



SPECIALIZED TELEVISION ENGINEERING

TELEVISION TECHNICAL ASSIGNMENT

POWER SUPPLIES

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730D

POWER SUPPLIES

FOREWORD

In this assignment we study an important application of diode tubes—namely, operation as a rectifier in a power supply for furnishing d.c. voltages from the a.c. power mains. Since no amplifier tube can function without plate (and grid) voltage, it is clear that the power supply occupies a key position in electronic equipment, and by far the most common type of supply is that discussed here.

The most obvious method of rectification is half-wave, but this is used only in special cases. The full-wave rectifier is in general preferred for smaller units, and is fully treated in this assignment. However, in larger power supplies it is found desirable to employ polyphase rectification, generally from a three-phase source. For example, most transmitters of any appreciable size use this type of rectification. The design considerations are, of course, more involved, but are readily understood after the simpler types of power supplies have been studied.

The next topic is that of filter sections, which smooth out the pulsating output current by by-passing the ripple components. The discussion is thorough, and treats the matter in considerable detail. Such treatment is necessary, for a power supply is of no practical value if the ripple components are not made negligible in value.

Finally, the subject of voltage dividers is taken up, and many illustrative problems are treated in order to give the student a practical grasp of the subject. The material is simple to understand, particularly since it involves mainly Ohm's Law, but there are a number of practical considerations—such as wattage ratings of resistors—which must not be overlooked.

When you have completed this assignment, you will undoubtedly be surprised at the large number of consider-

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ations involved. The material is not at all difficult to understand; nevertheless it requires study in order to have a good grasp of the subject.

E. H. Rietzke,
President.

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The unilateral conductivity of the two element tube makes it ideal as a rectifier. The only current that can flow is due to (but not necessarily limited to, as will be explained later) electron emission from the cathode. When the plate is positive with respect to the cathode, emitted electrons are attracted to the plate and current flows through the tube and associated circuit. When the plate is made negative with respect to the cathode, electrons are repelled by the plate and hence, even though the emission is the same as before, no current can flow through the tube. Reverse current is prevented because the electron emission is from one element only, the cathode. Thus if a two element tube is connected in series with an alternator as shown in Figure 1, plate current will flow only on the alternations which make the plate positive with respect to the filament. This is shown in Figure 2.

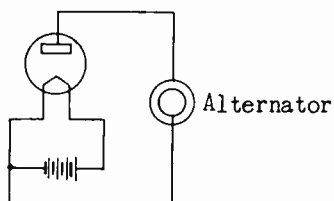


Fig. 1.

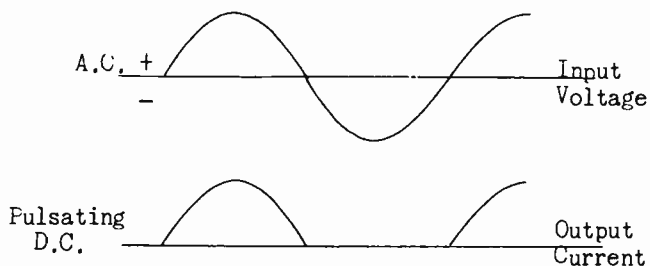


Fig. 2.

A more practical type of circuit is shown in Figure 3. This is a half-wave rectifier in its most simple form used for converting alternating current to direct current. The transformer may have a single primary winding and two secondary windings as shown, (a step-down winding for filament heating and a step-up winding for producing the desired plate voltage), or two separate transformers may be used.

The direction of load current I is shown, from filament to plate within the tube, from the plate through the load resistance, through the high voltage secondary winding, and back to the filament. On the second alternation in which the polarity of the high voltage is reversed, no current flows through the load.

Since current flows in a circuit *from negative to positive*, it particularly should be observed that *the terminal connecting to the plate is the negative load terminal*. This fact must always be remembered when working with tube rectifiers.

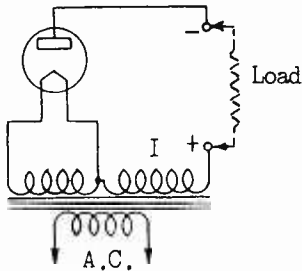


Fig. 3.

In radio the principal use of a rectifier is to supply plate voltage for vacuum tubes. Usually it is necessary that the plate voltage be perfectly uniform with negligible pulsations or ripple. This necessitates the use of a filter, and it can easily be seen that to supply a constant uniform flow of current from intermittent pulses as shown in Figure 2, will require a large and elaborate filter. If the output pulses of current from the rectifier can be made more frequent the filtering problem is reduced. This may be done with a full-wave rectifier consisting of two tubes as shown in Figure 4, the output of which is illustrated in Figure 5.

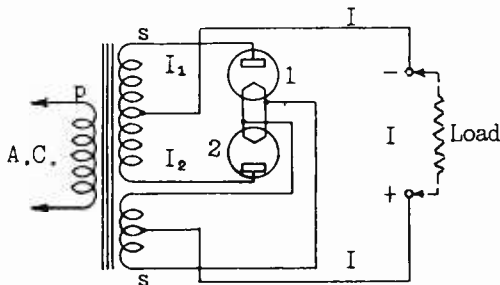


Fig. 4.

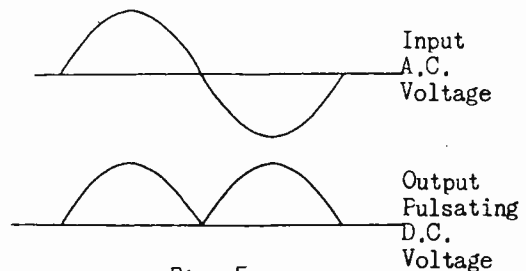


Fig. 5.

The plates of Tubes 1 and 2 are connected to opposite ends of the high voltage secondary winding, the center tap of which forms the negative terminal of the rectifier. *THE POSITIVE TERMINAL OF THE RECTIFIER CONNECTS TO THE FILAMENT WINDING AS SHOWN.*

Being connected to opposite ends of the high voltage winding, the voltages on the plates of Tubes 1 and 2 are 180° out of phase. When plate 1 is positive, plate 2 is negative and current flows only through Tube 1. On the next alternation the condition is reversed and current flows only in Tube 2. On both alternations, the current emerges from the center-tap of the high

voltage winding, flows down through the load, and to the common filament terminal. Thus the current in the load consists of two equi-directional pulses, one for each alternation of the cycle, and for a given desired load current, each tube is required to supply only one-half of the total current. With the pulses of rectifier current closer together, the problem of filtering to a smooth uniform current through the load is greatly simplified.

If a polyphase power supply is available the rectifier may be so designed as to rectify each alternation of each phase. Thus with a three phase rectifier the pulses are separated by only 60° instead of 180° , the output voltages overlap, and filtering is much easier because it is only necessary to smooth out the peaks. This can be seen from an examination of Figure 6. The circuits

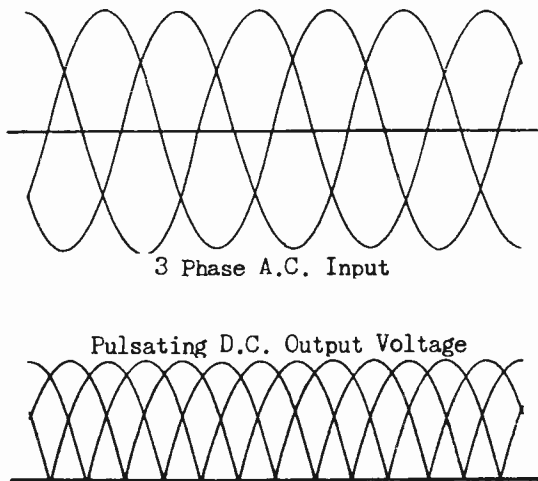


Fig. 6.

as used in such a rectifier will be discussed later. It should be pointed out that as the ripple frequency is increased the problem of filtering becomes easier, the constants of the filter elements varying inversely as the square of the ripple frequency. (This will be discussed in greater detail later in this lesson.)

Tube rectifiers may be divided into two principal groups, High Vacuum or Kenotron recti-

fiers, and Gaseous rectifiers. In both types, for high voltage operation, the output current that can be delivered by the rectifier is determined entirely by the filament emission. The operating characteristics of the two types are quite different. Practically all of the rectifiers being built for high voltage radio use today employ gaseous tubes because of their many advantages. Both types will be discussed.

HIGH VACUUM HIGH POWER RECTIFIER TUBES: The operation of the high vacuum rectifier tube is exactly the same as any two element tube as described in the preceding lesson. In order to obtain a high vacuum it is necessary to use a

tungsten filament so that the tube can be evacuated at high temperature. To approach saturation current it is necessary that the voltage between plate and filament be sufficient to completely counteract the space charge. With the high filament emission necessary for large output current this will ordinarily be in the neighborhood of 1500 to 1600 volts for a tube that can deliver 6 or 7 amperes to a load at around 15,000 volts.

Used in a three phase circuit in which six tubes are employed to deliver a steady load current of 12 amperes, two tubes operating at a time at 4 amperes each, the load being transferred from tube to tube according to the transformer voltage variations, an average voltage drop of 1500 volts at 12 amperes represents a plate power dissipation in the rectifier of 18 KW. This is a typical operating condition for a high voltage rectifier using tubes such as the Type 214. To supply filament emission each tube of this type requires 52 amperes at 22 volts, a total filament power of almost 6.9 KW. Thus the total power loss in such a rectifier is approximately 25 KW, neglecting losses in the transformer and filter. Due to the space charge loss of 3 KW per tube which is expended in anode heat from electronic bombardment, it is necessary to water-cool the plates.

With such a high space charge drop it is essential that the Kenotron rectifier tube be *very* well evacuated. If the tube contains an appreciable amount of gas, ionization will take place. The heavy ions, repelled toward the filament will bombard the filament to such an extent that it may be damaged.

In the design of the Kenotron rectifier to supply a given output current at a specified voltage, it is necessary to take the tube drop into consideration. Assume that the simple full-wave rectifier of Figure 4 is required to supply a voltage of 15,000 volts across the load and that the tube drop is 1500 volts. Each half of the high voltage secondary, (between the center tap and the plate) must be designed to deliver a voltage of $15,000 + 1500$ or 16500 volts at the specified current.

Assume in the case of the three phase rectifier just discussed, a load current of 12 amperes at 17,000 volts. This represents an output of 204 KW. Assuming perfect transformers, the power input to the rectifier will be $204 + 25$ (rectifier loss) = 229 KW, and the operating efficiency is $204/229 = .89$

or 89 per cent.

Because of the high resistance of the vacuum tube due to the effects of the space charge, the regulation of such a tube is poor. A good example of this can be seen in the characteristics of the Type 80 rectifier tube as used in receivers. With 300 volts RMS per plate, the d.c. output voltage at the input to the filter with load current of 30 mils is 245 volts, (with choke input to filter), representing a tube drop of $\frac{636}{.707} (300) - 245 = 25$ volts. When the load current is increased to 100 mils, the d.c. output drops to 220 volts, representing a voltage drop from an RMS transformer voltage of 300 volts to a d.c. output voltage of 220 volts, or a voltage loss of .27% in the tube itself. The poor regulation of such a tube makes it entirely unsuited for use in a circuit in which the load fluctuates widely. Such a load is a Class B audio amplifier.

Thus the principal disadvantages of the high vacuum rectifier are: poor regulation, large voltage drop within the tube, large power dissipation within the tube due to plate bombardment and in the case of high power tubes, high first cost and the use of an inefficient type of filament. Since the development of efficient gaseous rectifiers for both high and low voltages and wide current ranges, the high vacuum rectifier tube has no apparent advantages and is mostly used for replacements in installations of earlier design. The exception to this is in receiver design where the gaseous tube is not so popular due to interference set up in R.F. circuits. Regulation of the power supply is not a factor in Class A amplifiers.

HOT CATHODE GASEOUS RECTIFIERS: The principle of gaseous rectifiers has been known for many years. However up to several years ago the only practical use made of such a tube was in the Tungar rectifier used for low voltage rectification. The Tungar tube is first evacuated and then an inert gas, usually argon, is admitted to a quite high pressure, on the order of 3 to 8 centimeters of mercury. A tungsten filament supplies a limited number of electrons by thermionic emission. When the plate is positive electrons are attracted from the filament. These electrons will strike some of the gas molecules and dislodge additional electrons, which in turn may strike other gas molecules liberating more electrons, etc. Thus a few electrons from the hot filament

80

H V
Disadvantages

start the process of ionization and the resulting plate current may be hundreds of times greater than the actual filament emission. As the released electrons are attracted to the plate the positive gas ions are repelled toward the filament. Because of the high gas pressure the distance between gas molecules is quite small and the comparatively large ions are unable to attain a velocity sufficient to damage the filament by ionic bombardment. When a gas ion makes electrical contact with the filament it immediately neutralizes. Since the gas is inert it will not combine chemically with the filament and the neutralized ion again becomes a source of additional electrons by ionization. When the plate is negative there is no attraction for the emitted electrons, hence nothing to start ionization, and no current flows through the tube. The Tungsar tube cannot be used to rectify voltages in excess of 100 volts because, with the high gas pressure, ionization may occur simply due to the voltage drop across the gas and the tube would conduct on both alternations of the voltage cycle applied to the plate and would thus cease to be a rectifier.

THE HOT CATHODE MERCURY VAPOR RECTIFIER: Several years ago the hot cathode mercury vapor rectifier tube was developed for use at high voltages. It has been shown that the use of a *high* gas pressure prohibits the use of high plate voltages on the rectifier tube because of danger of ionization on the reverse alternation. At the same time it is this high gas pressure that prevents filament disintegration due to ionic bombardment. *Cathode disintegration can be prevented if the voltage drop within the tube is kept below a critical value which, in the mercury vapor tube, lies between 20 and 25 volts.*

It has been shown that the principle disadvantage of the high vacuum rectifier is in the large voltage drop within the tube, and that this drop is caused by the space charge. If the space charge can be counteracted a very low plate voltage will cause every emitted electron to reach the plate. This is exactly what is done in the hot cathode mercury vapor rectifier. This tube operates with gas at a very low pressure. In the smaller tubes a pressure of approximately 30 microns (.03mm) of mercury is used. The larger rectifiers use a much lower pressure on the order of 10 microns at 50° Centigrade. After evacuation pure mercury is admitted into the tube. The mercury vaporizes as the temperature of the tube is raised, the vapor pressure depending

upon the temperature of the coldest part of the tube. Thus by operating the tube within a compartment, the temperature of which can be controlled within a few degrees by means of blowers, the gas pressure is easily controlled.

The potential drop across ionized mercury vapor is substantially constant with variations in current up to the peak filament emission of the tube. Within limits, as the current through the vapor increases, ionization increases creating more electrons per primary electron and hence the resistance drops in practically the same proportion as the current increases maintaining the IR drop constant. (When the load current approaches the peak emission of the filament the internal tube resistance increases rapidly and the filament is bombarded by ions.) The gas pressure in the tube is such that when ionization sets in the positive ions created between plate and filament are just sufficient to neutralize the effects of the space charge. In modern mercury vapor tubes the voltage drop from plate to filament is approximately 15 volts at normal gas pressure. This low voltage does not accelerate the positive ions to a velocity sufficient to be dangerous to the filament. With low gas pressure only an occasional electron strikes a gas molecule, but due to the relatively slow movement of the positive ions compared to the electrons, a positive charge of ions quickly builds up which is sufficient to counteract the negative space charge. When a state of equilibrium is reached the low plate voltage is sufficient to attract practically all the electrons emitted from the filament.

