow low-value, low-cost coils and condensers to be used effectively.

Increased ripple reduction can be obtained by using one filter section following another, as shown for the coil input filter sections in Fig. *15B*. For example, if both coils were 10 henrys and both condensers were 1 mfd., the ripple reduction for a full-wave three-phase system would be 51.8 times 51.8 or about 2680 times. If, on the other hand, each coil were 5 henrys and each condenser 1/2 mfd. (half of the original values), each filter section would give only a ripple reduction of 12.6, and the two together would give 12.6 × 12.6, or about 159. We see that for the same total inductance and capacity in a filter, greater ripple reduction is obtained by dividing the filter into two sections (159 as compared to 51.8). This advantage is offset, however, by the increased cost of making two chokes and two condensers. The condenser cost will not increase appreciably, but the two small chokes will cost about twice as much as one large choke. Economy thus has con-



Courtesy Western Electric Co.

Final amplifier bias rectifiers (left) and main high-voltage rectifier (right) for Western Electric 5-kilowatt transmitter at station KTUL in Tulsa, Oklahoma. The bias rectifiers all use single-phase circuits, with their power transformers, filter chokes and filter condensers all mounted on the same rack with the type 249B rectifier tubes. The main rectifier employs six type 315A tubes in a three-phase circuit using separate filament transformers for each tube (directly under the tubes). The three single-phase power transformers for this rectifier are mounted separately on the floor because of their bulk and weight, and are delta-connected.

siderable bearing on filter design. As a general rule, not more than two sections are used in a filter.

The above discussion of filter design from the viewpoint of ripple reduction is based on choke input. The presence of an input condenser would materially reduce the ripple, but the initial surges of current as each phase charges the input condenser are not safe; this is particularly true when starting up a transmitter, for the initial condenser voltage is zero and the current surge is very large. Although condenser input gives lower ripple output, it presents a high peak-to-average current wave; a coil input gives a low peak-to-average current wave form. From now on, we will consider only coil input filters, as they are universally used.

2. Voltage Regulation. This is an important consideration in rectifier circuits. Using mercury-vapor rectifiers, the output voltage would be substantially constant if it were not for the resistance in the choke coils and resistance in the secondary phase windings of the power transformers. These windings are designed to have as low an ohmic value as is consistent with cost. Regulation is easily determined, for it is the drop in output voltage when changing from no load to full load, divided by the no-load voltage. To get the per cent regulation, multiply by 100.

3. Minimum Inductance of Input Choke. In referring to Figs. *17A, 17B* and *17C*, it will be observed that without a coil filter the load current has a high percentage of ripple. With a coil filter, however, the almost constant load current shown in these diagrams is obtained only with a very large input choke inductance; small inductance values give a varying load current, and can even make the load current stop flowing for a part of each cycle. Unless the rectifier supplies current to the filter circuit and load at all times, the voltage regulation and ripple output will vary with the load. It is highly desirable, therefore, that a choke be chosen *which will permit load current to flow at all times.* For a given rectifier circuit and a definite load, the input filter choke must be larger than a definite minimum value.

Now let us see how a choke input filter which is fed with a rectified a.c. voltage which never remains at zero can make the load current drop to zero for a part of each cycle.

The rectified a.c. voltage curves in Figs. *17B* and *17C* (curves *1*) may each be resolved into a d.c. component and several a.c. components. Each component acting on the filter circuit will produce its own current. The d.c. voltage acting on the choke resistance, load resistance and secondary winding resistance will determine the d.c. current (computed by dividing the d.c. voltage by the d.c. resistance of the circuit).

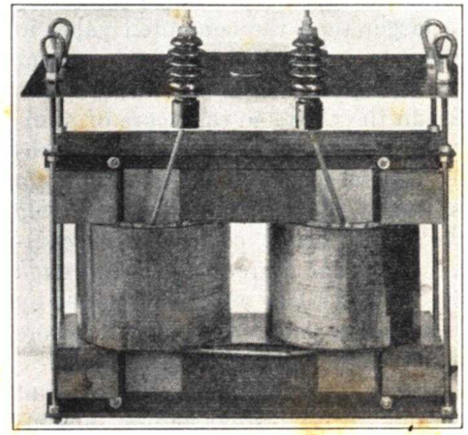
For all practical purposes, we can assume that the input choke is the important factor which determines the a.c. current value. We can further assume that only the fundamental (lowest) ripple frequency is important. The peak a.c. voltage divided by the reactance of the input choke will give the peak a.c. current flowing into the input of the filter. This a.c. current alternately adds to and subtracts from the d.c. current value; if the peak a.c. current exceeds the d.c. current value there will be times during the ripple cycle when no current flows at all.

