Rectifier Considerations

Rectifier-type power supplies employing electron tubes are used as sources of plate, screen-grid (grid-No.2), and other dc operating voltages in all types of electronic equipment. They are also used extensively in electroplating, in motor-speed control, and in many other applications requiring economical and conveniently controllable dc power.

The glass envelopes of the rectifier tubes used in such supplies normally show some darkening after continued operation. In addition, mercury-vapor tubes exhibit a blue glow in normal operation. These symptoms are characteristic of such tubes, and should not be considered signs of tube deterioration or failure.

Mercury-Vapor Tubes

A mercury-vapor rectifier tube must be handled with special care to prevent dispersion of the liquid mercury from its normal position at the bottom of the bulb. Spattering of the mercury over other portions of the bulb or on the anode or filament must be avoided because it may lead to internal shorts or arcs when the tube is placed in operation. A mercury-vapor tube should always be transported, stored, and operated in a vertical position with the filament end down, and should never be jarred, shaken, or allowed to rest even momentarily in a horizontal position. The tube should never be rocked or allowed to snap into place in its socket or mounting, and should be protected against excessive equipment vibration.

If spattering occurs, the dispersed mercury must be completely reconcentrated before the tubes are placed in service by means of special preheating and conditioning treatments. In the preheating treatment, the mercury-vapor tube is operated at normal filament voltage, but without anode voltage, for 30 minutes to assure complete vaporization of the mercury content. When filament voltage is removed at the end of this preheating period, most of the vaporized mercury recondenses in a pellet or pool at the bottom of the bulb. The conditioning treatment is then applied to flash out any mercury which may have condensed on the bulb walls or in the vicinity of the anode and filament seals. In this treatment, the tube is operated at normal filament voltage and at about one-sixth normal anode voltage for 5 minutes. The anode voltage is then gradually increased over a period of about 30 minutes to the normal operating value. If an internal flashover occurs at any time during the conditioning treatment, the anode voltage should be reduced until the flashover ceases. It should then be held at this reduced value for a few minutes to assure complete vaporization of the mercury before the treatment is resumed.

Filament Heating Time

Voltage should not be applied to the plates or anodes of vacuum, mercury-vapor, or inert-gas rectifier tubes (except receiving types) until the filaments or cathodes of the tubes have reached normal operating temperature. For gas tubes, this delay is necessary to allow the formation of a plasma (region of electrons and positive ions) which protects the emitting surface against damage from high-velocity positive-ion bombardment. In the case of a mercury-vapor rectifier, the application of anode voltage must also be delayed until the condensed mercury has moved to its normal condensing zone at the bottom of the tube, as discussed above.

Minimum heating times for individual rectifier types are given in the *Tube Types* Section. In each case, the time specified is measured from the instant when the filament voltage reaches its normal operating value and, consequently, may have to be increased if the filament supply has poor regulation.

It should be noted that measurement of the filament voltage of a power-rectifier tube may involve serious personal-safety hazards because the filament is usually a high-voltage terminal of the rectifier circuit. When continuous measurements are *required, suitable voltmeters should be permanently incorporated in the equipment. These meters must be insulated to withstand the maximum peak inverse voltage applied to the tubes, and should be recessed in the equipment and protected by glass or plastic viewing panels to prevent any possibility of injury through accidental bodily contact. Portable instruments should not be used for the measurement of rectifier-filament voltages unless adequate personal-safety precautions are taken by the user.*

Because a mercury-vapor tube may be severely damaged if the temperature of its filament varies excessively, the filament should be operated from a constant-voltage transformer, or its supply circuit should include under- and overvoltage relays which will open the primary circuit of the rectifier anode supply if the line voltage varies excessively. Relays having small operating delays (less than 10 seconds) may be used in this application to minimize interruptions to operation by normal surges or transient variations in line voltage.

The required delay in application of anode voltage can be obtained conveniently by means of a time-delay relay connected in the primary circuit of the high-voltage transformer, as shown in Fig. 53. This relay should permit adjustment of the delay time to a value sufficient to assure protection for the tubes under the most adverse conditions that can be expected in service.