If the gas pressure is too low, *due to the tube being operated at too low a temperature*, there is not sufficient ionization to fully neutralize the space charge. At lower than normal temperatures the gas pressure is reduced, that is, the average distance between mercury atoms is increased. This results in a decrease in the number of collisions between electrons and gas molecules and hence a reduction in the number of positive ions. The space charge is not sufficiently neutralized and the internal resistance of the tube rises. If the IR drop across the tube exceeds the critical value of approximately 25 volts the positive ions attain sufficient velocity to damage the filament by ionic bombardment. This is the condition that may occur in a tube that has been out of service for an appreciable length of time. During the idle period the mercury vapor slowly condenses to liquid mercury which greatly reduces the

internal pressure.

Warm up } When a mercury vapor tube is first put into service the filament should be heated with plate voltage removed for 15 to 30 minutes to vaporize the liquid mercury formed during the out-of-service period. If the tube has been out of operation for only a short period of time a delay of approximately 20 seconds should be provided between application of filament and plate voltages. In most transmitters this delay is provided automatically by a time-delay relay in the plate circuit of the rectifier tube. In many transmitters one or more standby sockets are provided for spare rectifier tubes. These sockets are wired for filament power only and the tubes are thus kept at the proper temperature for a quick change in case of tube failure.

If the temperature of the tube becomes too high the gas pressure may be raised to a point where a flash-back occurs at peak voltage on the reverse alternation. The "inverse peak voltage", that is, the peak inverse voltage applied between plate and cathode of the tube, is thus a function of the gas pressure and hence of the operating temperature of the *coldest* part of the bulb on which the mercury is condensed. With large tubes excessive gas pressure is prevented by forced air cooling. In Lesson 7 it was learned that a certain number of free electrons exist at any instant even in the very best of insulators. At normal gas pressures the mercury molecules are sufficiently spaced that the number of free electrons in the vapor at any instant is quite low. As the gas pressure increases the average distance between molecules decreases and the number of free electrons created by molecular collision is increased. When the plate voltage is negative these free electrons are repelled toward the filament. If the number of free electrons exceeds a critical value they may attain a velocity sufficient to start ionization. If this occurs the internal resistance of the tube drops to a low value and practically short circuits the transformer secondary. The resultant surge of current in the reverse direction usually destroys the filament.

Due to the low tube drop and hence the slow movement of positive ions toward the cathode, very efficient oxide coated cathodes may be used. The cathode must emit sufficient electrons to provide the desired current. Because of the low gas pressure the actual number of additional electrons cre-

ated by ionization is only a very small part of the total plate current.

Since the emission is not interfered with by the space charge it is possible to enclose the cathode within a perforated heat conserving shield. The positive ions as they drift toward the cathode draw the emitted electrons through the holes in the shield where they come under the attraction of the plate voltage. Conservation of cathode heat is important because the filament potential of a mercury vapor tube is limited to approximately 5 volts RMS. The sum of the peak filament voltage and the ionizing potential must never exceed 22 volts or the filament will be subject to ionic bombardment. With this limit on filament potential, mercury vapor cathodes must have large cross-section (to reduce resistance) and be operated at comparatively high current values.

A very interesting comparison can be drawn between the three phase rectifier previously discussed which provided 12 amperes at 17,000 volts with high vacuum water-cooled tubes, and a rectifier to provide the same output with six mercury vapor tubes Type 857, two tubes being operated in series at a time. The tube IR drop is 15 volts at 12 amperes and with two tubes in series and carrying current the plate power dissipation is $12 \times 30 = 360$ watts as compared with 18 KW. With six tubes each tube is required to dissipate $360/6$ or 60 watts at the plate. Each filament requires 37 amperes at 5 volts or a total filament power of $37 \times 5 \times 6 = 1.1$ KW as against 6.9 KW for the Kenotron rectifier. The total rectifier tube loss is $1.1 + .36 = 1.46$ KW. The output is 204 KW, the input $204 + 1.46 = 205.46$ KW, and the efficiency $204/205.46 = .992$ or 99.2 per cent as compared with 89 per cent for the high vacuum rectifier. Also, due to the very small plate power dissipation even with large plate current, water cooling is unnecessary, this of course simplifying the equipment and reducing the cost.

Figure 7 shows the gas pressure in microns of mercury, (H_g), for temperature of the coldest part of the bulb, at which point the mercury vapor will condense. Most commercial tubes are designed to have a temperature rise in the coldest part of the tube of 15° C above ambient temperature. (By ambient temperature is meant the temperature of the air surrounding the tube.) Thus it is a simple matter to determine the mercury vapor pressure in the tube

under operating conditions.

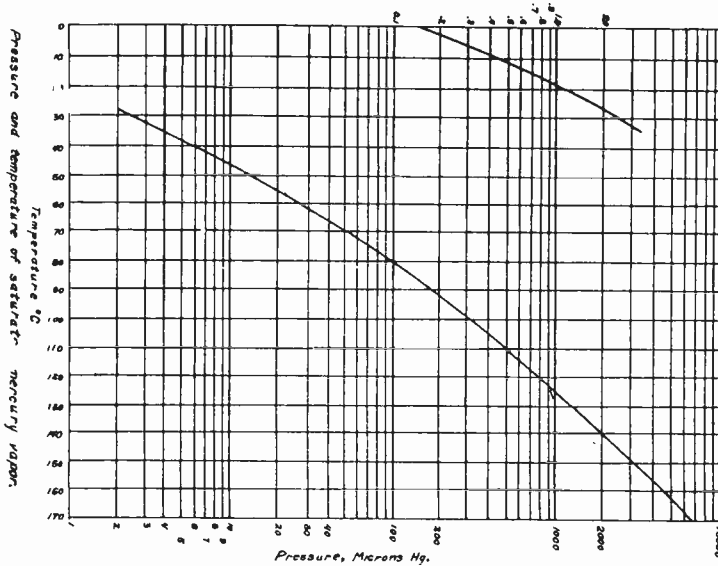


Fig. 7.

operate the tube about half way between these values, that is, at about 40° C. As the temperature limits are approached the tube drop rises very rapidly at the low end and the flash-back voltage drops very sharply at the high end. The low temperature limit corresponds to an ambient temperature of 32° F which is unlikely to be reached in practice except in aviation operation, in which case much lower temperatures may be reached and the enclosure design must be such as to conserve the heat in the tube compartment. The high temperature limit corresponds to an ambient temperature of 122° F which may very easily be reached or exceeded in the tube compartment on a hot summer day or in the tropics. In such case provision must be made for forced air cooling of the tube compartment.

Mercury vapor rectifier tubes are commercially available in standard sizes to meet all requirements of radio transmitters, from the small Type 866 which can supply a peak current of 1 ampere with a peak inverse voltage rating of 10,000 volts, to the Type 870 which has a peak anode current rating of 450 amperes and an average anode current of 75 amperes with a peak inverse voltage of 16,000 volts. Six tubes of the latter type in a three phase cir-

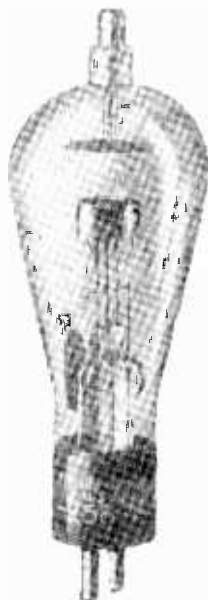
Commercial mercury vapor rectifier tubes are ordinarily designed to operate with a condensed mercury temperature of from 15° to 65° C. At lower temperatures the tube drop will become excessive and at higher temperatures the flash-back voltage will be decreased to an unsafe value. It is well to

cuit can furnish continuously 3000 KW of plate power for a radio transmitter

The accompanying illustrations show two typical mercury vapor rectifier



315A—Half-wave mercury vapor rectifier tube.



258B—Half wave, thermionic, mercury vapor rectifier.

tubes as manufactured by Western Electric. The 258B requires filament current of 7.5 amperes at 2.5 volts. The peak anode current is 1.5 amperes with peak inverse voltage of 7500 volts. The above characteristics are for ambient temperature of 0° to 50° C but the recommended range of ambient temperature is 10° to 40° C.

The 315 A requires filament current of 10 amperes at 5 volts. The peak anode current is 2.5 amperes with peak inverse voltage rating of 12,500 volts for ambient temperatures between 10° and 30° C. For a range of ambient temperature between 10° and 50° C, the peak inverse voltage rating is 7500 volts.

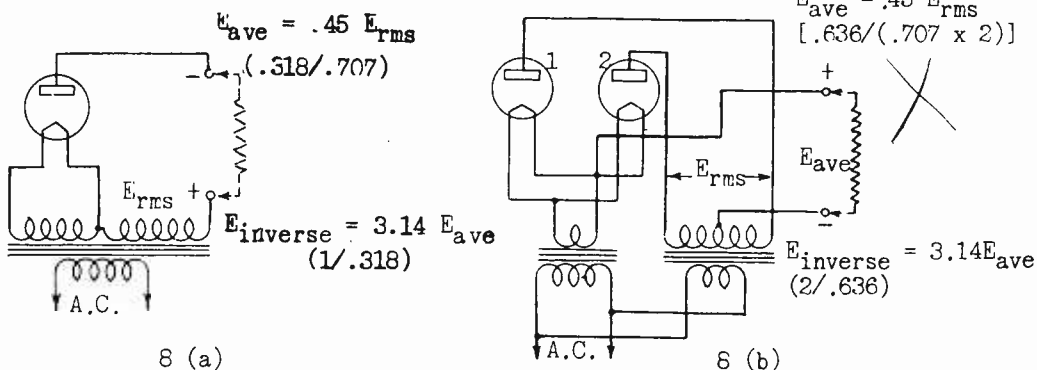
For forced air cooling where the temperature of the air stream directed on the coolest part of the tube is between 30° and 45° C, the peak inverse voltage rating is 12,500 volts. It will be seen that the ambient temperature is a very important factor in the operating characteristics of mercury vapor tubes.

In the 258B the anode is mounted above the cathode with the anode connection extending to a metal cap on the top of the tube. A perforated metal shield encloses the cathode to conserve heat. In the 315A the anode surrounds the cathode so that maximum conservation and use are made of the cathode heat with corresponding high emission efficiency.

Mercury vapor tubes are also available for use in receiver power supplies. Examples of such tubes are the Type 82 which will supply peak current of .345

ampere and average current of 115 mils, and the Type 83 which has a peak current rating of .675 ampere and average current of 225 mils. Both tubes have a maximum peak inverse voltage rating of 1550 volts.

RELATION BETWEEN OPERATING VOLTAGE AND INVERSE PEAK VOLTAGE: This relation must be thoroughly understood before attempting to design a rectifier to operate with mercury vapor tubes, because the operating conditions are considerably different than with high vacuum tubes. In the first place, with high vacuum tubes the danger of flash-back is negligible even with voltages several times higher than the rated operating voltage. In the gaseous tube that is not true, particularly as the operating temperature approaches the upper safe limit. Consider a simple half-wave rectifier and a full-wave rectifier as shown in Figure 8, (a) and (b) respectively.



The half-wave mercury vapor rectifier shown in Figure 8 (a) operates in a manner essentially similar to that of a rectifier employing a high vacuum tube except that since the tube drop is only about 15 volts, the voltage at the rectifier output from instant to instant during the alternation when the tube is conductive will be nearly equal to that across the high voltage secondary winding. On the reverse alternation, the tube is idle, no current flows in the load circuit, and the inverse voltage impressed across the tube is equal to that developed by the high voltage secondary winding.

It should also be noted that the inverse voltage applied to a tube depends in part upon the type of rectifier circuit in which the tube is employed. Consider the full-wave rectifier circuit of Figure 8 (b).

Assume that each half of the high voltage secondary is designed to develop an RMS voltage of 5000 volts or a maximum of 7050 volts. The entire peak voltage across the secondary is 14,100 volts. When the transformer voltage is such that the plate of Tube 1 is positive, current flows in Tube 1 and in the load, the drop in the tube is 15 volts, and the peak voltage across the load is 7035 volts. It would seem that a tube having an inverse peak voltage rating of 7500 volts should handle such requirement. However, examine the condition existing at Tube 2. The plate of Tube 2 is negative and the tube is not operating. The positive load terminal connects to both filaments. Tube 1 is operating with a voltage drop of 15 volts so that *essentially the filament of Tube 2 connects to the plate of Tube 1 with only a 15 volt difference of potential*. The plate of Tube 1 is connected to one end of the high voltage secondary winding and the plate of Tube 2 connects to the other end of this same winding. The peak voltage across the entire winding is 14,100 volts, so that the inverse peak voltage impressed across Tube 2 when Tube 1 is operating is $14,100 - 15 = 14,085$ volts. Obviously a tube having a maximum inverse peak voltage rating of 7500 volts can *not* be used in this circuit.

Fig. 9 shows a single phase full-wave rectifier circuit using 4 tubes (sometimes called a bridge circuit) which permits utilization of the full transformer secondary voltage while simultaneously giving full wave rectification. This is accomplished by using a secondary having a single winding instead of the split winding used in Fig. 8(b). In Figs. 8(a) and 8(b) an RMS secondary winding voltage of 5000 volts allows an average output voltage of 2250 volts with an inverse peak voltage of 7050 volts in both cases. To obtain the same output voltage as in Fig. 9, the RMS transformer voltage of Figs. 8(a) and 8(b) must be double that of Fig. 9 thereby requiring the tubes in 8(a) and 8(b) to have twice the inverse peak rating. In Fig. 9 the inverse peak voltage can be safely handled by tubes having a rating of 7500 V. with $E_{RMS} = 5000$ V. as long as the tube operating temperature does not be-

come excessive. It should be noted that the output current rating of the four tube full-wave rectifier is the same as that of the two tube full-wave rectifier.

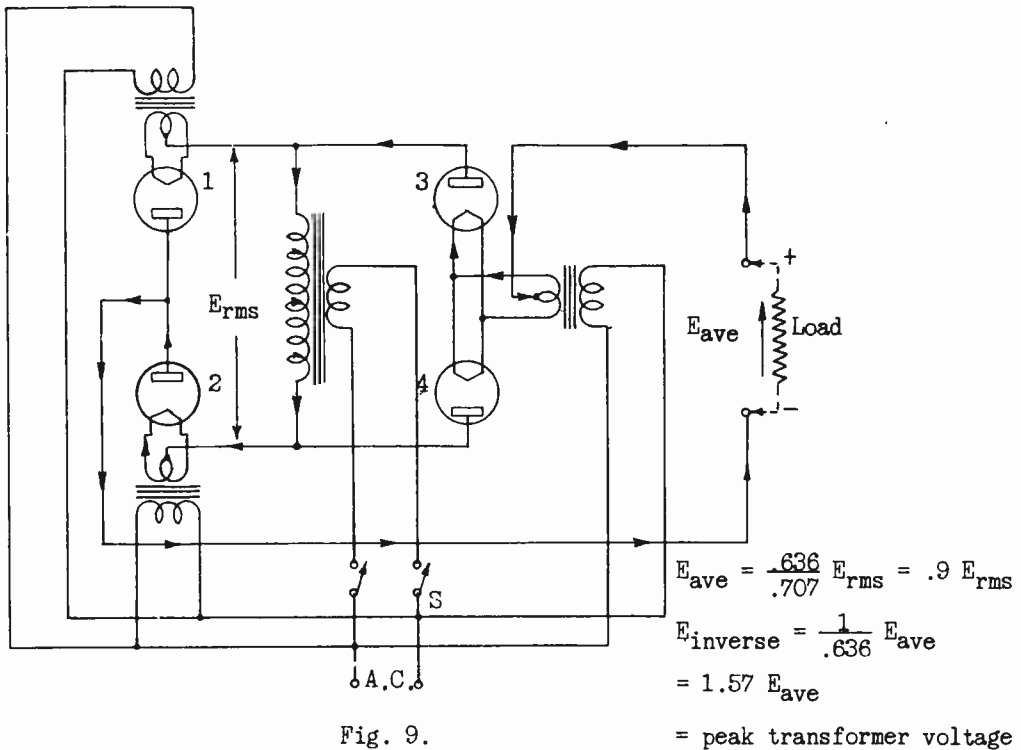


Fig. 9.