If the choke reactance is made large enough, the a.c. current value will be reduced sufficiently to prevent this undesirable condition. There is a minimum value of coil inductance for each definite set of conditions which will prevent the a.c. ripple current from driving the load current to zero. This condition is satisfied when the coil has

an inductance in henrys which is greater than the value $K \times R \div 6.28f$, where K is the ratio of the *peak value* of the fundamental ripple voltage at the filter input to the d.c. output voltage, R is the load resistance in ohms, and f is the frequency in c.p.s. of the fundamental ripple frequency.

As an example, let us choose a single-phase full-wave rectifier, for which the fundamental ripple frequency is 120 cycles and the peak value of the fundamental ripple frequency voltage at the filter input is .667 times the d.c. output voltage; the value of K is therefore .667 for this rectifier circuit.* The minimum value for L is $K \times R \div 6.28f$, which in this case is $(.667 \times R) \div (6.28 \times 120)$. This simplifies to $R \div 1130$ as the minimum value for L. The load resistance R can be assumed to equal the d.c. output voltage divided by the d.c. current drawn by the transmitter sections which are connected to this filter. For example, assume that a transmitter is supplied with 2500 volts d.c. and draws .4 amperes d.c. Hence, R would equal $2500 \div .4$, which is 6250 ohms. With a full-wave single-phase rectifier having choke input, then, the minimum value of L is $6250 \div 1130$, or about 5.5 henrys. A minimum value of 6 henrys would be selected, to account for choke and transformer resistances.

With this as a start, we can compute the values for the remaining parts of the filter. Knowing the value of the peak ripple component at the input of the filter (the value K previously discussed), and knowing what portion of the d.c. output voltage can be a ripple for the type of service we have in mind, we can determine the ripple reduction ratio required. Let us say that for one service the peak output ripple voltage must be less than 1/100 of the d.c. output voltage. If the initial ripple peak is .667 times the average d.c. output voltage, we need a ripple reduction ratio of about 67 to bring the ripple peak down to .01 times the d.c. output. With a single filter section, then, the condenser must have a reactance which is 1/67 of the reactance of the 6-henry choke at 120 c.p.s.



Courtesy Kenyon Transformer Co., Inc.

Typical filter choke coil for a high-voltage rectifier circuit, before being placed in its tank. The two sections of the winding, one on each leg of the core, are connected together in series.

If we choose to use two filter sections, both to be alike, then we need a ripple reduction ratio of only about 8.2 for each filter section. In this case, the condensers must have a reactance which is 1/8.2 of the reactance of a 6-henry choke at 120 c.p.s. At this frequency, the 6-henry choke has a reactance of about 4500 ohms. Dividing 4500 by 8.2 gives 550 ohms as the required condenser reactance. A 2.5-mfd. condenser will have this reactance at 120 c.p.s.

For radio telegraph work, the output ripple peak should be less than about 1/20 of the d.c. output voltage; for amateur and ordinary telephone communication, the output ripple should be less than 1/100 of the output voltage; for broadcast stations, the output ripple voltage should be less than 1/1000 of the output voltage.

*The value .667 is obtained from Table III, given later in this lesson.

4. Swinging Chokes. In the actual operation of a transmitter the current demand on the rectifier system is not constant, but varies with modulation. In computing the minimum inductance value for the input choke, normal current drain was assumed. When the current demand goes down, the effective resistance of the load increases, hence the input coil inductance should be larger than the computed value in order to prevent the output current from dropping to zero. Rather than design the choke to take care of minimum load conditions (a costly procedure), a special input choke design is used. In this so-called *swinging choke, the choke coil inductance increases as the current flowing through it decreases.* This effect is obtained by using an air gap in the choke coil core structure, with a gap length which will nearly allow saturation to occur at normal output current values. The inductance of a swinging choke thus decreases with increased d.c. polarization current. The current cycle is thereby much more alike in the range from low to high current drain, keeping regulation and hum output substantially constant. If load conditions are such that an excessively high inductance would be required to prevent load current from remaining at zero, a bleeder resistance is connected to the output of the filter so as to increase and fix the value of the minimum current drawn. *By increasing the value of the minimum d.c. output current,* a bleeder resistor across the filter output *makes a smaller swinging choke inductance adequate for preventing the output current from remaining at zero for any part of a cycle.*