Mercury Temperature

The life and performance of a mercury-vapor rectifier are critically dependent on the temperature of the condensed mercury. Low ambient temperatures retard vaporization of the mercury, thus limiting the degree of ionization available at normal filament voltage and raising the anode-cathode potential at which the tube starts to conduct. High ambient temperatures, on the other hand, are conducive to rapid vaporization, but tend to produce over-ionization and thus reduce the peak inverse anode voltage that the tube can withstand without breakdown. Rectifiers using mercury-vapor tubes, therefore, should be equipped with means for measuring condensed-mercury temperatures, and for maintaining these temperatures within limits specified for the tubes employed. Condensed-mercury temperature may be measured with a thermocouple or thermometer attached to the tube by means of a small amount of putty in a region near the bottom of the bulb. The proper measurement zone for each of the mercury-vapor tubes included in this Manual is shown in the *Outlines* Section.

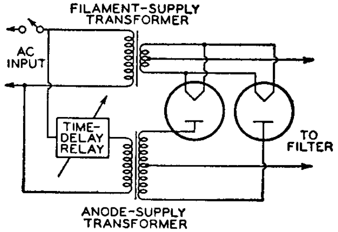

Fig. 53

The method used to control condensed-mercury temperature depends on the ambient-temperature conditions under which the tubes operate. If the ambient temperatures are near the minimum values specified in the tube data, some form of heat-conserving enclosure should be provided for the tubes. In extreme cases, it may also be necessary to employ electrical heating, together with suitable means for limiting the maximum temperatures developed. If ambient temperatures are above the maximum values specified in the tube data, forced-air cooling should be employed. The air flow should start when the anode voltage is applied to the tube, and should be directed horizontally onto the bulb about ½ inch above the base at the filament end of the tube. The air flow may be removed simultaneously with the anode voltage. The rise of mercury-vapor temperature above ambient temperature is given as a function of heating time under no-load and/or full-load conditions for mercury-vapor rectifier types in the *Tube Types—Technical Data* Section.

Shielding

Rectifier tubes, particularly mercury-vapor types, should be isolated from transformers and other components which produce strong external magnetic or electrostatic fields. Such fields are generally detrimental to tube life, tend to produce breakdown effects in mercury vapor, and frequently make it difficult to obtain adequate filtering of rectifier output. When tubes cannot be completely isolated from such fields, they should be enclosed in shields of the type described in the *Power-Tube Installation* Section. Mercury-vapor rectifier tubes used to supply transmitters or other types of rf power equipment should also be protected from large rf voltages. Such voltages should be prevented from entering rectifier circuits by rf filters such as that shown in Fig. 54.

Mercury-vapor rectifier tubes occasionally produce multi-frequency oscillations or "hash" which may cause interference in the af stages of associated equipment and in near-by radio receivers. These oscillations are caused by the development of a very steep wave front at the instant conduction begins in each rectifier unit, and may be propagated along internal circuit wiring and external power lines or radiated directly by the tubes. In a receiver, rectifier "hash" can usually be identified as a broadly tunable signal modulated at the rectifier "ripple" frequency. (The "ripple" frequency is equal to the power-line frequency times the number of half-wave rectifier units conducting independently.)

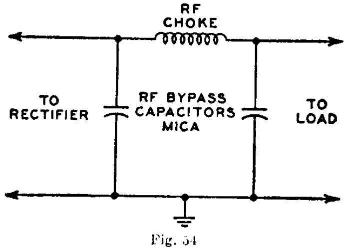

Fig. 54

In some cases, this type of interference can be minimized by the use of very short leads to the rectifier anodes. It is usually necessary, however, to determine whether the interference is transmitted by radiation or by conduction, and to select the most effective method for its elimination by experiment. Radiation of such interference can usually be minimized by shields of the type used t protect rectifier tubes against externa fields. The transfer of such interferenc to a power line can be minimized by th insertion of a low-pass inductance-capacitance filter in the input circuit of th rectifier, as shown in Fig. 55, or by th use of filament and high-voltage supply transformers having electrostatic shields between primary and secondary windings. Low-pass filters of the type shown in Fig. 56 are also useful. The bypass capacitors used in such filters must have a voltage rating at least equal to the peak voltage developed across each half of the transformer secondary (approximately 1.4 times the rms voltage).

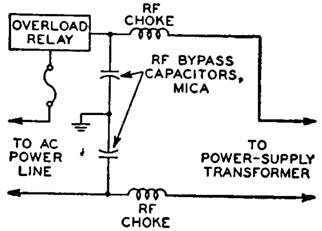

Fig. 55

Rectifier tubes operated in circuits in which peak inverse voltages are 16000 volts or higher produce X-rays. Because these rays constitute a serious health hazard, tubes operated in such circuits should be equipped with shielding designed to absorb X-ray radiation

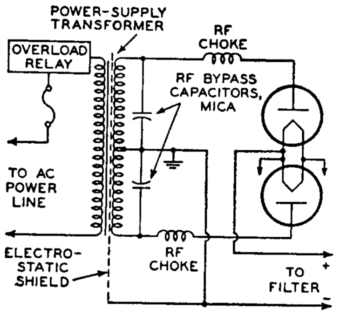

Fig. 56

RCA mercury-vapor and inert-gas rectifier tubes are equipped with internal cathode shields. These shields are connected to a filament or heater terminal designated as the "cathode-shield" or "anode-return" terminal. When two or more gas-rectifier tubes are operated from a common filament or heater supply, the cathode-shield or anode-return terminals of the tubes must be connected to the same side of the supply.