The dotted arrows in Figure 9 clearly show the current flow through the circuit. From the positive side of the load the current flows through Tube 3, down through the high voltage transformer winding, through Tube 2, back to the negative load terminal, and through the load. On the reverse alternation the current flows through the load in the same direction, through Tube 4, up through the high voltage transformer winding, through Tube 1, and back to the negative load terminal.

Three filament transformers are required, one each for Tubes 1 and 2, and one for both Tubes 3 and 4. It should be observed that the high voltage secondary winding is not center-tapped. Thus to develop an RMS output voltage of 5000 volts, this voltage plus the 30 volt drop in the two tubes must be developed across the transformer winding.

It is particularly essential that the filament transformers used in rectifiers be designed for such service. In practically all cases the negative side of the load is grounded. One side of the A.C. power line is also grounded. The filament of the rectifier, (any type of circuit), is at positive potential with respect to ground, thus the secondary of the filament transformer must be sufficiently well insulated from its primary and from the transformer core so as not to break down when the full peak output voltage is impressed between filament and ground. Since insulation becomes less effective when heated, a very generous insulation safety margin should be allowed in design, and the design of winding and core should be such that the temperature rise at full load is not excessive. The transformer is usually tested at 3 to 5 times the highest voltage expected during normal operation.

In Figures 8 and 9, it will be noted that average output voltages are given with respect to RMS transformer voltages. A.C. meters indicate effective or RMS values of currents and voltages, so that rectifier inputs, being A.C. are usually expressed in terms of RMS values. D.C. meters indicate average values of current and voltage. Since the rectifier output to the filter is in the form of pulsating direct current, the output is normally expressed in terms of average values. Where other values are given they may easily be converted into the desired terms.

Except in the case of very low power units, rectifiers used to supply plate power to radio transmitters are usually designed for three phase operation when a three phase power source is available. The three phase rectifier has all the ordinary advantages of the three phase power device plus the very decided special advantage of ease of filtering. The output phase voltages overlap so that the filter tank capacity is actually required to carry the load a very small portion of the time, and the higher frequency of the ripple component in the output allows the use of a filter having much smaller values of L and C for the same degree of filtering.

Figure 10 illustrates the circuit of a three phase FULL-wave rectifier using mercury vapor tubes. It will be seen that at any instant two tubes are operating in series, and the load simply transfers from one pair of tubes to another. Over any 360° period six series combinations of two tubes each will consecutively carry the load. This is clearly demonstrated in Figure 11, and the

circuit of each 60° period can be traced on Figure 10.

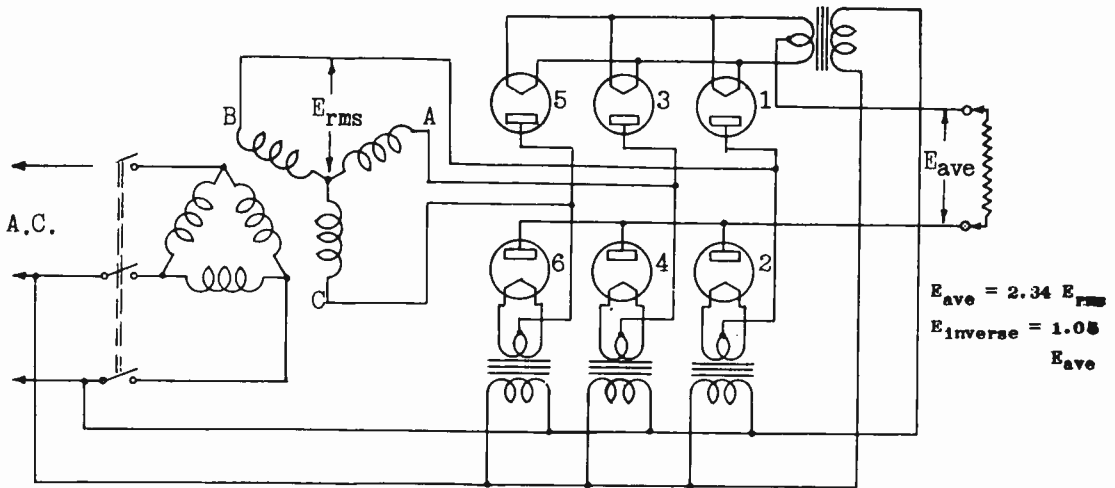


Fig. 10.

Assume an instant when Point A is positive in respect to point B. Electrons flow from point B through tube 2 through the load and then through tube 3 to point A. When the polarity reverses, that is, B is positive to A, electrons flow from point A through tube 4, through the load, and then through tube 1 to point B. Thus for any polarity assigned to points A, B, or C there will always be two tubes conducting and these tubes will be in series with the load. Since the drop across the two tubes is approximately 30 volts at any load the voltage across the load is very nearly equal to the voltage across the transformer.

It should be observed that while the average output voltage is 2.34 times the RMS voltage of a single high voltage winding, the inverse peak voltage is only slightly higher than the average output voltage. Thus full advantage can be

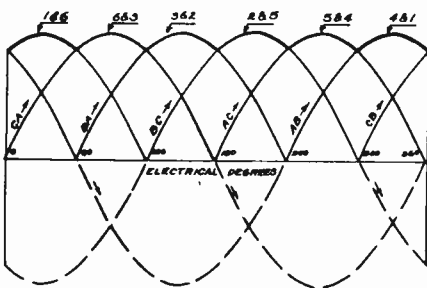


Fig. 11.

taken of the voltage capacity of the tubes used in such a circuit.

An examination of Figure 11 and a reference to the relations existing in a three phase power circuit will help to make clear the derivation of the factor 2.34. From Figure 11 it is seen that any one pair of tubes carries the load one-sixth of the time

or for 60° of the complete cycle. Figure 10 shows that the combined voltage of two secondary windings in series is impressed across each pair of tubes. Under that condition the *peak* voltage impressed between two tubes in series will be 1.73 times the *peak* voltage of one secondary winding. The *peak* voltage of one secondary winding will be 1.41 times the RMS voltage of that winding. Therefore the peak voltage impressed across any pair of tubes will be $1.41 \times 1.73 = 2.44$ times the RMS voltage of a single high voltage winding. During the 60° period of operation for each pair of tubes, the instantaneous voltages will be equal to $2.44 E_{RMS} \cdot \sin \theta$. The *average* voltage during this period may be determined by integrating or averaging all the instantaneous voltages during the 60° period or for the 30° between 60° and 90° inclusive, and this average value will be found to be $2.34 E_{RMS}$.

If higher output current is required it will be necessary to use larger tubes, connect tubes in parallel by means of a current dividing reactor in place of each single tube, or connect duplicate rectifier units in parallel, taking the load current through a current dividing reactor to distribute the load equally between the two units. In view of the fact that tubes of almost any desired capacity are commercially available, the rectifier as shown can be designed for practically any load voltage and current capacity.

The regulation of the mercury vapor rectifier depends entirely upon the design of the transformer and is not a function of the tube drop because the tube drop is essentially constant over the working range of the tubes. The three phase full-wave mercury vapor rectifier circuit of Figure 10 is particularly advantageous from the viewpoint of transformer capacity.

For example, in a single phase full-wave rectifier for a rectifier plate voltage of 1000 volts, the secondary of the transformer must be designed to develop 2000 volts from plate to plate. With a line supply of 120 volts the transformer turns ratio must be $2000/120$ or 16.7. In the Y connected secondary shown in Figure 10 to develop 1000 volts between points A and B the winding voltage must be $.58 \times 1000$ or 580 volts: With a line supply of 120 volts the turns ratio need only be $580/120$ or 4.9.

The mercury vapor rectifier must be well protected by a quick acting over-load relay against rectifier short-circuit or flash-back which is equivalent to a short-circuit. In the case of the Kenotron rectifier the tube current is definitely limited by the emission from a tungsten filament. The mercury vapor tube also has its limitations. If the load current exceeds the emission, double ionization occurs (over 22 volts drop) which may destroy the cathode by bombardment of ions. The plate current should not exceed the cathode emission. The maximum instantaneous current that a mercury vapor tube can furnish safely is determined by the emission and by the temperature as previously mentioned. The pressure varies with the gas temperature and the temperature is a function of the plate current.

The operating condition of the mercury vapor tube for a given load is largely determined by the type of filter used. If the first filter element is a condenser, when the rectifier voltage exceeds the condenser voltage, the condenser charges and the tube current is limited only by the reactance of the condenser. Since the filter condenser is normally large, its reactance is small and the tube current may reach values of from 3 to 5 times the D.C. load current, the tube current flowing for only a small part of the allowable period. This is a very undesirable condition and may quickly damage the tube, particularly if the normal load taken from the rectifier approaches the rated rectifier capacity. If the first filter element is a quite large inductance, the rectifier tube current will approach a square top form, will flow over the full period allowed, (in which the rectifier voltage exceeds the filter voltage), and the tube current will approximate the normal load current. This is a very desirable condition. THUS FOR USE WITH A MERCURY VAPOR RECTIFIER, THE FIRST FILTER ELEMENT SHOULD ALWAYS BE AN INDUCTANCE.

111
FILTERS: There are four principle types of electric wave filters: Low Pass filters which pass all frequencies BELOW a given cut-off frequency and greatly attenuate all frequencies above the cut-off frequency; High Pass filters which pass all frequencies ABOVE a given cut-off frequency, greatly attenuating the lower frequencies; Band Pass filters which pass a given band of frequencies and attenuate all frequencies above and below that band; Band Elimination filters which attenuate a given band of frequencies above and below the

specified band. The band pass filter consists of a high pass and a low pass filter in series; the band elimination filter consists of a high pass and a low pass filter in parallel.

An examination of the rectifier output current and voltage characteristics as shown in Figures 2, 5, and 6, and a consideration of the preceding discussion of rectifier operation, very clearly show the need for some means of smoothing out the pulsating output where a steady d.c. power supply is required. For example, in Figure 5, the output voltage per cycle input consists of two pulsations, each of which varies from zero to a maximum value approximately equal to the maximum A.C. voltage in the case of the mercury vapor rectifier and somewhat less than the maximum with high vacuum rectifiers. (Since the tube drop is so low in mercury vapor tubes it is usually neglected in discussions of rectifier operation and the peak output voltage assumed to equal that developed by the transformer winding.) The three phase full wave d.c. output voltage as shown in Figure 6 does not vary over such wide limits but it is still far from the smoothness required for the power supply of a radio transmitter. Thus in all cases a filter circuit is required. How elaborate the filter must be depends upon the character of the voltage supplied to the filter and the percentage of ripple that can be tolerated in the output.

The Low Pass type of filter is used for this purpose; that is, the filter must pass direct current and can pass all frequencies below cut-off. The cut-off frequency is always lower than the lowest ripple frequency developed by the rectifier. Such a filter will attenuate the main ripple frequency and all the harmonic frequencies, which of course are higher than the principle ripple frequency.

The lowest ripple frequencies with their amplitude at the filter input for a 60 cycle power supply are shown in Table 1.

Table 1

TYPE OF RECTIFIER	Ratio of the peak value of AC voltage (the lowest ripple frequency) at the filter input as compared with the DC component of the rectifier output	Lowest Ripple Frequency in The Output
Single phase, half wave	1.751	60 cycles
Single phase, full wave	.667	120 cycles
Three phase, half wave	.250	180 cycles
Three phase double Y, half wave	.057	360 cycles
Three phase, full wave	.057	360 cycles

The ideal low pass filter would have a very sharp cut-off at $F_c = 1/\pi\sqrt{LC}$ where L is in henries and C is in farads. However in practice the filter elements have resistance losses which decrease the sharpness of cut-off, so if effective attenuation is desired, it is well to design the filter to cut-off at a frequency somewhat lower than the ripple frequency. For example, if the ripple frequency is 120 cycles the filter should be designed to cut-off at from 60 to 90 cycles, depending on how much ripple attenuation is actually required. In general, in receiver power supplies where the choke resistance may be quite high, on the order of a few hundred ohms, the filter is designed to cut-off at a quite low frequency whereas in transmitter power supplies a higher cut-off frequency may be used because transmitter chokes have quite low resistance.

In the study of the low pass filter two general conditions will be found to exist. First, the higher the ripple frequency the easier it is to remove; the lower the values of L and C required for the same filtering effect. Second, the greater the ripple amplitude the more difficult it will be to filter out. This means that a specified filter will provide a given degree of attenuation, and if the A.C. input voltage is higher there will be a greater voltage of ripple component getting through the filter.

Before going into the actual design of the filter it is well to study the form of the rectifier output voltage in order to determine just what frequencies and ripple amplitudes it is necessary to filter out. Essentially the rectifier must deliver its power to a condenser, and the capacity of that condenser must be sufficiently large that the load current cannot discharge it more rapidly than it can charge from the rectifier. If the load on the condenser, (see Figure 12),

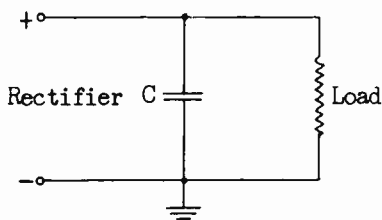


Fig: 12.

is very light, the condenser will charge from the rectifier to almost the peak voltage and will practically hold the peak charge due to the small current drain by the load. However this is not the normal operating condition because it would require a rectifier capable of supplying much more power than that consumed

by the load, and a very large condenser which is not an economical arrangement. Thus the normal operating condition allows an average load current not too much

less than the average normal output current of the rectifier. This means that the voltage of the condenser will rise when the output voltage of the rectifier is greater than the condenser voltage, and fall off when the rectifier voltage falls below that of the condenser, due to the discharge of the condenser through the load.

Figure 13 shows the pulsating output from a single-phase full-wave rectifier and (straight full lines) the fluctuating voltage across the condenser.

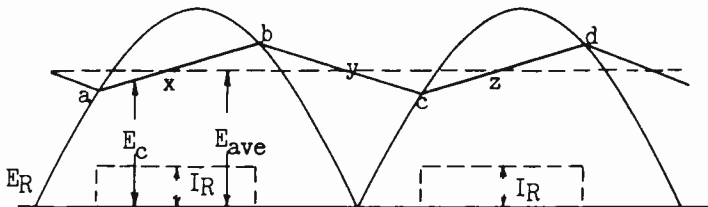


Fig. 13.

(straight full lines) the fluctuating voltage across the condenser.

E_R represents the actual transformer voltage variations at the

plate of the rectifier tubes. E_c is the voltage of the condenser and E_{ave} is the average voltage applied across the load. The condenser is shown as charging from a to b, discharging from b to c, charging from c to d, etc. (The charging current from the rectifier is I_R .) This produces an alternating component of voltage that varies above and below the *average* d.c. voltage, crossing the average voltage value in an increasing direction at points x and z and in a decreasing direction at point y and at other points between alternations.