In choosing a filter choke, whether it be the input choke or the choke for the following filter section, consideration should be given to the d.c. current, for under no condition should magnetic saturation be high enough to destroy the coil inductance. Both maximum and minimum d.c. currents must be specified along with the maximum and minimum inductance values when ordering a swinging filter choke.

5. Filter Condenser Ratings. The condenser used in a filter must be capable of withstanding continuously a d.c. voltage equal to the peak voltage value applied to it; this voltage value will not exceed the *peak value* of the a.c. voltage applied to the rectifier. It is better to use single condensers rather than several in series, since the voltages across individual condensers of a series combination divide according to their leakage resistances; this leakage may not be the same for all the condensers, and one condenser may break down. Whenever condensers with low voltage ratings are connected in series to meet the voltage requirements of a filter circuit, *each condenser should be shunted with a resistor of high ohmic value, with all resistors having the same value* so that the same voltage will exist across each resistor and each condenser.

6. Resonance. It is important to choose values for L and C such that each section of the filter will resonate at a frequency lower than the fundamental ripple frequency.

7. Reactance of Output Filter Condenser. The output condenser of the filter must be large enough so that its reactance is negligibly small compared to the load resistance at the lowest frequency which the load is designed to handle. Thus, if the load is an audio modulator which must carry speech frequencies down to 30 cycles, the reactance of the output condenser at 30 cycles must be small. On the other hand, if the load is a modulated class C radio-frequency amplifier, the usual filter output condenser reactance will be relatively small in comparison to the amplifier tube impedance, for in this service high voltage and low current drain is demanded; the value of the output filter condenser would in this case be determined by the other design considerations already mentioned. The output condenser requirement presented in this paragraph insures that low-frequency signals entering the power pack will be shunted to ground by the output filter condenser, so they cannot wander through the entire power pack and cause regeneration.

	TYPE OF RECTIFIER CIRCUIT				
	Single-Phase Full-Wave	Three-Phase Half-Wave	Three-Phase Half-Wave Double Y	Three-Phase Full-Wave	Single-Phase Full-Wave Bridge
(a) R.M.S. value of transformer secondary voltage in each phase for 1 volt d.c. output.	1.11	.86	.86	.43	1.11
(b) Peak inverse voltage for 1 volt d.c. output.	3.14	2.09	2.09	1.05	1.57
(c) Lowest ripple frequency at filter input.	120	180	360	360	120
(d) Peak amplitude of lowest ripple frequency voltage at filter input for 1 volt d.c. output.	.667	.250	.057	.057	.667
(e) Minimum input choke inductance in henrys.	$R_L/1130$	$R_L/4530$	$R_L/39{,}600$	$R_L/39{,}600$	$R_L/1130$
(f) Primary utilization factor.	.900	.827	.955	.955	.900
(g) Secondary utilization factor.	.637	.675	.675	.955	.900

TABLE III. Important data relating to various types of rectifier circuits is combined in one table here for your convenience.

8. Transients. In choosing the values of L and C for a filter, care must be taken to prevent transient oscillations in the load current during sudden changes in the load. This generally requires an accurate knowledge of the operating conditions, and these are best determined under operating conditions. Resistors are often connected in series with filter condensers to minimize current surges.

9. Tabulated Filter Design Characteristics. In the discussion of single and polyphase rectifier systems, a number of important circuit characteristics were considered for typical circuits. We considered the importance of secondary voltages, peak inverse voltages, the fundamental ripple frequency, minimum input choke inductance, etc. These important characteristics have been worked out by engineers, and are presented in convenient reference form in Table *III* for various types of rectifiers. In each case, a very large choke input filter, zero d.c. voltage drop across the choke, and negligible tube voltage drop are assumed. Let us consider, one by one, the meanings of the various values given in this table.