Tube Ratings

Rectifier-tube ratings usually include maximum permissible values for peak inverse anode voltage, peak anode current, average anode current, and fault anode current. Before these ratings are defined and their application to rectifier circuit design is discussed, it is desirable to define certain other terms frequently used in connection with rectifiers.

Forward voltage is voltage applied between the anode and cathode in the direction in which the tube is designed to pass current, *i.e.*, anode positive with respect to cathode. **Inverse voltage** is voltage applied between the anode and cathode in the direction opposite to that in which the tube is designed to pass current, *i.e.*, anode negative with respect to cathode.

Forward current is current flowing through a rectifier as a result of the application of a forward voltage. **Reverse current** is current flowing through a rectifier in the direction opposite to that of normal conduction. The flow of reverse current in a rectifier is an abnormal condition.

Peak inverse anode voltage is the highest instantaneous voltage applied between the anode and cathode during the fraction of any input cycle when the tube is normally not conducting. A maximum peak-inverse-voltage rating indicates the highest value this voltage may attain without danger of arc-back in the tube, electrolysis of glass, and reduced tube life.

Peak anode current is the highest instantaneous value reached by the forward current during the normal conduction interval. A maximum peak-anode-current rating indicates the highest current the tube can safely conduct during this interval. The peak current is determined by the duration of the conduction interval and, therefore, depends on the type of rectifier circuit in which the tube is employed.

Average anode current is the value obtained by integrating the instantaneous anode currents of a rectifier tube over a specified time and averaging the result. A maximum average-anode-current rating indicates the highest average current that should be permitted to flow through the tube in the direction of normal conduction. This current may be measured by means of a dc meter inserted in the anode circuit of the tube. When the rectifier load is constant, the average anode current may be read directly on the meter. When the rectifier load is varying, the meter readings should be averaged over the period specified in the tube data (usually 15 to 30 seconds).

Fault anode current is the highest current flowing through a rectifier tube in the forward direction under abnormal or fault conditions, *e.g.*, during a load short circuit or an arc-back in an associated tube. A maximum fault-current rating indicates the highest current that should be permitted to flow through the tube in the direction of normal conduction over a period not exceeding 0.1 second under fault conditions. Rectifier circuits should be designed to limit fault currents to values within the maximum ratings because even a single fault current of the maximum value will materially shorten or terminate the life of the tube.

Rectifier tubes of the same type can be connected in parallel to provide increased output current. When mercury-vapor or inert-gas types are operated in parallel, it is necessary to employ a resistor or a small inductance in the anode circuit of each tube to assure equal division of the total load current. Stabilizing resistors for high-voltage circuits should produce an average voltage drop of not less than 50 volts. Stabilizing inductors should have a value of approximately one-sixth henry each for a supply frequency of 50 to 60 cycles per second. Stabilizing inductors are generally preferable to resistors because they minimize power losses and help to limit the peak anode currents in the tubes. Center-tapped inductors (interphase reactors) can be used as stabilizing elements for pairs of parallel tubes. These inductors assure simultaneous starting as well as equal division of current. Vacuum rectifier tubes do not generally require the use of stabilizing devices when operated in parallel.

Corresponding filament terminals of mercury-vapor or inert-gas rectifiers operated in parallel must be connected together. Failure to observe this precaution will seriously unbalance the voltage drops in the paralleled tubes and may make it necessary to use undesirably high stabilizing impedances.

Circuits

The most suitable type of rectifier circuit for a particular application depends on the dc voltage and current requirements, the amount of rectifier "ripple" that can be tolerated in the output, and the type of ac power available.

The half-wave single-phase circuit shown in Fig. 57 delivers only one pulse of current for each cycle of the ac input voltage. Because its output contains a very high percentage of ripple, this type of circuit is used principally in low-voltage, high-current applications (*e.g.*, in power supplies for ac/dc receivers) and in low-current, high-voltage applications (*e.g.*, in ultor-voltage supplies for kinescopes and other types of cathode-ray tubes).