An examination of the condenser voltage line with respect to the average d.c. voltage shows that from point a to point c the condenser voltage goes through *one complete cycle*, the zero voltage of this A. C. ripple component being taken as the *average d.c. voltage*. This cycle occurs *in the time of one alternation* of the alternating voltage or one pulsation of voltage from the rectifier. Therefore the fundamental frequency of the ripple component which must be filtered out is, in the case of the single-phase full-wave rectifier, *twice the frequency of the A. C. power supply*. Thus if this rectifier is operated from a 60 cycle power supply the filter must be designed to eliminate a 120 cycle ripple frequency. Of course, since the filter to be used is a low pass filter it will also attenuate the harmonics of the ripple component.

Figure 14 shows the condenser connected across a single-phase half-wave rectifier. The output of this rectifier consists of a single pulsation per

cycle of power supply voltage. There is one cycle of ripple component, based on the average d.c. voltage, for each pulsation of direct current from the rectifier, that is, from point a to point c. Since there is only one pulsation of current from the rectifier for *each cycle* of the A. C. power supply voltage, the ripple frequency must be the same as the frequency of the A. C. power supply. Thus in the case of a 60 cycle single-phase half-wave rectifier the predominating ripple frequency to be filtered out is 60 cycles.

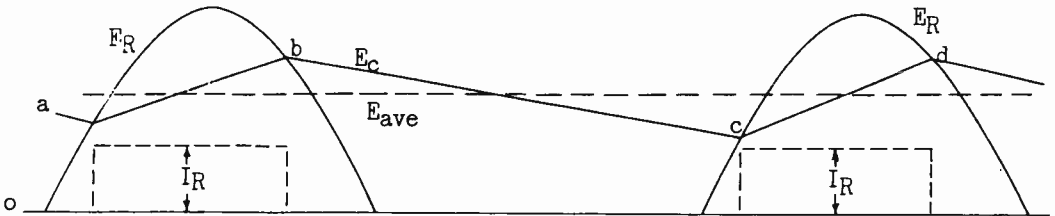


Fig. 14.

Figure 14 also brings out other factors which must be taken into consideration. Since the rectifier is completely idle during the time between points b and c, more than a half-cycle, and since the load is active during this time in discharging the condenser, the condenser discharges continuously from b to c, more than twice the time of discharge as shown in Figure 13 for the full-wave rectifier. This means that with the same voltage at point b, the same condenser, and the same load current, the voltage at the end of the discharge interval, point c, will be considerably lower than at the end of discharge in Figure 13. In order to make up the original voltage by point d, the rectifier tube must be capable of supplying a much higher charging current than in the case of Figure 13 where the load is carried by a full-wave rectifier. Also, with the same condenser, the condenser voltage E_c will fluctuate over greater limits than in Figure 13 giving the ripple component both a higher amplitude as well as a lower frequency. To keep the load ripple voltage amplitude within the same limits as in Figure 13, a larger condenser is necessary in order that the percentage of charge lost during the discharge interval will not be so great. This simply means that it will be more difficult to filter the 60 cycle ripple of the half-wave rectifier than the 120 cycle ripple of the full-wave rectifier.

If, a three-phase full-wave rectifier could be used, the ripple would be at 360 cycles, the amplitude of the ripple component would be *much* lower, and it would be much easier to filter. However such a rectifier would not be practical for receivers; it is easier and more economical to use a larger filter, even if a three-phase power supply were generally available.

If a sufficiently large condenser is used the fluctuations of the voltage applied to the load can be held within any desired limits. However to keep the ripple component to the point where it will not cause bad hum, filtering by capacity alone is somewhat impractical due to the size of the condenser required, although in some inexpensive receivers essentially such a filter has been used, employing a quite large electrolytic condenser. The more practical filter consists of a combination of inductance and capacity so designed as to form an efficient low pass filter which will eliminate the ripple frequency from the output. Figure 15(a) shows a single section low pass filter and 15(b) shows two sections of the same filter; 15(c) and 15(d) are equivalent to 15(a) and 15(b) in operation. All are assumed to be designed for the same cut-off frequency, the values of C in all are assumed to be equal, and the values of L are assumed to be the same. Thus two sections of $.5 L$ equals one section of L . In all, one principal characteristic is apparent; the inductance is *in series* with the line and the capacity is *across* the line.

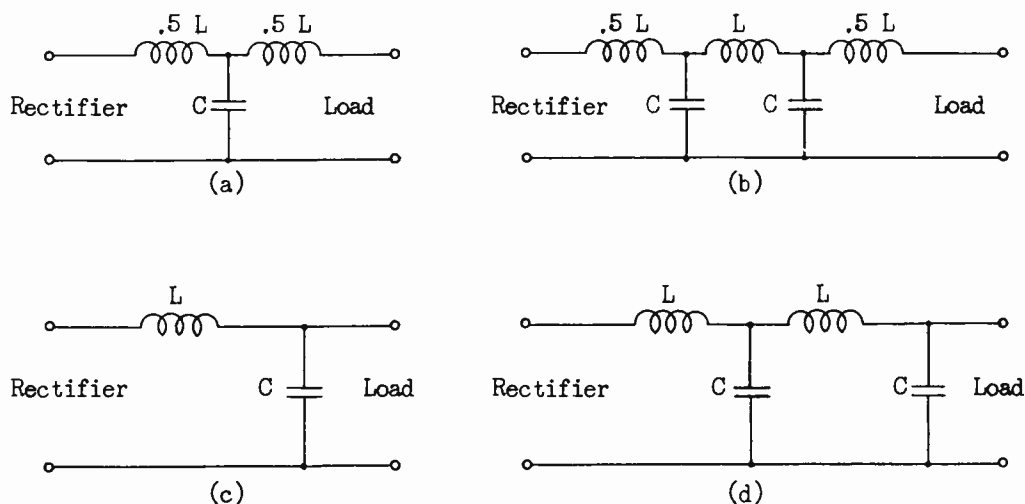


Fig. 15.

The higher the frequency the more difficult it is for the A. C. component to pass through L, and the more easily that component is short-circuited by C; conversely, the lower frequencies meet with less opposition in L and lose less by the short-circuiting effect of C. Thus with such an arrangement, the lower the frequency the less the attenuation, and vice versa. A high pass filter has the opposite characteristics. A high pass filter is built up by connecting the *capacities in series* with the line and the *inductance across* the line, thus passing the higher frequencies and opposing the lower frequencies. Of course a high pass filter, since the condensers are in series in the line, cannot pass a d.c. component.

The cut-off frequency of a low pass filter is derived as follows: (See Figure 15(c).) The series arm is L, the shunt arm is C. Assume no resistance losses.

The impedance of the series arm is, $Z_1 = \omega L$ (L in Henries).

The impedance of the shunt arm is, $Z_2 = \frac{1}{\omega C}$ (C in Farads).

$$\omega = 2\pi f$$

From the above, the ratio, $\frac{Z_1}{Z_2} = \frac{\omega L}{\frac{1}{\omega C}} = LC\omega^2$

Any low pass filter in which the losses are zero or so low that they may be assumed to be negligible will transmit frequencies within the limits of

$$\frac{Z_1}{Z_2} = 0 \text{ and } \frac{Z_1}{Z_2} = 4$$

The first limit, $\frac{Z_1}{Z_2} = 0$ is when $LC\omega^2 = 0$. Since L and C have tangible values and 2π is a constant, then $LC\omega^2 = 0$ when f equals 0.

The high frequency limit or cut-off frequency is determined as follows:

$$\frac{Z_1}{Z_2} = 4$$

$$4 = \frac{\omega L}{\frac{1}{\omega C}} = \omega^2 LC$$

$$\pm 2 = \omega \sqrt{LC} \quad (\text{Extracting square root})$$

$$\omega = \frac{2}{\sqrt{LC}} \quad (\omega \text{ includes the cut-off frequency } f_c)$$

$$2\pi f_c = \frac{2}{\sqrt{LC}}$$

$$f_c = \frac{2}{2\pi\sqrt{LC}} = \frac{1}{\pi\sqrt{LC}} \quad (L \text{ and } C \text{ in units, } f_c \text{ in cycles per second})$$

Thus the filter consisting of L in the series arm and C in the shunt arm will pass all frequencies between 0 and $f_c = \frac{1}{\pi\sqrt{LC}}$, frequencies above f_c being

greatly attenuated.

In order to design a filter it is necessary to have a definite cut-off frequency given, with the values of L and C required to obtain this cut-off to be determined. Thus,

$$f_c = \frac{1}{\pi\sqrt{LC}}$$

$$\sqrt{LC} = \frac{1}{\pi f_c}$$

$$LC = \frac{1}{(\pi f_c)^2} \text{ or } \frac{1}{\pi^2 f_c^2}$$

It will be observed that this equation simply denotes the required LC product. Since $L = \frac{LC}{C}$ and $C = \frac{LC}{L}$, it is necessary to first determine the value of one in order to find the other. These values are determined largely by practical and economic considerations. Since the filter is used for the purpose of holding or storing up power to supply the receiver during the periods of low rectifier voltage, as well as for the attenuation of the hum or ripple component, it is apparent that a fairly large capacity should be used. Assume that it is desired to have a cut-off frequency of 90 cycles for use with a 60 cycle full-wave rectifier where the ripple frequency is 120 cycles. Then,

$$LC = \frac{1}{(\pi f_c)^2} = \frac{1}{(3.14 \times 90)^2} = \frac{1}{283^2} = \frac{1}{8 \times 10^4} = 125 \times 10^{-7}$$

Assume that it has been decided to use a capacity of $4\mu\text{F} = 4 \times 10^{-6} \text{ F}$.

$$\text{Then } LC/C = \frac{125 \times 10^{-7}}{4 \times 10^{-6}} = \frac{125 \times 10^{-1}}{4} = 3.1 \text{ Henries.}$$

In the case of a half-wave rectifier where the ripple frequency to be filtered is 60 cycles, a cut-off frequency of about 40 cycles should be adequate, then,

$$LC = \frac{1}{(\pi f_c)^2} = \frac{1}{(3.14 \times 40)^2} = \frac{1}{126^2} = \frac{1}{16 \times 10^3} = 63 \times 10^{-6}$$

Using the same value of C as before, $4 \mu\text{F}$, then,

$$LC/C = \frac{63 \times 10^{-6}}{4 \times 10^{-6}} = 15.7 \text{ Henries.}$$

It will be seen from the above examples, and from the equation for the cut-off frequency and its arrangement to determine the filter values of L and C, ($LC = \frac{1}{\pi^2 f_c^2}$), that the LC value required varies inversely as the square of the cut-off frequency. In other words, if the frequency is doubled, it is four times as easy to filter, if tripled, nine times as easy, etc.

With a single filter section as shown in Figures 15(a) and 15(c) the cut-off frequency is not very sharply defined, largely because of the losses in the inductances and mismatching of input and output impedances. Therefore for practical purposes two sections in series are customarily used, as shown in Figure 15(b) and 15(d). These are actually two separate filter sections, *each section* being designed for the required cut-off frequency. For example, in 15(d) for a cut-off frequency of 40 cycles as calculated above, *each reactor*, L should have an inductance of 15.7 henries and *each capacity*, C, should be 4 μF . In 15(b) which is essentially the same, only the actual arrangement of apparatus being different, there are two inductances, .5 L, or 7.85 henries each, and one, L, of 15.7 henries, each capacity being 4 μF .

It must be understood that the values of inductance as calculated must be the effective inductance with the average load current to be filtered.

The reactors necessary to obtain the values of inductance required at the low frequencies used must be iron core reactors. The effective inductance of an iron core reactor to a small alternating current will be greatly different from the effective inductance of the same reactor when it is carrying a current made up of a large average component of direct current and a superimposed alternating component. If the average or direct current component is sufficiently large to almost saturate the iron core magnetically, the ripple component will make very little change in the magnetic field and the effect of the inductance on the ripple component will be almost negligible. If only the small ripple component of current is present the permeability of the iron core is high and, since L varies directly with permeability, the inductance is also high. When a large d.c. component is introduced, the iron core tends to become magnetically saturated and the permeability is greatly lowered. In electrical design work the permeability of iron, unless otherwise stated, is usually assumed to be 1500. For filter reactors to eliminate ripple in a large direct current, the permeability of the core varies between 100 and 400 thus making the effective inductance for the ripple component only from 1/4 to 1/15 of what it would be if the direct current were not present.

It is important in the selection of a reactor for use in the filter of a rectifier, that the effective inductance at the desired average direct current

load be known. If the average d.c. component is to be 100 mils, and calculations show that an L of 15 henries is required, the design specifications must call for an effective L of 15 henries with a direct current component of 100 mils. With such a reactor, if the d.c. component is decreased the effective inductance will increase, thus lowering the cut-off frequency. On the other hand, an increase in the d.c. component will decrease L and raise the cut-off frequency. In such a case, if the filter is designed to have a cut-off frequency just slightly below the frequency to be eliminated, a small increase in the rectifier load current may easily decrease L to the point where the cut-off frequency is *higher* than the frequency to be eliminated. It is well to allow a generous safety margin of cut-off frequency in the design of the filter.

In some cases the filter is preceded by a condenser, C_1 , as shown in Figure 16. This arrangement has the advantage that a somewhat higher d.c. voltage can

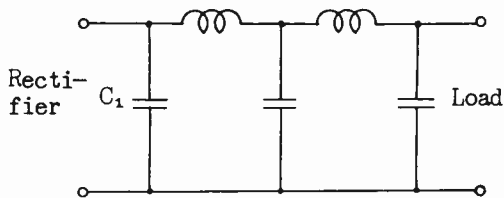


Fig. 16.

be obtained from the filter with the same A. C. rectifier plate voltage.

On the other hand the power dissipation within the rectifier tubes is increased and the regulation under varying loads is large. This ar-

range should *never* be used with a mercury vapor rectifier because such a rectifier, if there is no series inductance to limit the current, can deliver a current surge that will injure the tube. With a $4 \mu\text{F}$ condenser at C_1 the current surges from a mercury vapor rectifier tube may be from 600 to 800 per cent higher than the load current, this greatly shortening the tube life.

In the case of a mercury vapor rectifier tube, which has a low internal resistance and is therefore subject to very high current surges if there is no limiting device, it is not only essential that an inductance be used between the first condenser and the rectifier, but also that sufficient inductance be used. It has been found that there is a critical value of L for use in the first reactor, this critical value being determined only by the load resistance and the frequency. If the value of L in the first reactor is made less than the critical value the current surges in the rectifier tube will not be sufficiently attenuated and the ratio between the tube current amplitudes and the

load direct current will be too great. By the use of a sufficiently large value of L the difference between the tube current amplitude and the direct load current can be kept to a minimum.

The load resistance is calculated from E/I . With an output potential of 400 volts and a load current of 100 mils, the load resistance will be $400/.1$ or 4000 ohms. Experimental work has shown that the critical value of L for the first reactor of a full-wave 60 cycle rectifier where the ripple frequency is 120 cycles, is, $L_c = R/1000$; L_c is the critical value of L in Henries, R is the load resistance in ohms. With the values assumed above, $L_c = 4000/1000 = 4$ Henries. It further has been found that the first reactor will produce the most satisfactory results when its inductance is about twice the critical value; thus $L_o = 2L_c$ will be the optimum first inductance to use in such a filter. Therefore for best results under the conditions specified above, the first reactor should have an inductance of 8 Henries.

The cut-off frequency is equal to $f_c = \frac{1}{\pi\sqrt{LC}}$, and $LC = \frac{1}{\pi^2 f_c^2}$ With the optimum value of L as calculated above, $C = LC/L$.

For a cut-off frequency of 90 cycles, $C = \frac{125 \times 10^{-7}}{8} = 1.6 \mu\text{F}$. Ordinarily 2 μF would be used.

The factors affecting the critical value of L are load resistance R , and frequency. The critical value of L , and hence the optimum value, will be inversely proportional to frequency. If the frequency of the power supply is one-half as great, the value of L should be doubled, etc.