Item a. This line in Table *III* gives the r.m.s. value of supply voltage required for each phase to get a d.c. output voltage of one volt with various types of rectified circuits. To find the total r.m.s. voltage required per phase in a particular actual circuit, simply *multiply the d.c. output voltage by the factor specified for that circuit in the table.* For a single-phase, full-wave circuit, the result will be the r.m.s.

voltage between the center of the secondary and an end terminal; for polyphase circuits, assuming Y-connected secondaries, this will be the r.m.s. voltage across one phase winding (or leg). Here is an example: A three-phase half-wave circuit is to deliver 2500 volts. The table gives .86 as the factor for this circuit, so we multiply 2500 by .86, getting 2150 volts r.m.s. as the a.c. voltage required per phase. For a full-wave three-phase circuit, the factor is .43, so the a.c. voltage per phase required for an output of 2500 volts d.c. would be 2500 × .43, or 1075 volts r.m.s.

Item b. Here the peak inverse voltage rating of each rectifier circuit for a d.c. output voltage of 1 volt is given. To find the peak inverse voltage rating of an actual circuit, *multiply its d.c. output voltage by the factor given in the table.* Thus, for a three-phase half-wave circuit supplying 2500 volts d.c., the inverse peak voltage is 2.09 × 2500, or 5220 volts. This rating is based on the fact that when the plate of a rectifier tube is driven to the peak negative value, the voltage across the input filter condenser is in series with and adds to the peak negative voltage. The two voltage values acting on the tube in this way will be nearly equal, but will be various amounts out of phase depending on the circuit used. (The single-phase, full-wave circuit is an exception, for here the voltages are *in phase* and nearly equal.)

Item c. The values given are for a 60 c.p.s. supply source; for other supply frequencies, the values will change proportionately.

Item d. Any rectified pulsating voltage can be considered as a d.c. value plus harmonic components having definite peak amplitudes. The d.c. component is the d.c. output voltage of the power pack, and the peak amplitude of the lowest a.c. voltage component *at the filter input* is given as item *d* in the table. For a 2500-volt d.c. output in a three-phase, half-wave system the peak ripple voltage at the filter input will be 2500 × .25, or 625 volts.

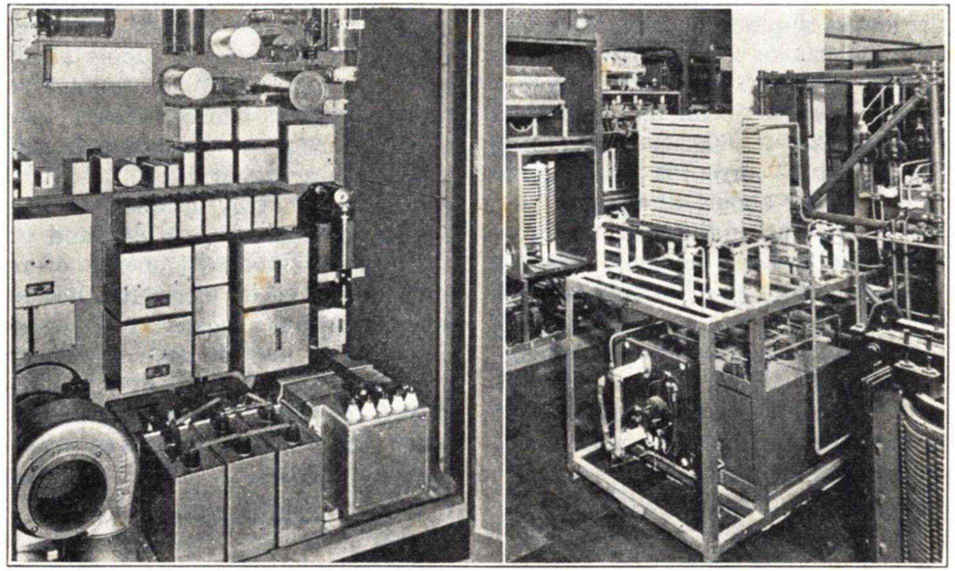
Item e. The values in this line were computed by placing the corresponding values from items *c* and *d* in the minimum-inductance formula given previously. Example: in a three-phase half-wave circuit supplying 2500 volts at .4 amperes, the load resistance $R_L = 2500 \div .4 = 6250$ ohms. The minimum inductance for the input choke will be $6250 \div 4530 = 1.38$ henrys.