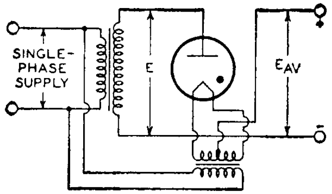

Fig. 57

A full-wave single-phase circuit using two half-wave rectifier tubes is shown in Fig. 58, and a series single-phase circuit in Fig. 59. Although the bridge circuit requires four half-wave rectifier tubes and three filament transformers (or three independent filament windings), it can deliver twice as much output voltage as the two-tube circuit for the same anode-transformer voltage, and does not require a center-tapped high-voltage winding.

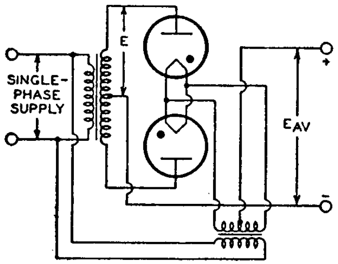

Fig. 58

Fig. 60 shows a half-wave three-phase circuit using three rectifier tubes. This circuit delivers three current pulses per cycle and its output, therefore, contains a smaller percentage of ripple than that of a full-wave single-phase circuit. The parallel three-phase circuit employing six half-wave rectifier tubes

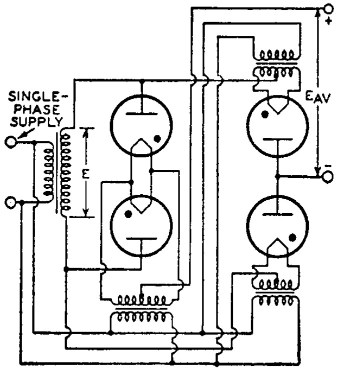

Fig. 59

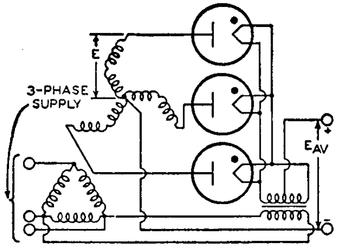

Fig. 60

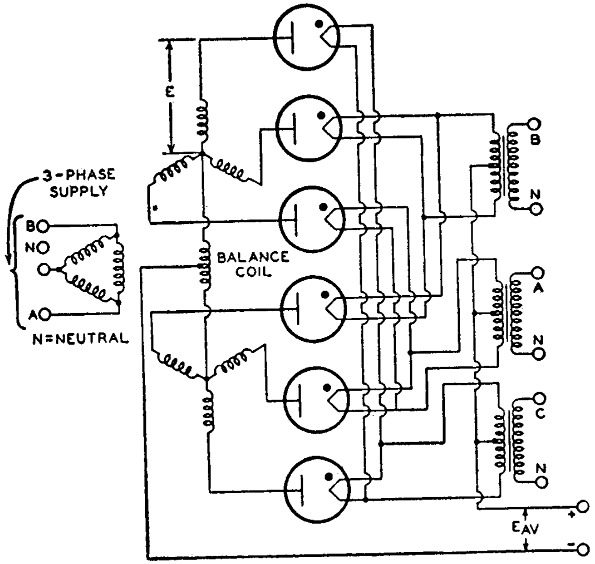

Fig. 61

shown in Fig. 61 delivers six current pulses per cycle. This circuit delivers twice as much output current as the circuit shown in Fig. 60 for the same average anode current per tube. The balance coil used in this circuit assures equal division of the load current and proper phasing in (or simultaneous starting of) the parallel branches.

In the series three-phase circuit shown in Fig. 62, two half-wave rectifier tubes are connected in series across each leg of the high-voltage transformer. This circuit delivers twice as much output voltage as the half-wave three-phase circuit shown in Fig. 60 for the same transformer voltage and peak inverse anode voltage per tube. Figs. 63 and 64 show half-wave four-phase and six-phase circuits, respectively.