Another factor must be taken into consideration if the rectifier is to be used where the load is intermittent or variable. With full load the value of load resistance, $R = E/I$, is at a minimum value and therefore $L_c = R/1000$ is also at a minimum. With the load removed and only the bleeder current present, if the bleeder current is assumed to be equal to 20 per cent of the current at full load, then R (no load) = $E/.2$ or $5R$ (full load). This means that the critical value of inductance, L_c , when the load is removed, will be five times as great as when the rectifier is fully loaded.

The optimum value of L under the load conditions assumed above is 8 Henries. The critical value with the load removed will be $5 L_c$ or 20 Henries. It is possible here to make use of the fact that due to core saturation L de-

creases as the d.c. component of current increases. Thus a reactor can be designed such that its inductance will vary somewhat between the values desired for full and no load conditions. Such a reactor is called a swinging choke. In A. C. receiver work such wide fluctuation of load will not often be encountered. However in the case of a receiver employing a Class B power amplifier, the total load can swing over comparatively wide limits which should be taken into consideration in designing the first filter reactor.

When the load current varies over wide limits the first filter element is usually a swinging choke to obtain better voltage regulation. When the load current is low the inductance of the filter choke is high but as the current increases the choke inductance decreases and the filter approaches the characteristics of a condenser input; that is, as L decreases C charges to a higher peak voltage. Thus as the load current increases the resultant drop in the output voltage due to the increased IR drop in the filter is offset by the rising voltage across the first filter condenser. With the correct value for the swinging choke the output voltage regulation can be made very small.

Calculating the proper range of the swinging choke to use as the first reactor in a power supply for a Class B load is quite simple. Assume that with no signal to the Class B amplifier the load current is 30 MA and at peak output the load current rises to 120 MA. The output voltage of the rectifier is 300 volts. With a load current of 30 MA at 300 volts the load resistance is $300/.03 = 10,000$ ohms and the critical L of the reactor is $10,000/1000 = 10$ Henries. Optimum L would then be 2×10 or 20 Henries. When the load current rises to 120 MA the load resistance drops to $300/.12 = 2500$ ohms. Critical L = $2500/1000 = 2.5$ Henries and optimum L = 2×2.5 or 5 Henries. Thus the swinging choke should be rated at 20 Henries at 30 MA and 5 Henries at 120 MA.

Swing
choke

By the use of a mercury vapor rectifier and a properly designed filter, excellent voltage regulation at the load can be obtained. By "regulation" is meant the ratio of the "change in voltage with load" to the "full load voltage". In other words, Voltage regulation = $\frac{E - E_1}{E_1}$ where E is the "no load" voltage and E_1 is the full load voltage. To obtain the regulation in percentage, multiply the decimal obtained above by 100.

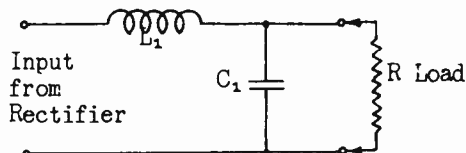
It has been found that if the inductance of the first reactor exceeds L_0

under all load conditions, the output voltage is always equal to the average of the impressed A. C. voltage, less the resistance drop in the filter reactors. By careful design and the use of low resistance reactors, the variation of voltage at the load can be kept to a minimum and the transformer can be designed to give the desired average voltage required. Since the voltage drop in the mercury vapor rectifier is practically constant at all loads, (approximately 15 volts), it can easily be compensated for in transformer design.

POWER SUPPLY FILTERS: The design of a filter for use in a receiver power supply is a relatively simple matter. Current drain and output voltages are comparatively low and high inductance chokes and high capacity filter condensers are available at low cost. The usual design procedure, as discussed previously, is to select a cut-off frequency well below the fundamental ripple frequency and with a given condenser calculate the required inductance. In most cases L and C are much larger than is actually required for satisfactory filtering. Such a filter is of the "brute force" type. The problem is quite different in filters for transmitter power supplies. With high current drain the choke must be wound with large wire and the core must contain plenty of iron to avoid saturation. The high voltages also necessitate additional insulation precautions. The filter condensers must also be rated at a much higher breakdown voltage. Where a 30 henry choke for a receiver supply may be quite inexpensive, the same choke for a 20,000 volt 6 ampere supply would be enormous in size and practically prohibitive in cost. Where an 8 μ F electrolytic condenser costs only a few cents, a one microfarad filter condenser for use in a 20,000 volt power supply may cost several hundred dollars. Thus in the design of filters for transmitter power supplies economy is a major factor. The filter is designed to provide just sufficient attenuation of the ripple frequency to satisfy the requirements of the transmitter. This necessitates an understanding of the attenuation factor of the filter. The attenuation factor is defined as the ratio of A. C. component across the load to the A. C. component at the input to the filter.

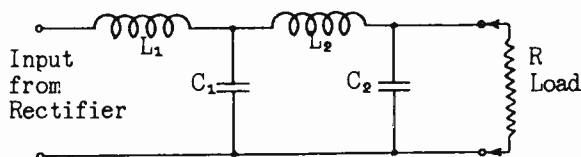
The low pass filter in its most simple form consists of an inductance in series with the line and a condenser across the line as shown in Figure 17. The attenuation ratio of such a filter is given by the equation. (A. C. volt-

age is the ripple component of voltage.) In Figure 18 is shown a filter con-



$$\frac{\text{A.C. Voltage across load}}{\text{A.C. Voltage applied to filter input}} = \frac{1}{(2\pi f)^2 L_1 C_1}$$

Fig. 17.



$$\frac{\text{A.C. Voltage across load}}{\text{A.C. Voltage applied to filter input}} = \frac{1}{(2\pi f)^4 L_1 L_2 C_1 C_2}$$

Fig. 18.

sisting of two units of the simple filter of Figure 17, in series. The attenuation ratio of this filter is also shown by an equation.

An examination of the two equations will immediately disclose two important facts.

First, in 17 the attenuation is a squared function of f and in 18 it is a 4th power function of f , so that in either case if the principal ripple frequency is well attenuated the harmonics of the ripple frequencies may be neglected. In this connection, with given values of L

and C , either filter will be much more effective in attenuating the ripple frequency of 360 cycles from the three phase full-wave rectifier than the 120 cycles from the single phase full-wave rectifier. Conversely, for the same attenuation ratio, much smaller values of L and C may be used for 360 cycles than for 120 cycles. This is true even if the input ripple voltage component has the same amplitude in both cases, which it will not have. It has been shown that the input ripple amplitude is much less with three phase than with single phase rectification for the same d.c. output voltage.

Second, the two unit filter of Fig. 18 is much more effective at any given frequency than is the single unit filter of Fig. 17; the attenuation increases as the square of $(2\pi f)^2$, as the product of $L_1 L_2$, and as the product of $C_1 C_2$.

The equation $F_c = \frac{1}{\pi\sqrt{LC}}$ provides the basic formula for calculating the values of L and C to obtain the desired cut-off frequency. $LC = \frac{1}{(\pi F_c)^2}$. If L is known, it is a simple matter to calculate C , and vice versa. However, one of these factors, L or C , must be selected from conditions beyond the scope of

this simple equation. Just what are those conditions?

First, as has previously been shown, it is very desirable that the form of the rectifier tube current be rectangular and that tube current flow during the greatest possible operating period of each tube. This period should be 180° for full-wave single phase and 120° for full-wave three phase. Under such condition the tube peak current will approximate the average load current and long tube life may be expected. How closely the ideal condition is approached is determined by the value of L_1 . An idea of the effect of the inductance of L_1 is shown for a single phase full-wave rectifier in Fig. 19. The figure is self-explanatory. The condition in 19(c) should always be avoided.

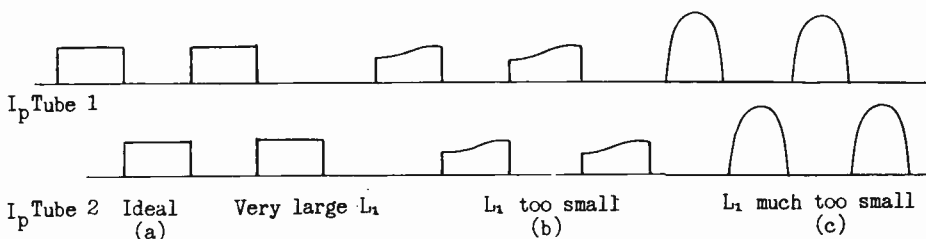


Fig. 19.

In order to draw current from the tubes during the entire cycle, each choke must have a reactance (X_L) large compared to the X_C of the condenser following it. The output condenser C_2 should have a reactance small compared with the load resistance. That is, C_2 should be large in order that it may act as a large reservoir to supply continuous power to the load.

In order that the load and filter may draw tube current continuously from the rectifier, the peak AC or ripple component in L_1 should be less than the d.c. load component. Thus the minimum value of L_1 is a function of the load resistance and of the lowest ripple frequency. As the load resistance is increased and the load direct current is decreased, it becomes increasingly difficult to maintain a continuous flow of current from the rectifier. Experience shows that $2\pi f L_1 / R_L$ must be calculated using the proper values from Table I for the type of rectifier circuit used and where f is the lowest ripple frequency. Thus $\omega L_1 / R_L = .667$ for single phase, full-wave circuits for minimum value of L_1 . R_L includes the sum of the actual load resistance plus the resistance of the chokes L_1 and L_2 (see Fig. 18).

For example, assume a 60 cycle, single phase, full-wave rectifier, used to

supply a load of .4 ampere at 3000 volts. (As shown in Table I, the lowest ripple frequency is 120 cycles). The load resistance is $R_L = E/I = 3000/.4 = 7500$ ohms. X_{L_1} must be at least $7500 \times .667 = 5000$ ohms. $L_1 = X_{L_1}/2\pi f = 5000/6.28 \times 120 = 6.64$ Henries. This is the minimum value of L_1 that will give satisfactory results. The factor .667 at 60 cycles corresponds to a value $L = R_L/1130$ which is usually rounded off to $R_L/1000$ for calculations. (see page 28)

Using the formula just mentioned, $L_c = R_L/1000 = 7500/1000 = 7.5$ Henries. This is a conservative value compared to that found above and would give less ripple in the load current. Any value of L_1 greater than 6.64 Henries would be suitable, but in general twice the value L_c is considered optimum. To calculate the value of C_1 used with L_1 for cut-off at 60 cycles in order to assure satisfactory attenuation at 120 cycles;

$$C = 1/L(\pi f_c)^2 = 1/7.5(3.14 \times 60)^2 = 3.75 \mu\text{f}$$

A 4 μf condenser would be used. The cut-off frequency desired in the second filter unit L_2C_2 is the same and can be achieved by the same LC product. In this case C_2 acts as a "reservoir" to reduce load variations and the design trend is to use larger C and smaller L. In some cases L_2 and C_2 may be chosen equal to L_1 and C_1 , depending on the type of load and the voltage regulation desired, or from consideration of available values.

The ripple component of voltage at 120 cycles in the output as compared with the A.C. component at the filter input is equal to: $\frac{1}{(2\pi f)^2 L_1 L_2 C_1 C_2}$. Assuming the values of L and C as determined above, L_1 and L_2 each equal 7.5 Henries; C_1 and C_2 each equal 4 μF ; the fraction becomes,

$$\frac{1}{(6.28 \times 120)^4 (7.5 \times 7.5 \times 4 \times 4 \times 10^{-12})} = .003 = .3\%$$

From Table 1, the A.C. component of voltage at the filter input is .667 $E_{d.c.} = .667 \times 3000 = 2001$ volts. Due to filter attenuation the ripple in the output becomes $2001 \times .003 = 6$ volts. Thus the percentage of ripple in the output is $6/3000 = .002 = .2\%$.

For broadcast transmitters a power supply ripple of from 0 to .1 per cent should be inaudible. From .1 to .25 per cent should be satisfactory and anything over .25 per cent unsatisfactory. For ordinary radio telephony or for

C. W. telegraphy, a somewhat higher ripple can be tolerated. In broadcast receivers the percentage of ripple at the plate of the detector tube should not exceed .1 per cent but can be somewhat higher on the other tubes and considerably higher at the push-pull final amplifier. Thus the filter as designed above would probably be satisfactory for use between a mercury vapor full-wave single phase rectifier and the tube plates of a broadcast transmitter.

Using the same rectifier and load, if it is desired to reduce the percentage of ripple, it will be necessary to use larger values of L or C, this reducing the cut-off frequency of the filter and increasing the cost of the filter.

From Table 1 and from the filter attenuation equation, it can easily be seen how desirable it is to use three phase rectification, both from the viewpoint of the higher ripple frequency and from the fact that the A.C. component of voltage at the filter input is much less, therefore requiring less filter attenuation for the same percentage of ripple in the output. The filter calculations for a three phase rectifier are similar to those for the single phase job except that a higher cut-off frequency is used and, in calculating ripple attenuation, the A.C. component of voltage at the filter input is much less, being only .250 for the half-wave and .057 for the full-wave, both being taken as decimal proportions with respect to the d.c. component. The ease of three phase filtering is apparent when it is remembered that the A.C./D.C. factor for the full-wave single phase rectifier is .667, more than 10 times as high as the .057 for the full-wave three phase rectifier.

By reversing the calculations, setting the limits of the percentage of ripple in the d.c. output that can be tolerated, and taking the value of filter capacity that is available or that it is desired to use, it is not difficult to solve for the value of inductance necessary to obtain the required ripple attenuation.

For example, assume that with a 60 cycle 3 phase half-wave rectifier designed for a d.c. output potential of 2800 volts, it is desired that the peak ripple voltage in the output does not exceed 3.5 volts. It is desired to use a two unit filter as shown in Figure 18 and two 2 μF condensers are available. Calculate the required values of L. Table 1 shows that for this type of rectifier the peak ripple voltage at the filter input is .25 times the d.c. or

put potential or $2800 \times .25 = 700$ volts; also that the lowest ripple frequency will be 180 cycles. The ratio of the ripple voltage across the load to the ripple voltage at the filter input is $3.5/700 = .005$. Calling this Ratio_1 , from the equation of Figure 18,

$$\text{Ratio}_1 = \frac{1}{(2\pi f)^2 L_1 L_2 C_1 C_2}$$

$$\text{Rearranging, } L_1 L_2 = \frac{1}{(2\pi f)^2 C_1 C_2 \cdot \text{Ratio}_1}$$

$$\text{Ratio}_1 = .005$$

$$2\pi = 6.28$$

$$f = 180$$

$$C_1 C_2 = 4 \times 10^{-12} \quad (\text{Each capacity is } 2 \mu\text{F} \text{ or } 2 \times 10^{-6} \text{ Farads.})$$

$$L_1 L_2 = \frac{1}{(6.28 \times 180)^2 \times (4 \times 10^{-12}) \times .005}$$

$$L_1 L_2 = \frac{1}{1633 \times 10^6 \times 4 \times 10^{-12} \times 5 \times 10^{-3}}$$

$$L_1 L_2 = \frac{10^5}{3266} = 30.6$$

With

$$L_1 = L_2$$

$$L_1 = \sqrt{L_1 L_2} = \sqrt{30.6} = 5.5 \text{ Henries}$$

$$L_2 = 5.5 \text{ Henries}$$

Calculation for the cut-off frequency shows that f_c is approximately 100 cycles per second. While the ratio of the output ripple voltage to the input ripple voltage is .005 or .5 per cent, the ratio of the ripple voltage to the d.c. output voltage is only $3.5/2800 = .00125 = .125$ per cent. This would be satisfactory for a broadcast transmitter plate supply.