Items f and g. These deal with the power ratings of the transformers. If we assumed there was no loss in the filter and rectifier, we might expect that the transformer would only have to supply the power drawn by the load. But this is not true; the currents flowing through the transformer windings are not of simple sine wave form, but are more or less distorted by the rectifier and filter action. This distortion increases the transformer losses considerably, hence the transformer must draw more power than it delivers. Engineers use a factor known as the *utilization factor* of a transformer, this being equal to the *power delivered divided by the power drawn;* items *f* and *g* in Table *III* give this factor for the primary and secondary respectively of a power transformer.

To find the power rating for a transformer winding, divide the power delivered by the utilization factor for that winding and circuit. In the three-phase, half-wave example we have been considering, the rectifier furnishes 2500 × .4, or 1,000 watts of d.c. power. The primaries of the three-phase transformer must be rated at 1,000 ÷ .827, or 1210 volt-amperes; the secondaries must be rated at 1000 ÷ .675, or 1,480 volt-amperes. Since there are three windings or phases in the transformer, each winding handles one-third of this power, or 404 volt-amperes and 493 volt-amperes respectively.*

All these factors are based on ideal conditions. A final filter design must take into account tube drops as well as choke coil and power transformer winding resistances. These may be included as part of the transmitter load by increasing the effective load resistance.

*Power transformers are rated on the basis of input voltage times input current, which is apparent input power; the ratings will be in kilovolt-amperes (abbreviated kva.) or in volt-amperes. When the transformer load is purely resistive (unity power factor), the true power is the same as the apparent power; in this case, 1 kva. will correspond to 1 kilowatt (kw.) and 1 volt-ampere will correspond to 1 watt. The power factor for the transformer load (the transmitter circuits) is usually slightly less than unity; in these practical cases, then, the transformer must be able to handle the apparent power passing through it, for this will be larger than the true power.



Courtesy Western Electric Co.

Left: Rear view of Western Electric 443A-1 1,000-watt transmitter, with back doors of rack swung open to show the equipment. At the bottom of the rack is the blower which provides forced air cooling for the entire transmitter, along with three large filter condensers for the main single-phase, four-tube bridge-type rectifier, and the power transformer for this rectifier. Right: Filter condensers for the main power pack of a 50-kilowatt Western Electric transmitter. Because of their great size and weight, these condensers are placed directly on the floor of the transmitting station. Note the high-tension insulators supporting the condenser terminals. On the left side of the condenser rack is the automatic condenser discharge relay, which operates when the transmitter is turned off and serves to discharge the large filter condensers through resistors.

Calculation of Peak Tube Current. Let us see how we can calculate the amount which must be added to the d.c. load current value to determine the peak tube current. This calculation merely involves computing the peak ripple voltage across the choke coil for the lowest-frequency ripple, then dividing this peak ripple voltage by the reactance of the choke at the ripple frequency to get the peak ripple current. Adding this current to the d.c. load current value gives the peak tube current.

An example will illustrate the procedure. Let us assume that a three-phase half-wave circuit delivers 2500 volts at .4 ampere, and the input choke value is 6 henrys (this choke size is all right since it is greater than the minimum value of 1.38 henrys indicated by item *e*).

Item *d* tells us that the peak amplitude of the lowest peak ripple voltage will be .25 × 2500, or 625 volts. At the lowest ripple frequency, 180 c.p.s., the input choke will have a reactance of $6.28 \times 180 \times 6 = 6800$ ohms. By Ohm's Law, the peak a.c. current is equal to $625 \div 6800 = .092$ ampere. The peak tube current is then equal to $.4 + .092$, or about .49 ampere. (An exception occurs in the case of a three-phase half-wave double-Y circuit, where each tube supplies only half the load current; in this case, the peak tube current is equal to the peak ripple current plus half the d.c. load current.)

With the input choke value specified in the above example, the peak ripple voltage was 625 volts. If we wanted to reduce this peak ripple voltage to 1 per cent of the output d.c. voltage (to 1 per cent of 2500 volts, or to 25 volts) while using the same choke, how large should the shunting filter capacity be when there is only one filter section? With peak ripple voltages of 625 volts at the filter input and 25 volts at the filter output, the ripple reduction factor required is $625 \div 25$, or 25. The filter condenser must have a reactance of $6800 \div 25$, which equals 272 ohms. To find the condenser capacity in microfarads, divide 1,000,000 by condenser reactance, by ripple frequency in c.p.s. and by the number 6.28, as follows: $1{,}000{,}000 \div (272 \times 180 \times 6.28)$, which is $1{,}000{,}000 \div 307{,}000$, or 3.25 microfarads, the value required for the filter condenser.