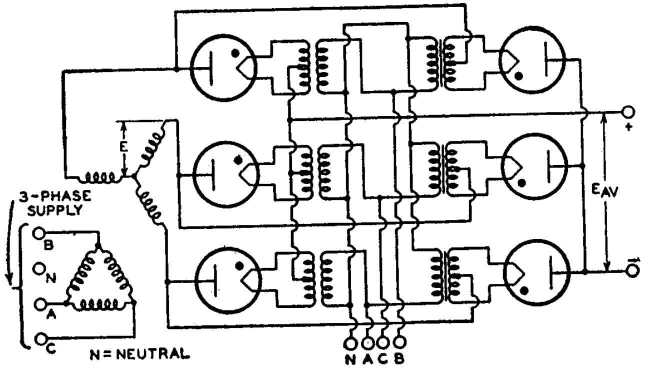

Fig. 62

Quadrature Operation

The filament current of a rectifier tube is composed of two components: the normal heating current supplied by the filament transformer, and the anode current, the greater part of which flows through the most negative portion of the filament. When the filament-supply voltage and anode voltage of a rectifier are in phase (the normal relationship when both voltages are obtained from the same ac supply line), the two components of the filament current reach peak value simultaneously during each conduction interval, and cause a localized increase in filament temperature which may seriously shorten the life of the tube.

In single-phase rectifier circuits, which have a conduction interval per tube of 180 degrees, the ratio of peak anode current to peak filament-supply current is relatively small and the effects of "in-phase" operation are usually negligible. In polyphase rectifier circuits having conduction intervals per tube of 120 degrees or less, however, the ratio of peak anode current to peak filament-supply current is relatively large, and the use of in-phase filament and anode voltages may result in extremely short tube life.

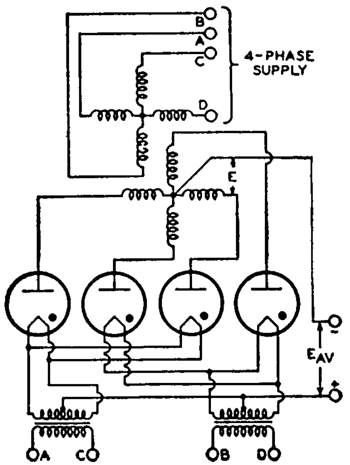

Fig. 63

This difficulty can be minimized by the use of "Quadrature Operation." In this method of operation, the peak value of the total filament current is minimized

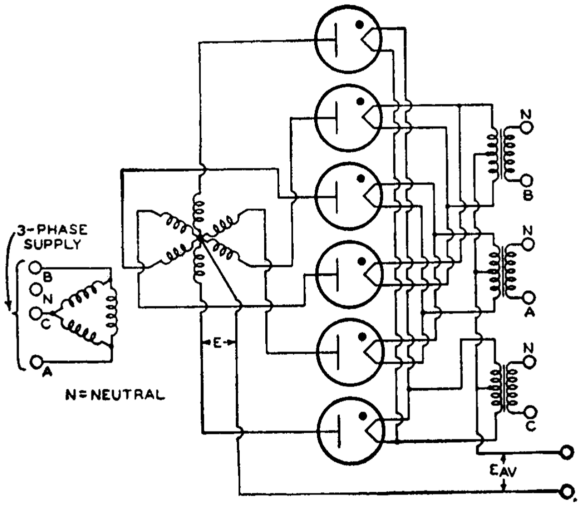

Fig. 64

by supplying the filament of each rectifier tube with voltage out of phase with its anode voltage. Although the ideal phase relationship between filament-supply voltage and anode voltage is 90 degrees (true "Quadrature"), substantial benefits are also realized at phase angles of 60 or 120 degrees, which are readily obtainable in three-phase and six-phase rectifier circuits.

Table IV gives the voltage, frequency, current, and power ratios for the basic rectifier circuits shown in Figs. 57 through 64. These ratios apply for sinusoidal ac input voltages. Current and power ratios given for inductive loads apply only when a filter choke is used between the output of the rectifier and any capacitor in the filter circuit. This table does not take into consideration voltage drops which occur in the power transformer, the rectifier tubes, or the filter components under load conditions. When a particular tube type has been selected for use in a specific rectifier circuit, the ratios given in Table IV can be used in conjunction with the tube data to determine the parameters and characteristics of the circuit.

Example of the Use of Table IV

Problem. Select the most suitable type of rectifier tube for use in a full-wave single-phase circuit which must deliver a dc voltage (E_{av}) of 2500 volts at an average dc current (I_{av}) of 500 milliamperes to the input of a filter. Also determine the rms voltage (E) that must be delivered by each half of the high-voltage transformer secondary winding.