If the value of inductance is calculated on the basis of proper operation of the rectifier tubes with a given load, a similar calculation can be made for the amount of capacity necessary to give the required ripple attenuation.

DESIGN OF A TRANSMITTER PLATE POWER SUPPLY: In the design of a radio transmitter plate power supply, it is first necessary to outline the entire requirements of load voltage, current, and permissible percentage of ripple. Second, it is necessary that the design engineer have on hand complete data on the available tubes and circuits so that he may intelligently select the tubes and circuits most nearly suited to his requirements. It is assumed here that these data are available as they can easily be obtained from the tube manufacturers

at little cost. The problem outlined below is based directly on a broadcast transmitter of modern design by one of the leading manufacturers. Similar specifications may be written for any transmitter.

The load circuit is to consist of four Type 204-A tubes operating as Class C radio frequency amplifiers, and two Type 849 tubes operating as Class B modulators. It is desired to operate the modulator tubes with plate potential of 3000 volts and the R.F. amplifiers at plate potential of 2000 volts, the difference between the two voltages being lost in a dropping resistor. An examination of the tube data sheets shows that the maximum plate current of the 204-A tube under such operating conditions is .275 ampere, and the maximum plate current of the 849 tube is .35 ampere. Thus for four 204-A tubes, the maximum plate current is 1.1 ampere and for two 849 tubes .7 ampere, a total maximum load current of 1.8 amperes at 3000 volts.

A 60 cycle three phase power supply is available and it is desired to use mercury vapor rectifier tubes. Examination of tube data sheets indicates that three Type 872 mercury vapor tubes in a three phase half-wave circuit as shown in Figure 20 will most nearly meet the load requirements. Such a rectifier will deliver a maximum load current of 3.75 amperes at 3500 volts with a peak inverse voltage of 7500 volts, which does not exceed the rated tube limits. The filter is also shown in Figure 20. The ripple in the output is not to exceed .15 per cent of the d.c. potential.

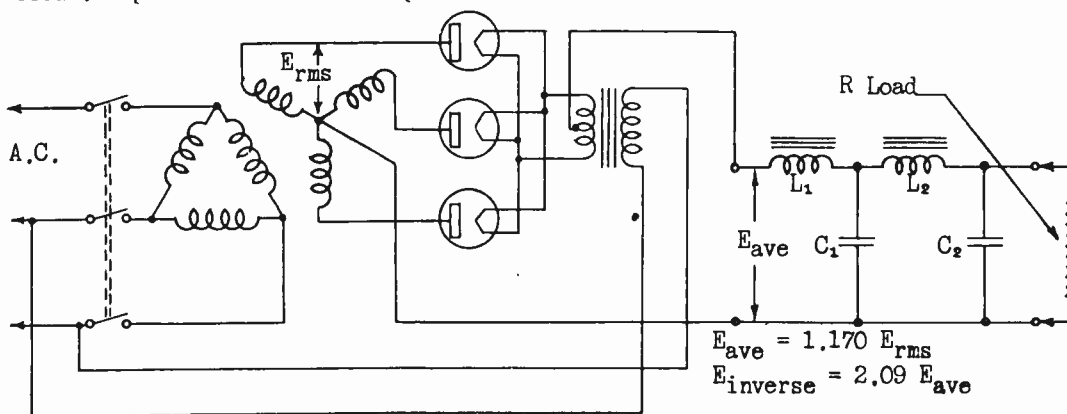


Fig. 20.

Assume that the filter reactors L_1 and L_2 are to have a resistance of not

more than 50 ohms each. To develop at the load 3000 volts, E_{ave} input to the filter must then be $3000 + (100 \times 1.8) = 3180$ volts. This will require that $E_{rms} = 3180/1.17 = 2718$ volts. (It is assumed that the transformer primary is tapped or other arrangements are provided for adjusting the transformer secondary voltage over reasonable limits above and below the calculated voltage to take care of tube drop, load variations, etc.) With the above voltages, the inverse peak voltage per tube will be $3180 \times 2.09 = 6646$ volts, well within the safe operating limits of the tubes selected.

The filter is to be such as to draw continuous tube current and to attenuate the A.C. component so as to allow a ripple in the d.c. output of not more than .15 per cent. This will represent an A.C. component of voltage in the output of $3000 \times .0015 = 4.5$ volts. From Table 1 the A.C. component at the filter input for this type of rectifier is $.25 E_{ave}$; thus the A.C. voltage component at the filter input is $3180 \times .25 = 795$ volts. The lowest ripple frequency is 180 cycles. The filter attenuation factor is $4.5/795 = .005$.

The smallest amount of inductance it is permissible to use at L_1 is such that $X_{L_1} = R_{load}/4$. $R_{load} = 3000/1.8 = 1666$ ohms, and minimum $X_L = 1666/4 = 416$ ohms. $L_1 = 416/2\pi f = 416/(6.28 \times 180) = .37$ Henry. In practice a considerably larger inductance will be used.

The actual values of L and C necessary to keep the ripple within the required limit of .0015 are calculated by means of the equation in Figure 18. Thus, the filter attenuation factor as calculated above,

$$.005 = \frac{1}{(2\pi f)^2 L_1 L_2 C_1 C_2}$$

Since this equation can be solved only for the product ($L_1 L_2 C_1 C_2$), it is necessary to select arbitrarily either the desired value of L or C and solve for the other. Since filter condensers come in standard sizes, it is most simple to arbitrarily select values of C_1 and C_2 . After preliminary calculations are made, it may be necessary to select other values of C and again solve for $L_1 L_2$ if the first calculation results in L of unreasonable value.

The load circuit contains a Class B audio amplifier and the load current can fluctuate over quite wide limits; thus C_2 should be fairly large. $C_2 = 4 \mu F$ and $C_1 = 2 \mu F$ should be reasonable values of C. Then, rearranging the

equation,

$$.005 = \frac{1}{(2\pi f)^2 L_1 L_2 C_1 C_2}$$

$$\text{and } L_1 L_2 = \frac{1}{.005(2\pi f)^2 C_1 C_2} = \frac{1}{.005(6.28 \times 180)^2 (4 \times 2 \times 10^{-12})}$$

$$L_1 L_2 = 15.3$$

This will allow the use of very reasonable values of inductance. In order that the two filter units may have the same cut-off frequency, $L_1 C_1$ must equal $L_2 C_2$. Thus the values of L_1 and L_2 must be inversely proportional to C_1 and C_2 . $C_1 : C_2 :: 2 : 4$. Therefore $L_1 : L_2 :: 4 : 2$ and $L_1 = 2 L_2$.

Therefore,

$$L_2 \times 2 L_2 = 15.3$$

$$2(L_2)^2 = 15.3$$

$$(L_2)^2 = 7.65$$

$$L_2 = \sqrt{7.65} = 2.76$$

$L_2 = 2.76$ Henries and $L_1 = 5.52$ Henries. In practice L_1 will be 5.5 Henries and L_2 will be 2.75 Henries. $L_1 C_1 = 5.5 \times 2 \times 10^{-6}$ and $L_2 C_2 = 2.75 \times 4 \times 10^{-6} = 11 \times 10^{-6}$. The cut-off frequency,

$$F_c = \frac{1}{\pi\sqrt{LC}} = \frac{1}{3.14\sqrt{11 \times 10^{-6}}} = 96 \text{ cycles.}$$

The filter values of L and C as determined above are in line with general practice. If it is desired to use condensers or inductances that are of reasonable values and that happen to be on hand, it is a simple matter to calculate the constants of the additional material which must be purchased. It is necessary to allow sufficient safety factor in the selection of condensers and inductances to take care of the peak voltage and current to be handled.

A power supply to operate from a single phase source is designed in a similar manner, the usual arrangement being a two tube full-wave circuit, or a four tube full-wave circuit where it is desired to take advantage of the full inverse peak voltage rating of the tubes. The voltage ratios for each type of standard circuit are given in Table 1.

POWER TRANSFORMERS: A transformer used to supply power to a rectifier will run hotter than when delivering the same amount of power to a pure resistance load. This is due to the irregular current pulses passed by the rectifier tube. The ratio of the direct current output to the normal A.C. power output of a

transformer is called the transformer utilization factor and depends on the rectifier connections. Table 2 shows this factor for various rectifier connections.

TABLE 2.

	Secondary Utilization Factor
Single phase full-wave center tap connection	.637
Single phase full-wave bridge connection	.9
Three phase half-wave connection	.675
Three phase full-wave connection	.955

For example, if the d.c. output is to be .5 ampere at 5000 volts in a three phase half-wave rectifier the transformer must be rated at $(5000 \times .5)/.675 = 3710$ watts or $3710/3 = 1230$ watts per leg. Thus a transformer capable of delivering 2500 watts of A.C. power would not be satisfactory for this rectifier. Because of this, high voltage rectifier transformers are usually built to specifications.

Usually in transmitter supplies the filament and high voltage transformers are separate units. This simplifies construction and is more economical since the failure of any one unit will not necessitate replacement of all the transformers. Also in high voltage tubes the high current required for the tube filaments makes it advantageous to mount the filament transformer as close to the tube socket as practical to reduce the IR drop in the filament connecting leads to a minimum. By using a separate plate supply transformer it is practical to use a tapped primary which will permit control of the output voltage and hence the transmitter power.

Since receiver installations are in the low power class it is customary to use a single power transformer for high and low voltages. This transformer has one primary and several secondary windings. The number of secondary windings and the voltage developed across each winding will depend entirely upon the arrangement and requirements of the tubes in the receiver. Most modern receivers use the 6.3 volt heater type tubes as R. F. amplifiers and detectors with 6.3 volt filament type tubes as power A. F. amplifiers, or else a group of similar tubes requiring heater voltage of 6.3 volts. It would seem that in

such a receiver all the filaments and heater currents could be taken from a single 6.3 volt winding. This is not practical because the power amplifiers require a different bias than do the other tubes, and the bias is usually obtained by the voltage drop across a resistor connected between the center-tap of the filament secondary winding and ground, the plate current returning to filaments through this resistance. Since this voltage between ground and heater would be entirely unsuitable for the other tubes, it is necessary to use separate windings, one of which must be center-tapped. In some cases, as when using certain types of automatic volume control, it also becomes necessary to isolate certain of the R. F. tubes due to great voltage differences. In such a case a third 6.3 volt winding would be required. In other receivers 6.3 volt tubes may be used in the R. F. and first audio stages with 2.5 volt tubes as final power amplifiers. The transformer secondary windings must be arranged to meet the particular receiver requirements which are determined by the combination of tube types and the type of circuit used.

One standard full-wave rectifier tube, Type 80, requires 2 amperes at 5 volts for filaments. One secondary winding must therefore supply 5 volts for the rectifier filaments and, *since the filament circuit forms the high voltage positive side of a rectifier*, this winding must be insulated for more than the full peak voltage of the high voltage winding with a sufficient safety factor. The rectifier filament winding need not be center-tapped, the terminal connection being made to one side of the winding. The Type 80 tube will normally supply up to 125 mils at 350 volts. A larger full-wave high vacuum tube of similar construction, the Type 5Z3, will supply up to 250 mils at 500 volts. The 5Z3 requires 3 amperes at 5 volts for the filament. A somewhat similar tube is the Type 83 full-wave rectifier which will supply 250 mils at 400 volts. The filament requires 2 amperes at 5 volts. The Type 83 is a mercury vapor tube.

The other secondary winding is the high voltage winding. Where a half-wave rectifier is used this winding need supply only the single high voltage between the plate of the rectifier tube and ground. Where full-wave rectification is desired the high voltage winding must be center-tapped and each side supply the required high voltage for one rectifier plate, the center-tap con-

POWER SUPPLIES

necting to ground. A transformer having two 6.3 volt windings, one being center-tapped, a 5 volt winding for rectifier filaments and a center-tapped high voltage winding is shown schematically in Figure 21.

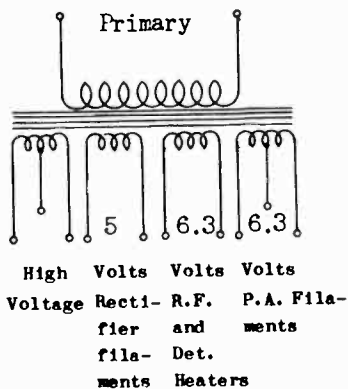


Fig. 21.

In the design or selection of a power transformer careful consideration must be given to the current carrying capacity of the secondary windings. For example, if a single Type 6L6 tube is used as the power amplifier, the heater winding need supply only .9 ampere at 6.3 volts. If the transformer designed to supply .9 ampere at 6.3 volts is used in a receiver employing two 6L6 tubes in push-pull, unless the transformer design engineer was generous in his safety factor, two effects will be observed. First, due to the higher current the winding will heat excessively under continuous operation; second, due to the increased voltage drop in the secondary winding, the voltage at the heaters will be low. A similar condition will exist in the R.F. heater winding if it is used to supply current to more tubes than for which it was designed.

Some receivers employ a voltage regulating device such as a ballast tube in the line to the transformer primary winding. The ballast tube is simply a device the resistance of which varies in accordance with the applied voltage. Suppose the receiver is to operate from a 110 volt power supply. This power supply voltage in various localities at different times of the day may vary from 100 to 120 volts or ten volts above and below the standard voltage; (in some extreme cases even more). To take care of such variation the power transformer may be designed to supply the correct secondary voltages with a primary potential of 80 volts. The ballast tube must then have such characteristics that, with the normal load current taken by the receiver with a line voltage of 110 volts it will provide a voltage drop of 30 volts; $110 - 30 = 80$ volts across the primary winding.

Now as the line voltage rises the current tends to increase in proportion, this causing the filament of the ballast tube to heat up and its resistance to

increase, the increase in resistance causing a higher voltage drop across the ballast tube. With a properly designed ballast tube the voltage drop across the tube will increase or decrease in almost exact accordance with the variations in line voltage thus keeping the actual voltage at the transformer primary constant.

It is absolutely essential in the selection of a power transformer to know whether or not it was designed for operation with some type of ballast regulator. If a transformer so designed is placed in a receiver in which the primary connects direct to the line all the secondary voltages will be greatly in excess of the required values with probable damage to apparatus or tubes. On the other hand, if the transformer was designed for operation direct from the power supply and is used with a ballast regulator in the primary, all the secondary voltages will be low and the equipment will operate inefficiently.

If a half-wave rectifier tube Type 81 is used, the filament transformer must supply 1.25 amperes at 7.5 volts. Thus, so far as the filament supply is concerned, the 81 and the 80 tubes are not interchangeable. The type 80 tube is used where comparatively low voltage (350 volt maximum) full-wave output is desired. The maximum current that the 80 can supply at this voltage is 125 mils. The Type 81 tube is used where an output potential of from 500 to 600 volts with a direct current of not more than 85 mils is desired. If more current is desired at such high voltage it will be necessary to use two such tubes in a full-wave combination, or a 5Z3 full-wave tube may be used if the required voltage does not greatly exceed 400. The 80, 81, and 5Z3 tubes are quite well evacuated and the voltage drop within the tube is high. For that reason the actual voltage delivered to the load is largely a factor of the load current, rising when the current is low and falling off rapidly as the load current increases.

With Class A operation of the power amplifier tubes where the plate current remains substantially constant during all variations in signal amplitude, this current-voltage characteristic is not particularly important during operation because it can be taken care of in the rectifier design. In some receivers and particularly in public address systems where it is desired to obtain the greatest possible power output from comparatively small power tubes, there has been

considerable use of push-pull Class B amplification. Since for good quality of reproduction it is necessary to assume a constant plate voltage supply, the high-vacuum rectifier tubes, (80, 81 and 5Z3), would not be at all suitable because of the variation of tube voltage drop, and hence of output voltage, with load current variations.