Rectifiers Required in Transmitters

There is a wide difference between the d.c. voltage values required for the control grids, screen grids and plates of the various tubes in a transmitter. Furthermore, when several amplifier tubes are used in cascade for power amplification, there will be considerable difference in the plate voltages, with the voltage increasing as the amount of power handled goes up. Only in low-power transmitters, with outputs of 250 watts or less, is a single rectifier system used to supply all the voltages required. When voltage requirements for various tubes in a transmitter vary widely and some tubes require high currents, too, it becomes economically unwise to use the conventional single rectifier and get the lower voltages by means of resistance voltage dividers. It is not uncommon to find a separate rectifier circuit used to provide each basic voltage value.

In a large transmitter you can expect to find one rectifier circuit serv-

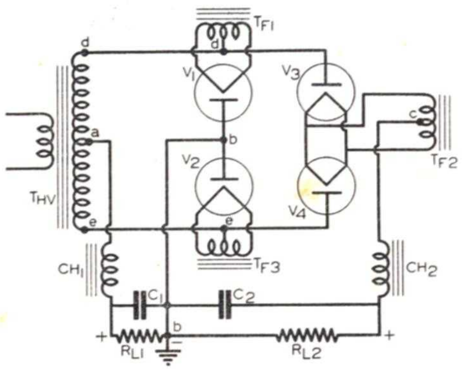


FIG. 18. Double-duty single-phase rectifier circuit serving as a conventional full-wave rectifier for load R_{L1} and as a full-wave bridge-type rectifier for load R_{L2}.

ing as the grid bias source; this will usually be a half-wave rectifier circuit, and will be preceded by a constant-voltage transformer if a constant output voltage is necessary. There will be a separate rectifier circuit for screen grid and low plate voltages, and another rectifier circuit for the high plate voltages.

It is possible to economize on space and transformer costs by making one power transformer furnish high a.c. voltages simultaneously to two rectifier-filter circuits. We will now consider three different types of these double-duty transformer hook-ups for rectifiers.

Double-Duty, Full-Wave, Single-Phase Rectifier Circuit. The unique

full-wave, single-phase bridge circuit shown in Fig. *18* uses only one power transformer, and yet this circuit provides two distinct d.c. voltage sources. This circuit is employed in some low-power transmitters. Note that four rectifier tubes are used in a so-called bridge rectifier arrangement; a connection to the center tap of the high-voltage secondary makes this same circuit act as a full-wave two-tube circuit. Low d.c. voltage is obtained from terminals *a* and *b*, and high d.c. voltage is obtained from terminals *b* and *c*. Three filament transformers, T_{F1}, T_{F2} and T_{F3}, are employed.

To see how this circuit supplies a high d.c. voltage, let us temporarily ignore the secondary mid-tap *a*. When point *d* on the high-voltage secondary is positive, point *e* on this winding will be negative. At that instant, the electron path will be from point *e* to the center tap on T_{F3}, through V_2 to point *b*, through load R_{L2} and choke CH_2 to point *c*, and through V_3 to terminal *d*. If we neglect the voltage drops through the tubes, the choke and the secondary winding, we can say that the positive half-alternation acts through filter CH_2-C_2 on load R_{L2}. When *e* is positive on the next half-cycle, point *d* is negative and the conduction path is d-V_1-b-R_{L2}-CH_2-c-V_4-e. In each case, point *c* is positive with respect to point *b*. Two positive half-wave cycles appear alternately across *c* and *b*, and we have full-wave rectification; the full voltage across *e* and *d* of the transformer is utilized in this section of the rectifier.

Now let us consider the full-wave rectifier circuit which includes secondary center-tap *a*. When point *d* is negative with respect to point *a*, the conduction path will be d-V_1-b-R_{L1}-CH_1-a. When point *e* is negative with respect to point *a*, the conduction path will be e-V_2-b-R_{L1}-CH_1-a. Since *d* and *e* alternate in becoming negative with respect to point *a*, tubes V_1 and V_2 alternately conduct once each cycle. We thus have a full-wave rectifier circuit. Since only half the secondary voltage is active at any one instant in this circuit, the d.c. voltage produced across R_{L1} is only half of that produced across R_{L2}. In this manner we obtain a double rectifier circuit while using only one high-voltage transformer, T_{HV}.