TABLE IV

RATIO	Fig. 57	Fig. 58	Fig. 59	Fig. 60	Fig. 61*	Fig. 62	Fig. 63	Fig. 64
Voltage Ratios								
E/E_{av}	2.22	1.11	1.11	0.854	0.854	0.427	0.785	0.74
E_{bmi}/E	1.41	2.83	1.41	2.45	2.45	2.45	2.83	2.83
E_{bmi}/E_{av}	3.14	3.14	1.57	2.09	2.09	1.05	2.22	2.09
E_m/E_{av}	3.14	1.57	1.57	1.21	1.05	1.05	1.11	1.05
E_r/E_{av}	1.11	0.472	0.472	0.177	0.04	0.04	0.094	0.04
Frequency Ratio								
f_r/f	1	2	2	3	6	6	4	6
Current Ratios								
I_b/I_{av}	1	0.5	0.5	0.33	0.167	0.33	0.25	0.167
Resistive Load								
I_p/I_{av}	1.57	0.785	0.785	0.587	0.294	0.587	0.503	0.408
I_{pm}/I_{av}	3.14	1.57	1.57	1.21	0.52	1.05	1.11	1.05
I_{pm}/I_b	3.14	3.14	3.14	3.63	3.14	3.14	4.5	6.3
Inductive Load▪								
I_p/I_{av}	–	0.707	0.707	0.577	0.289	0.577	0.500	0.408
I_{pm}/I_{av}	–	1	1	1	0.5	1	1	1
Power Ratios								
Resistive Load								
P_{as}/P_{dc}	3.49	1.74	1.24	–	–	–	–	–
P_{ap}/P_{dc}	2.69	1.23	1.24	–	–	–	–	–
P_{al}/P_{dc}	2.69	1.23	1.24	–	–	–	–	–
Inductive Load▪								
P_{as}/P_{dc}	–	1.57	1.11	1.71	1.48	1.05	1.57	1.81
P_{ap}/P_{dc}	–	1.11	1.11	1.21	1.05	1.05	1.11	1.29
P_{al}/P_{dc}	–	1.11	1.11	1.21	1.05	1.05	1.11	1.05

* Bleeder current of 2-per-cent full-load current will provide exciting current for balance coil and thus avoid poor regulation at light loading.

▪ The use of a large filter-input choke is assumed.

E = transformer secondary voltage (rms)
E_{av} = average dc output voltage
E_{bmi} = peak inverse anode voltage
E_m = peak dc output voltage
E_r = major ripple voltage (rms)
I_{av} = average dc output current
I_b = average anode current
I_p = anode current (rms)
I_{pm} = peak anode current
f = supply frequency
f_r = major ripple frequency
P_{al} = line volt-amperes
P_{ap} = transformer primary volt-amperes
P_{as} = transformer secondary volt-amperes
P_{dc} = dc power ($E_{av} \times I_{av}$)

Note: *Conditions assumed include sine-wave supply, zero voltage drop in tubes, no losses in transformer and circuit, no back emf in the load circuit, and no phase-back.*

Procedure. (1) Determine the maximum peak inverse anode voltage which each rectifier tube must withstand. From Table IV, the ratio of peak inverse voltage (E_{bmi}) to dc output voltage in single-phase full-wave circuits is 3.14.

$$E_{bmi} = 3.14 \times 2500 = 7850 \text{ volts.}$$

(2) Determine the average anode current (I_b) in each tube. From Table IV, I_b in a full-wave single-phase circuit is one-half the total dc output current.

$$I_b = 0.5 \times 500 = 250 \text{ milliamperes.}$$

(3) Select a tube having suitable voltage and current ratings from the *Application Tables* Section. The 866A, which has a maximum peak-inverse anode-voltage rating of 10000 volts and a maximum average-anode-current rating of 250 milliamperes, meets the requirements. (Although the 872A, which has a maximum peak-inverse anode-voltage rating of 10000 volts and a maximum average-anode-current rating of 1.25 amperes, would also be more satisfactory, the 866A is the more economical type for this application.)

(4) Determine the rms voltage (E) which must be developed by each half of the high-voltage transformer secondary for the rectifier to deliver 2500 volts dc to the filter at the specified load current of 500 milliamperes under full-load conditions.

$$E = 1.11 \times (2500 + 15) = 2790 \text{ volts} \quad (1)$$

The second term within the parentheses represents the voltage drop in the 866A. For exact calculation of E, the full-load voltage drop in one half of the high-voltage secondary winding must also be added to the values within the parentheses.

Regulation

The voltage drops in filter-choke windings or current-limiting resistors which follow the rectifier, as well as those in the rectifier tubes and transformer windings, become a very important consideration when a rectifier filter is required to supply a varying load. Except for the drop in a gas-tube rectifier, which is substantially constant at all anode-current values up to the maximum rating for the tube, these drops vary with load current and cause a corresponding variation in output voltage. This variation is known as the **voltage regulation** of the supply, and is usually expressed as the per-cent change in output voltage for load-current variations between zero and the maximum value. For example, a power supply which has a no-load output of 1000 volts and a full-load output of 900 volts has a voltage regulation of 10 per cent. The regulation of well-designed rectifier-type power supplies is usually 10 per cent or less.