The solution to this problem is the use of a mercury vapor rectifier tube. This type of tube is entirely satisfactory as a power supply for Class B amplifiers because of its constant tube drop and suitable tubes have been developed for that purpose. Such tubes are the Type 82 full-wave rectifier which will supply continuous direct current of 115 mils with peaks of 345 mils at over 400 volts, and the Type 83 which will supply double the above currents at the same voltage. Of course the d.c. voltage drop through the filter reactors and transformer winding will vary with load current but this is taken care of by the use of low resistance windings.

Vacuum or low-gas-content rectifier tubes with their high internal voltage drop have a serious disadvantage where comparatively high voltage power tubes are used in conjunction with a large number of the slow-heating heater types. The rectifier filaments warm up quickly and deliver a high voltage output to the filter. Until the tube cathodes reach emission temperature the plate current drain on the filter is low and the voltage correspondingly high. This sometimes results in punctured filter and by-pass condensers and must be allowed for in the selection of such condensers. With mercury vapor tubes where the regulation is so much better, the voltage varies over much narrower limits with varying loads.

Figure 22 shows the circuit of a full-wave rectifier and power transformer with the windings as shown in Figure 21. The full-wave rectifier has two sets of filaments and plates within the single tube, the filaments being paralleled within the tube.

VOLTAGE DIVIDERS FOR A.C. OPERATED RECEIVERS: The output from the rectifier and filter is supplied to the tubes, (plate, screen and grid bias voltages), through a voltage dividing circuit. An early lesson discussed fundamental voltage divider circuits in which, with a given d.c. voltage supply source, several different voltages could be taken off for the operation of the various

tubes in a receiver or transmitter. In this lesson will be discussed in greater detail the methods by which the individual voltages are obtained in actual practice.

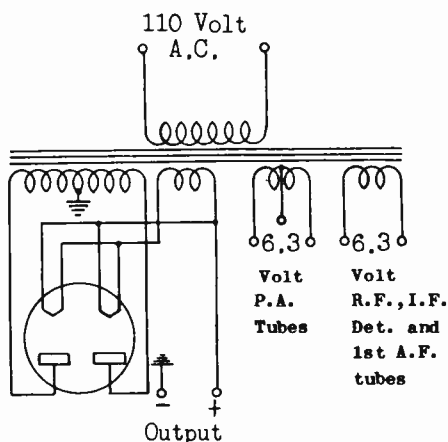


Fig. 22.

Since the voltage dividers used in receivers are in general more complex than those in transmitters this discussion will be devoted primarily to receiver networks although exactly the same methods may be applied to the voltage dividers used in transmitters.

In the modern broadcast receiver operating from an alternating current supply the voltage arrangement which must be obtained from a single rectifier source is quite complex. For example, in

the superheterodyne receiver the circuit components include the radio frequency amplifier, the first detector, the oscillator, the intermediate frequency amplifier, the second detector, the first stage of audio frequency amplification, the second stage of A. F. amplification, (power amplifier), and the automatic volume control. (Also possibly automatic bass control, automatic frequency control, tuning tube, and other special circuits.) During the past several years a great variety of tubes have been developed to provide the most efficient operation in each circuit of the receiver. One superheterodyne receiver for example uses the Type 6K7 variable- μ Screen Grid tubes as radio frequency amplifier and intermediate frequency amplifier, a Type 6H6 as combined second detector and automatic volume control a Type 6C5 as oscillator, a 6C5 as 1st A.F. amplifier, a 6L7 1st detector, and two Type 6F6 tubes in push-pull in the power amplifier stage.

Where greater power output is desired, the last stage may consist of two 6L6's in push-pull. There are a great number of other tube arrangements used in modern receivers, both for broadcast and other purposes, and each tube as used for its particular purpose will operate most efficiently when all the voltages are correct.

What voltages must be considered in the design of a resistance network to obtain the best results? In a combination such as outlined above, the same

plate voltage may be used for the R. F. amplifier, the first detector, the intermediate frequency amplifier and first audio amplifier. A lower plate voltage is ordinarily used for the oscillator, with a higher plate voltage for the power amplifier tubes.

All tubes, with the exception of the oscillator, operate with a negative biasing voltage on the control grid and *the normal biases for most of these tubes are different.* In addition the control grid bias for the two Type 6K7 tubes must be so arranged as to permit variation over quite a wide range by means of automatic volume control.

Figure 23 shows a simple arrangement for obtaining several plate voltages.

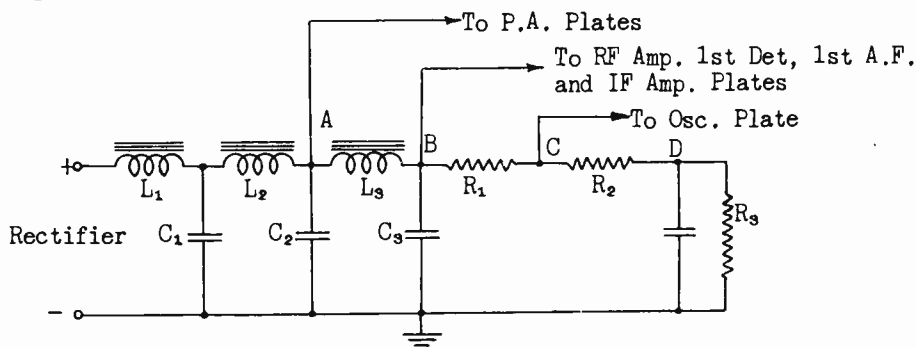


Fig. 23.

The filter consisting of L_1 , L_2 and L_3 , and C_1 , C_2 and C_3 is shown because one of the filter reactors, L_3 , also serves as one of the voltage divider resistors. There are several reasons for this: First, the reactor is necessary in order to provide the additional filtering needed for the tubes other than the power tubes; second, this reactor has a certain amount of resistance which, if the plate current for the power amplifier stage passed through it, would drop the plate voltage for those tubes to too low a value; third, it tends to keep the cost of construction down because it eliminates the necessity for an additional comparatively high wattage dropping resistor.

A previous assignment indicates the method of calculating the values of resistance to use in L_3 , R_1 , R_2 and R_3 . Since the plate current return to the cathodes is made through ground, the chassis of the receiver, it is not difficult to trace the fundamental circuit. The plate current for all the tubes plus the bleeder current, flows through L_1 and L_2 therefore the

plate voltage for the power amplifiers taken off at point A is equal to the rectifier terminal voltage minus the drop across L_1 and L_2 . The bleeder current plus the current for all tubes *except the power amplifiers* flow through L_3 , and the voltage taken off at point B is equal to the voltage at point A minus the drop across L_3 . The plate current for the oscillator plus the bleeder current flows through R_1 so that the voltage at point C is equal to the voltage at point B minus the drop through R_1 . Only the bleeder current flows through R_2 and R_3 as shown. The value of each resistor is calculated from the desired voltage drop divided by the known current through the resistor. $R = E/I$. Unfortunately in the modern A. C. operated receiver the actual arrangement is not so simple as that shown in Figure 23, but the principle of the voltage divider design is similar.

The screen grid voltage is usually obtained in a manner similar to that of the plate voltage. In Figure 23, the screen voltage could be taken from point D, R_2 and R_3 being so proportioned as to give the desired voltage at this point, or the screen voltage can be taken directly from the plate voltage tap through a dropping resistor.

One method of obtaining a negative grid bias voltage from the voltage divider is shown schematically in Figure 24. Here R_1 , R_2 and R_3 form the positive side of the divider circuit, points A, B and C being positive with respect to ground. Point D will be negative with respect to ground by the amount of the

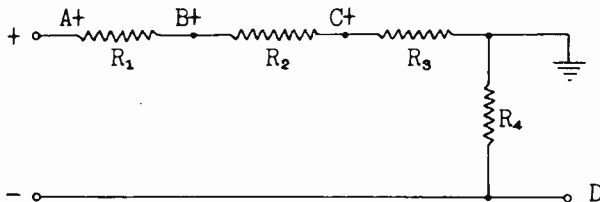


Fig. 24.

IR drop across R_4 , I being the full rectifier current. With the tube cathodes or filaments connected to ground (chassis) the negative grid bias voltage can be taken from point D and the positive plate and screen grid voltages from points A, B and C. This arrangement of obtaining the negative bias voltage has two serious disadvantages: First, it does not permit any simple method of obtaining different and variable bias voltages for the individual tubes; second, the grid circuit must be insulated from the chassis and the leads run for considerable distances to the source of negative voltage. This latter objection

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is the most serious because in a receiver in which several circuit tuning condensers are operated by means of a single tuning control it will be difficult to line the circuit up with grid leads of various lengths. The alternative of feeding the bias voltages through R. F. chokes is both troublesome and expensive. The insulation of the grid circuits can be employed however by using sufficiently large bypass condensers to ground in all circuits. This is not the preferable arrangement.

From the viewpoint of the radio frequency circuit it is very desirable to have the grid circuit connections of uniform length and as short as possible, the ideal connection being direct to the chassis of the receiver. This can be done by *insulating the filament and cathode circuits above ground*. It is not at all essential that the grids be negative with respect to ground; *they must be negative with respect to their cathodes*. If the grid is connected to ground and the cathode made 6 volts positive *with respect to ground*, there will be a 6 volt negative bias on the grid. This can be very simply arranged by connecting the cathode to ground through a resistor as shown in Figure 25. The plate

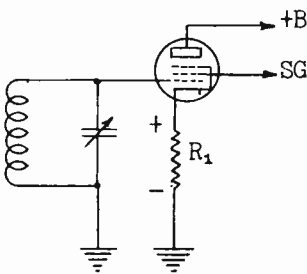


Fig. 25.

current within the tube flows from cathode to plate and, through the external circuit, back to the cathode. Thus the plate and screen currents must return to the cathode through ground and R_1 . Since current flows from negative to positive, the ground side of R_1 is negative with respect to the cathode and, since the grid connects through its tuned circuit directly to ground, the grid is negative with respect to the cathode by the amount of the IR drop across R_1 , I of course being the sum of the plate and screen currents of this particular tube.

To calculate the value of resistance necessary to obtain the correct bias for a triode, it is only necessary to know E_g and I_p . Assume that a normal operating bias of 3 volts is required and the normal plate current of the tube is 8 mils. Then $R = E/I = 3/.008 = 375$ ohms.

Suppose the power amplifier consists of two Type 2A3 tubes operating Class AB_1 in push-pull, the tubes taking plate current of 40 mils each and requiring a grid bias voltage of -62 volts. Figure 26 shows the arrangement for obtain-

ing the bias. The filaments are taken from a common 2.5 volt winding on the power transformer. The plate voltage from the rectifier is fed into the center

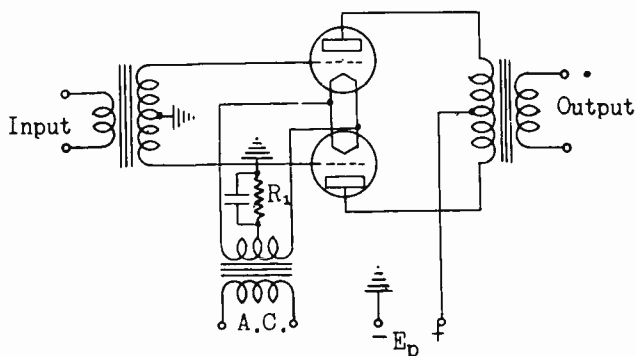


Fig. 26.

of the primary of the output transformer, the extremes of the primary connecting to the two plates. The center-tap of the secondary of the input transformer connects directly to ground placing the grids at ground potential. The filament circuit is insu-

lated above ground and the connection to a ground is made through R_1 . Since the plate current flows through R_1 from ground to filament, the filament will be positive with respect to ground, and consequently with respect to the grids, by the amount of the drop across R_1 .

Since the plate current of each tube is 40 mils, the total current through R_1 will be 80 mils. Therefore, $R_1 = 62 / .08 = 775$ ohms. In the selection of this resistor it must be remembered that it must carry, without overheating, 80 mils. $\text{Watts} = I^2 R = .08^2 \times 775 = 4.96$ watts. A 10 watt resistor should be used here.

It is considered good engineering practice to use resistors the wattage rating of which are from 2 to 3 times the actual power required to be dissipated by the resistor in service. Manufacturer's ratings are based on free air circulation on all sides of the resistor, a condition rarely obtained in practice.

When designing the power supply for a combination as shown in Figure 26 where a high value of negative grid bias is to be used, it must be remembered that the bias voltage subtracts from the effective plate voltage because it is in series between the plate and cathode. Therefore if an effective d.c. plate voltage of 250 volts is desired with a 62 volt negative bias, the voltage between the plate tap and ground should be 312 volts.

If power pentodes are used in the power amplifier stage instead of the 2A3 triodes, the screen current of the pentodes must also be considered in the de-

sign of the bias resistor because it is an appreciable portion of the total current through the resistor. Operating Class A with $E_p = 250$ the plate current of the Type 6F6 tube is 34 mls while the screen current is 6.5 mls. Thus for two 6F6's in Class A push-pull the current through the biasing resistor would be 68 mls plus 13 mls or 81 mls total. On the other hand the 6F6 operated as stated requires only 16.5 volts of negative bias so that the biasing resistor for the push-pull combination should be, $R = 16.5/.081 = 204$ ohms.

Where plate detection is used, the normal type of detection where a high gain I. F. amplifier and power detector are employed, the operating bias is usually from about 12 to 20 volts depending upon the tube used. In the case of a Type 6C5 triode with grid bias of -17 volts the plate current will be about .2 MA or .0002 ampere. In this case the biasing resistor may have a value of $R = 17/.0002 = 85,000$ ohms.

In practice with various types of tubes, the correct value of resistance will usually be between about 35,000 ohms and 100,000 ohms.

While the arrangement of resistances as described above to obtain individual voltages is extremely simple, the actual combination of these various resistances in a modern high quality, high gain receiver in which all the values must be coordinated, is somewhat more complex. Probably the most comprehensive manner in which to discuss the complete operation of such a circuit is through a very detailed study of the actual voltage divider circuit as used in an A.C. operated receiver. Figure 27 illustrates such a circuit. Only the d.c. circuits are shown. This is a superheterodyne receiver employing one stage of tuned radio frequency amplification, a first detector, one stage of intermediate frequency amplification, a second detector, a first audio amplifier, a push-pull power amplifier, an oscillator and an automatic volume control tube.