Tapped Y Three-Phase Half-Wave Double Rectifier Circuit. The circuit in Fig. *19* shows a simple and quite

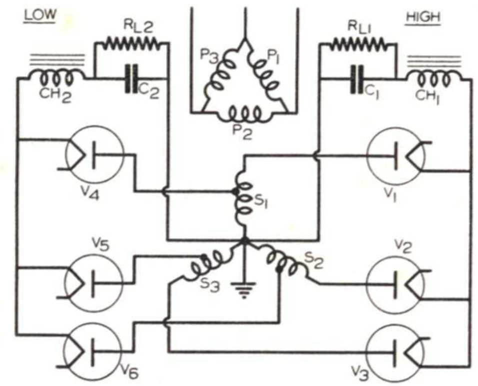


FIG. 19. Three-phase half-wave double-duty rectifier system employing a single three-phase transformer.

common means for making one transformer serve two rectifier circuits. The full secondary voltages are used to furnish a high d.c. voltage output through diodes V_1, V_2 and V_3, while a tap on each secondary winding is utilized to furnish a lower d.c. voltage output through diodes V_4, V_5 and V_6. Each rectifier and filter is designed independently, but the transformer must be able to supply power for both systems. Space is saved, and the transformer cost is considerably less than for two separate transformers.

Three-Phase, Half-Wave, Voltage-Doubling Rectifier Circuit. Voltage doubling is quite possible in polyphase circuits, as the number of charging "shots" per second is materially increased over that in single-phase operation; this keeps the charge across the condenser very near its peak value. Voltage doubling in a three-phase, half-wave circuit is shown in Fig. *20;* this arrangement also provides two separate d.c. voltage sources without requiring an extra three-phase power transformer. Let us analyze a single phase, keeping in mind that the other two phases act on the charging condenser in the same manner, 120° and 240° later in each cycle. Thus, there are three "shots" per cycle in comparison to only one per cycle for single-phase voltage doubling circuits.

Concentrating on secondary winding S_3 and rectifier tubes V_5 and V_6, let us consider the alternation when b is positive and a is negative. This makes the plate of V_6 positive, and the tube conducts; the electron path is a-CH_1-f-C_1-e-d-V_6-c-b. This makes terminal e of C_1 positive, and terminal f negative. If winding S_3 has a voltage e_S having a peak slightly greater than 1,500 volts, C_1 will be charged to 1,500 volts, and can serve as one d.c. supply voltage.

For the following a.c. alternation, point a will be positive and point b will be negative. This applies a negative voltage to the cathode of V_5, and if a conducting path exists, its plate will be positive. A path does exist: b-h-V_5-i-CH_2-g-C_2-f-CH_1-a. Since a is positive, terminal f of C_2 will be positive; terminal g, connecting to b through V_5, will be negative. Condenser C_2 is charged to 1,500 volts. Since condensers C_1 and C_2 are in series, their voltages add together, and 3,000 volts is obtained between e and g.

Racked Units. Large power outputs are obtained in transmitters by power amplification. Thus, a 5,000-watt amplifier might be driven by a 500-watt amplifier. Input power is required if high efficiency is to be obtained along with high tube output, for the grids are driven positive in high-power stages, making grid current flow.