For good voltage regulation, the voltage drops in all sections of the supply should be held to a minimum. Voltage drops can be minimized by the use of transformers and chokes having generous overload ratings and low-resistance windings, mercury-vapor or inert-gas rectifier tubes or vacuum types having close anode-cathode spacing, and choke-input filters employing "swinging" chokes of the proper value. In addition, a "bleeder" resistor drawing about 10 per cent of the total output current should be permanently connected across the output of the supply. Although this resistor reduces the maximum useful output current slightly, it prevents the output voltage from rising excessively when the external load is reduced, and thus improves regulation and provides a substantial measure of protection for the filter capacitors. It also discharges the filter capacitors when the equipment is switched off and thus minimizes shock hazards.

Good regulation is desirable even when substantially constant output voltage under varying load conditions is not a primary requirement. Because good regulation minimizes variations in the voltage across the output terminals of a power supply, its effect is similar to that obtained when a very large bypass capacitance is connected across the output of the supply, *i.e.*, the amount of ac ripple in the output is substantially reduced. The internal impedance of the supply is also reduced, so that there is less danger of undesirable coupling and feedback in associated equipment when the supply is used for two or more stages.

Filters

The filter employed to minimize ripple in the output of a rectifier may be either a choke-input or a capacitor-input type. Careful consideration must be given to the selection and design of the filter if the maximum ratings of the tubes are not to be exceeded.

One of the most important considerations in the choice and design of a filter is its effect on the peak current in the rectifier circuit, and particularly on the current surge which occurs when the rectifier circuit is turned on. The sudden application of anode voltage to a rectifier causes a sudden flow or surge of current. The maximum value of this current is determined by the instantaneous amplitude of the ac input voltage and the surge impedance of the rectifier circuit. If the rectifier output is shunted by a large capacitor, the surge impedance is low and, therefore, the surge current may reach dangerously high values. On the other hand, if a relatively large choke is connected between the rectifier and the first filter capacitor, the surge impedance is high, and the surge current usually does not exceed the normal peak current through the tubes.

Choke-input filters limit surge and normal peak currents and, therefore, make it possible to obtain maximum continuous dc output current from rectifier tubes under the operating conditions most favorable for long tube life. They also provide the best regulation and are especially recommended for use with rectifiers employing mercury-vapor and inert-gas tubes or vacuum tubes having closely spaced electrodes. An additional advantage of choke-input filters is that their performance can be predicted accurately by calculation.

Capacitor-input filters provide the highest dc output voltages obtainable from given transformers and rectifier-tube combinations. They cause high current surges when the circuit is turned on, however, and have poor voltage regulation. In addition, the dc load current obtainable from a given rectifier-tube-and-transformer combination is less when a capacitor-input filter is used than when a choke-input filter is used.

When a capacitor-input filter is used, a current-limiting resistor should be connected between the rectifier tubes and the filter to limit current surges. The total resistance, R_t, required to limit the surge current to a safe value, including the effective resistance of the power-transformer secondary (or one half of the secondary of a full-wave transformer) is a function of the dc output voltage (E_{av}) and the rated peak anode current (I_{pm}) of the tube.

$$R_t = \frac{K \times E_{av}}{I_{pm}}$$

The factor K is equal to 3.14 for the circuit shown in Fig. 57, 1.57 for the circuits shown in Figs. 58 and 59, 1.21 for the circuit of Fig. 60, 1.11 for Fig. 63, and 1.05 for Figs. 62 and 64. The balance coil used in the circuit shown in Fig. 61 limits the peak anode current so that a limiting resistor is not needed. The current-limiting resistor may be short-circuited after the rectifier-filter system has been switched on to avoid a reduction in useful dc output voltage. The resistor must be employed, however, each time the circuit is switched on. Capacitor-input filters may be used in rectifier circuits employing mercury-vapor or inert-gas rectifier tubes only when a current-limiting resistor is used as described above.

Design of Choke-Input Filters

The filter-design charts shown in Figs. 65 and 66 permit quick determination of inductance and capacitance values for choke-input filters for use with full-wave single-phase rectifier circuits operating from 60-cycle supplies. For other supply frequencies, the inductance and capacitance values indicated by these charts should be multiplied by the ratio 60/f, where f is the supply frequency used.