In this diagram the values of all resistors are stated as are the values of most of the currents, the direction of flow of some currents where the direction of flow is not apparent, and the voltages along the main portion of the voltage divider. A number of minor discrepancies will be observed; for example, between the total current and the sum of the individual currents shown, between the voltages at certain points along the circuit and the products of IR by

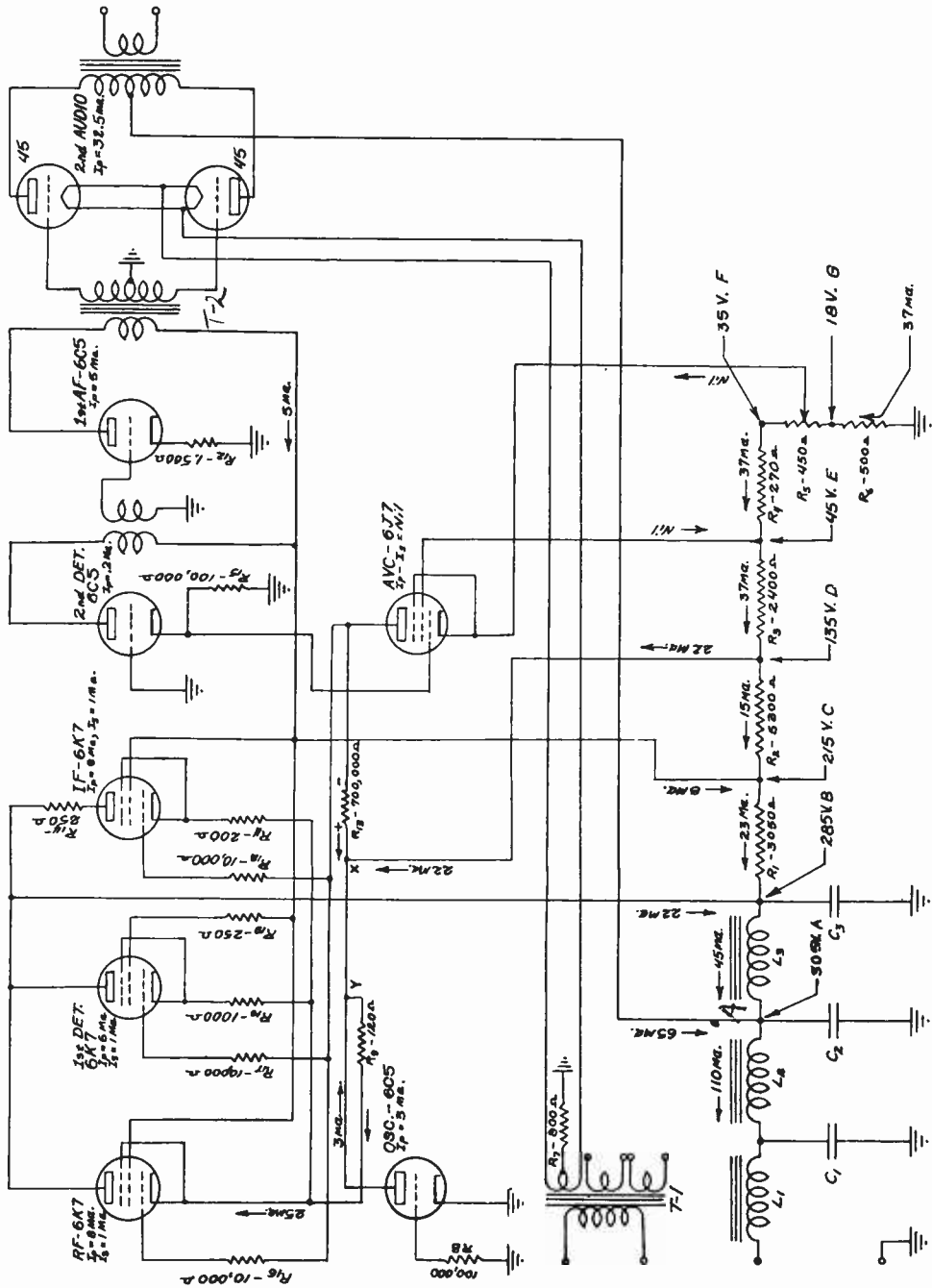


Fig. 27.

which the various voltage drops are obtained. There are several reasons for these discrepancies; first, the high voltages shown were actually measured with respect to ground (chassis) and the current flow through the voltmeter introduces a small error; second, there are a number of currents which are classed as individually "negligible" but which add up to an appreciable current when flowing through the higher values of resistance; third, the actual current in the tubes is not *exactly* as given in the values shown when the readings were taken; fourth, standard values of resistances are used instead of the *exact* values as calculated; the error introduced by the variation in resistance however is not greater than that introduced by slight changes in tube characteristics during operation and by the differences in individual tubes. The slight discrepancies due to these various causes are not sufficient to make the understanding of the operation of this circuit difficult.

The rectifier delivers power to the filter circuit consisting of L_1 , L_2 , L_3 and C_1 , C_2 and C_3 as shown in Figure 27. Just as in Figure 23, the filter reactor L_3 also serves as one of the voltage divider resistors. The voltage at point A between L_2 and L_3 is 305 volts *with respect to ground*. The current flowing to this point is the 65 mils from the two power tubes and 45 mils (approximately) from the rest of the voltage divider system, a total of 110 mils flowing through the filter reactors L_1 and L_2 to the rectifier. (Current directions are shown as *from negative to positive*, the actual direction of electron flow.) As this current flow leaves the rectifier, 65 mils must return to the two power tube filaments. An examination of the circuit shows that that current can return only through R_7 which connects between ground and the center-tap of the power tube filament transformer secondary of T_1 . As 65 mils flows through R_7 from ground to the filament, a voltage drop equal to IR or $.065 \times 800 = 52$ volts is developed across R_7 . The center-tap of the grid or secondary winding of T_2 , the input transformer to the power amplifier, connects to ground. Since ground is negative with respect to the filaments by the amount of the drop across R_7 , the power amplifier grids are *negative* with respect to the filaments by 52 volts. Since R_7 is in the filament side of the plate circuit and since the voltage applied to the power amplifier plates at point A (305 volts) on the voltage divider circuit is measured with respect to ground, the

actual difference of potential between plate and filament circuits is 305 - 52 or 253 volts.

With 65 mils from the rectifier leaving the ground connection and returning to the cathodes through R_7 , it is necessary to look for ground connections in order to trace the path of the rest of the current flow through the filter and voltage divider circuit. Immediately above T_1 is the oscillator tube, Type 6C5, with cathode connected directly to ground. Since the plate current of this tube is given as 3 mils, this current must enter the tube at the cathode connection to ground. The grid of the oscillator connects to ground through R_8 , a 100,000 ohm grid leak, and the oscillator bias is equal to the grid current voltage drop across R_8 .

Another ground connection is found at R_{15} . The cathode of the second detector tube, (Type 6C5), connects to ground through R_{15} , a 100,000 ohm resistor. The plate current of .2 mil returns to the cathode through this resistor making the cathode *positive* with respect to ground by the amount of IR_{15} , about 20 volts. The grid connects directly to ground and is therefore negative with respect to its cathode by 20 volts.

Another ground connection is found at the cathode of the first audio amplifier, this cathode connecting to ground through R_{12} , a 1500 ohm resistor. I_p returning through R_{12} produces a grid bias of approximately 7.5 volts.

The only other connection to ground is at R_6 , the low potential end of the main voltage divider circuit. A current of approximately 37 mils enters the divider system at this point. Flowing through R_6 , point G is made positive with respect to ground by IR , $.037 \times 500$ or 18 volts. The next resistor, R_5 , is a 450 ohm potentiometer which makes point F 35 volts positive with respect to ground. The movable contact of R_5 connects to the cathode of the A.V.C. tube, a Type 6J7. By means of the movable contact the cathode of the A.V.C. tube can be varied between 18 volts and 35 volts *positive* with respect to ground. The grid of the A.V.C. tube connects to the cathode of the second detector tube above R_{15} and is therefore positive with respect to ground by 20 volts. With both the grid and cathode positive with respect to ground the actual difference of potential between them is equal to the difference between the grid and cathode voltages, each measured with respect to ground. The grid

voltage is largely fixed at +20 volts. The cathode voltage can be varied between +18 and +35 volts. Therefore the grid voltage with respect to the cathode can be varied between +2 volt and -15 volts. The cathode current to the A.V.C. tube is very small, and since the resistance values of R_5 and R_6 are small, the error introduced by neglecting this current will not appreciably affect the calculations of the current. It will be noted that the plate current of the A.V.C. tube flows through a 700,000 ohm resistor so that I_p is *extremely* small and practically, in the study of the circuit, may be neglected.

The next resistor, R_4 , 270 ohms adds its voltage drop to those of R_5 and R_6 to establish a potential of 45 volts positive with respect to ground at point E. At this tap the screen of the A.V.C. tube is connected. The drop across R_4 is 10 volts. Thus when the potentiometer arm of R_5 is at the 35 volt end, the screen grid of the 6J7 is 10 volts positive with respect to its cathode. With the potentiometer arm at the other end of R_5 the screen is 27 volts positive with respect to the cathode. The current through R_4 is still approximately 37 mils because the screen current of the A.V.C. tube is negligible.

Next is R_3 , a 2400 ohm resistor. With the current still approximately 37 mils there is a voltage drop of 90 volts across R_3 , making point D 135 volts positive with respect to ground. The circuit tapping into this point is very interesting. 37 mils flow into this point from R_3 . The diagram shows 15 mils flowing from point D through R_2 and 22 mils to the receiver tubes. An examination of the circuit from point D shows the following connections: Through the 700,000 ohm resistor R_{13} to the plate of the A.V.C. tube; directly to the plate of the oscillator tube; through the 120 ohm resistor R_9 to the cathode of the R. F. amplifier tube; through a further resistance of 1000 ohms, R_{10} , to the cathode of the First Detector; through a 200 ohm resistor, R_{11} , to the cathode of the Intermediate Frequency Amplifier Tube. Thus point D connects to the plate of the A.V.C. tube, the plate of the Oscillator tube, and the cathodes of the three 6K7 tubes. To study the current distribution through this circuit it is necessary to resort to Kirchoff's First Law which states, "The sum of the currents flowing from any point in a circuit is equal to the sum of the currents flowing to that point." Also note two additional points, x and y.

The current leaving point D and flowing toward the receiver tubes is 22

mils. This current flows toward point x. A small and *negligible* current also flows toward point x from the plate of the A.V.C. tube. Thus 22 mils flows from point x toward point y. At point y another current of 3 mils approaches from the plate of the Oscillator tube. Thus the combined current of 22 + 3 or 25 mils flows toward point y.

At point y there is a third connection, to the cathodes of the three 6K7 tubes. Since this is the only other connection to point y the 25 mils flowing toward point y from the other two branches must flow away from y through this third circuit. The cathode current of the three 6K7 tubes is seen to equal the sum of the plate and screen grid currents of these tubes as listed on the diagram. It will be seen that the return of the plate circuits to the cathodes of the 6K7 tubes is quite complex being partly through two other tubes, and partly through the main divider circuit.

This leads to a consideration of the actual voltages applied between the tube elements connected at this point. Point D is 135 volts positive with respect to ground as is point x. The plate of the oscillator tube connects directly to this point and its cathode connects directly to ground therefore the plate of the oscillator tube must be 135 volts positive with respect to its cathode.

The plate voltage of the A.V.C. tube is difficult to calculate or measure because of the high value of R_{13} , 700,000 ohms, in its plate circuit. When measured it merely gives a positive deflection on the voltmeter due to the comparatively high value of current taken by the meter through such a high resistance. In operation the plate current of this tube depends upon the R. F. signal voltage impressed on the grid. The tube is biased as explained above and normally the voltage drop across R_{13} is not great due to the extremely small value of current, but this voltage drop is a function of the control bias as regulated by the potentiometer R_5 , and of the magnitude of the incoming signal voltage.

The *cathodes* of the three 6K7 type tubes connect, through their respective bias resistors, to point D through point Y. It will be observed that they also connect along this same circuit to the lower or *positive* side of R_{13} . To the plate of the A.V.C. tube which is also the negative side of R_{13} connect the

grids of the 6K7 tubes through 10,000 ohm stabilizing resistors, R_{16} , R_{17} , R_{18} . With no plate current in the A.V.C. tube, that is, no current through R_{13} , the 6K7 grid potentials will be that of point x, and point x will be negative with respect to the 6K7 cathodes by the amount of the IR drop through the respective bias resistors, R_9 , R_{10} and R_{11} . As the signal amplitude increases and current flows through R_{13} , the grids of the 6K7 tubes are driven more negative by the drop across R_{13} , thus decreasing their sensitivity and the signal amplitude. (The detailed operation of the A.V.C. tube is explained in another lesson.)

Assuming no current through R_{13} the normal grid biases for the 6K7 tubes can be calculated. The plate and screen current for all three tubes, 25 mls, flows through the 120 ohm resistor, R_9 . The drop across this resistor is $IR = .025 \times 120 = 3$ volts. Since the cathode of the R. F. amplifier connects directly above R_9 , the normal bias on the grid of this tube is 3 volts.

The next 6K7 tube, first detector, cathode connects above R_9 through a 1000 ohm resistor R_{10} . The combined plate and screen current of this tube is shown as 7 mls, therefore the drop across R_{10} is $.007 \times 1000$ or 7 volts. This voltage drop adds to the drop across R_9 providing a total normal negative bias for this tube of 10 volts.

The cathode of the third 6K7 tube, I. F. Amplifier, connects above R_9 through a 200 ohm resistor, R_{11} . The plate and screen currents of this tube total 9 mls giving a voltage drop across R_{11} of $.009 \times 200$ or 1.8 volts. This added to the drop across R_9 provides a normal operating bias of $3 + 1.8$ or 4.8 volts negative for the I. F. amplifier.

As the amplitude of the signal voltage becomes sufficiently great to cause plate current flow in the A.V.C. tube and consequently through R_{13} , or when the volume control potentiometer R_5 is moved to a point which allows plate current to flow in this tube, the drop across R_{13} adds to the normal bias voltages of the first three tubes thus reducing their sensitivity and gain. Since these tubes are all of the variable- μ type, a very gradual control of volume over a very wide range is obtained.

At point C the voltage with respect to ground is 215 volts, the drop across the 5300 ohm resistor R_2 by the bleeder current of 15 mls being approximately 80 volts. The screen grids of the three 6K7 tubes connect here, their poten-

tial with respect to the cathodes being 80 volts minus the amount of the biasing voltage since the cathodes connect at the 135 volt tap. At this point also connect the plates of the 2nd detector and the 1st audio amplifier, both Type 6C5 tubes. The plate potentials of these tubes is 215 volts less the individual bias voltages.

At point B the voltage with respect to ground is 285 volts. The plates of the first three tubes, the 6K7's connect to this point. Since the cathodes connect to the 135 volt tap, (point D), the plates are positive with respect to their cathodes by $285 - 135$ or 150 volts minus the bias voltages. It should be observed that the current through the 3050 ohm resistor, R_1 , is the bleeder current of 15 mils, the screen current of the 6K7 tubes, and the plate currents of the first audio amplifier and the second detector. The latter current is neglected in the calculations as it is quite small.

At point B the plate currents of the three 6K7 tubes add to the bleeder current of 15 mils giving a current flow through L_3 of approximately 45 mils. With a d.c. voltage drop across L_3 of $305 - 285$ or 20 volts, L_3 must have a resistance of $20/.045$ or 445 ohms. At point A the current of 45 mils joins the 65 mils of plate current from the power tubes producing a total current to the rectifier of 110 mils.

This circuit should be restudied thoroughly because it has a number of interesting features. It will be observed that the current is greater in both ends of the voltage divider circuit than in the middle of the main divider circuit. This is because of the peculiar arrangement whereby the cathodes of the first three tubes are held at such a high positive potential with respect to ground, this being required by the particular system of automatic volume control used. This circuit demonstrates very clearly that in any tube operation the actual difference of potential between tube elements must be considered, and not the voltage with respect to ground.

It is practically impossible to accurately check such a circuit by means of a conventional set tester because with so many high values of resistance and interconnected circuits, the current taken by the test meters will give very erratic readings as compared with the actual operating conditions. The condition of the tubes may be tested individually on a tube tester and then the

various resistances measured and checked against the circuit data furnished by the manufacturer.

In studying this circuit it should be remembered that no attempt has been made to show any of the radio frequency circuits, bypass condensers, etc. Only the actual d.c. circuits are shown. It can easily be seen that there is a very distinct connection between the operation of all parts of the circuit. A short-circuit or loss of emission in any one tube will change the voltages applied to all other tubes as will the opening or shorting of any one of the principal resistors. For this reason the greatest care must be taken in diagnosing trouble in such a circuit because an incorrect diagnosis can easily be made.