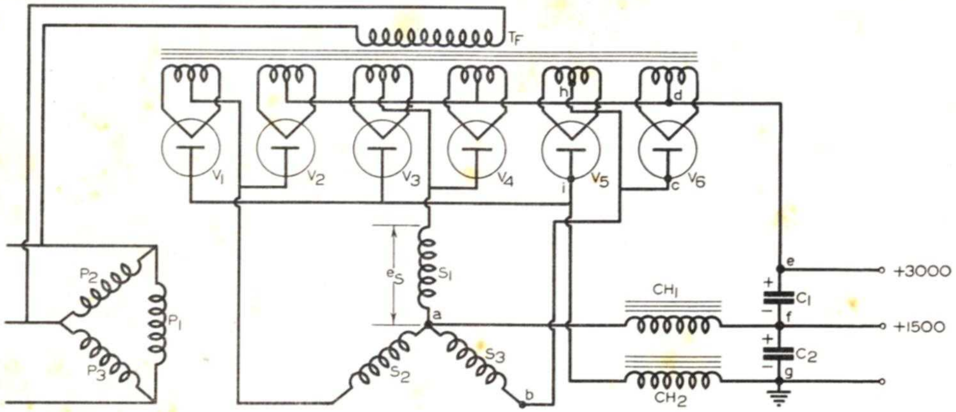


Fig. 20. A three-phase half-wave voltage-doubling rectifier circuit providing two different d.c. voltage values.

It has become standard practice to build high-power transmitters in units, with the units mounted on vertical racks. Each unit has a definite function and delivers r.f. power at a definite level. It is customary to provide a separate rectifier circuit for each rack. Oftentimes there will even be separate rectifiers for individual units on a rack.

Thus, in one vertical rack you might find the crystal oscillator and its emergency unit, the buffer and the frequency doublers, along with the required rectifier systems. The next vertical rack may house the modulator and the r.f. modulated amplifiers, along with their rectifiers. A final unit could house the linear r.f. power output amplifier; since the power transformers, filter chokes, and filter condensers for this rectifier are usually too large and bulky for panel or rack mounting, they will probably be on the floor nearby, with the rectifier tubes on the rack. All controls and relays will be on the front of the rack. The rear of each rack, along with all separate high-voltage units will be enclosed by steel cages, to prevent any one from coming in contact with dangerous high-voltage terminals. To make adjustments or repairs from the rear, a door must be opened (it is usually locked with a key); upon opening the door, an interlock switch throws off the main supply to the high-voltage rectifiers. Where high-voltage terminals are accessible from the front, they will also be protected by metal screen doors, each having an interlock switch.

TEST QUESTIONS

Be sure to number your Answer Sheet with the *number* appearing on the front cover underneath the title of this text.

Place your Student Number on every Answer Sheet.

If you want to know your grade as soon as possible, mail your answers immediately, or you may send in two sets at a time. However, don't hold answers to send in more than two sets at a time, or you may lose them or run out of lessons before new ones can reach you.

1. How is the percent voltage regulation of a power transformer determined?
2. In an auto-transformer, what is the relationship of the current through the common portion of the winding to the currents in the primary and secondary circuits?
3. Why is the delta-Y transformer connection so widely used in three-phase rectifier systems?
4. What is meant by the maximum peak inverse voltage of a rectifier tube?
5. Why is it essential to allow the filament of a mercury-vapor rectifier to heat up for a specified period before applying plate voltage?
6. Should the number of phases in a rectifier system be *decreased* or *increased* to make the d.c. output voltage more nearly approach the peak a.c. voltage per phase?
7. What should be the relationship between the reactances of L and C in a conventional choke input filter to get effective ripple reduction?
8. In a rectifier system employing a swinging choke, what effect does a *decrease* in output current have upon the inductance of the swinging choke?
9. Why is a bleeder resistor sometimes connected across the filter output of a rectifier system employing a swinging choke?
10. What precaution should be taken to prevent voltage breakdown when two or more identical condensers with low-voltage ratings are used in series to meet voltage requirements of a filter circuit?

"WISHERS" AND "DOERS"

How often have you said, "I wish I had more money?" Thousands of times, possibly. But do you realize that if you are living in a town of, let us say, 5000 inhabitants, there are exactly 4999 others in your town who are saying exactly the same thing?

And yet, of these 5000 "wishers," only about 100 are going to do something about it. The others are going to continue being "wishers."

Now, any man who shows enough "get-up-and-go" spirit to undertake this Course proves that he is not a mere "wisher." When you enrolled, you showed that you wanted to be a "go-getter." Your job now is to keep going forward on the road you have mapped out for yourself.

Every lesson in this Course, every radio job you work hard to get, is a step along this road. So don't let yourself wish that the lessons were easier, or that you could become successful without studying, or that radio jobs would come looking for you. Stay out of the class of the "wisher," and stay in the class of the "doer."

The "wisher" is a very unhappy individual because he is constantly thinking and worrying about what he does not have. The go-getter is so busy getting what he wants that he doesn't have time to be unhappy.

J. E. SMITH