The chart shown in Fig. 65 is used to determine component values for single-section choke-input filters or for the first section of a multisection choke-input filter. Single-section and double-section choke input filters are shown in Fig. 67. The R_L curves in Fig. 65 are used to determine the minimum value of choke inductance required. The equivalent load resistance (R_L) in ohms is equal to the dc output voltage (E_{av}) of the rectifier in volts divided by the load current (I_b)

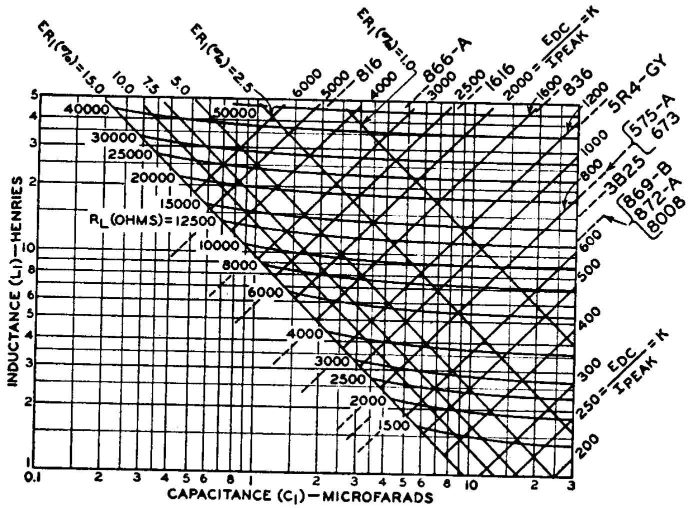

Fig. 65

in amperes. A dc output voltage equal to 90 per cent of the rms voltage (E) per rectifier-tube anode is used in this calculation (from Table IV, $E/E_{av} = 1.11$). This value does not include the voltage drops in the power transformer, filter choke, or rectifier tubes. The load current used must assure operation of each rectifier tube within its maximum average-anode-current rating. Inductance and capacitance values must always lie in the region of the chart above the applicable R_L curve.

The K curves in Fig. 65 indicate combinations of minimum filter inductance (L_1) and maximum filter capacitance (C_1) which will keep the peak anode currents (I_{pm}) of the rectifier tubes within their maximum ratings at a given rms anode voltage. The factor K is equal to the dc voltage from the rectifier tubes at the input to the filter (in volts) divided by the maximum peak-anode-current rating of the rectifier tubes (per anode, in amperes). The K curves shown in Fig. 65 represent the following relation:

$$L_1 = C_1 \times (K/1000)$$

Filter component values must always lie in the region of the chart to the left of the proper K line.

When a particular rectifier tube is used at its maximum peak-inverse-anode-voltage rating and maximum peak-anode-current rating simultaneously, the applicable K line may be determined directly by placing a ruler across the appropriate pair of dashed lines shown in Fig. 65. When a tube is used at voltages below its maximum peak-inverse anode-voltage rating, a lower value of K determined from the above equation must be used.

The R_L and K curves, therefore, indicate limiting values of inductance and capacitance which will assure that average and peak anode-current ratings of the rectifier tubes will not be exceeded. Filter-component values can now be chosen within the wedge-shaped portion of the chart outlined by the appropriate R_L and K curves on or above the E_{R_1} line for the maximum percentage of ripple which can be tolerated in the output of the filter section.

In power supplies for cw transmitters, a ripple of not more than 5 per cent is usually satisfactory. Power supplies for variable-frequency oscillators and phone transmitters generally should have ripple of 0.25 per cent or less. Power-supply ripple in high-gain speech amplifiers and receivers should not exceed

0.1 per cent to prevent hum modulation of output signals.

The most economical method of obtaining ripple voltages below 1 per cent is by the use of double-section filters of the type shown in Fig. 67(b). Values of L_2 and C_2 for the second section of such filters are determined from the chart shown in Fig. 66. After the value of E_{R_1} for the first section is determined, the values of L_2 and C_2 (as a product) for any desired ripple percentage E_{R_2} at the output of the second filter section may be determined from the appropriate E_{R_1} curve in Fig. 66. Although any values of inductance and capacitance having the indicated product $L_2 \times C_2$ will provide the desired filtering, serious instability may result if the combination selected is resonant at or near the ripple frequency. The inductance of L_2, therefore, should always be greater than

$$\frac{3 \times (C_1 + C_2)}{2 \times (C_1 \times C_2)}$$

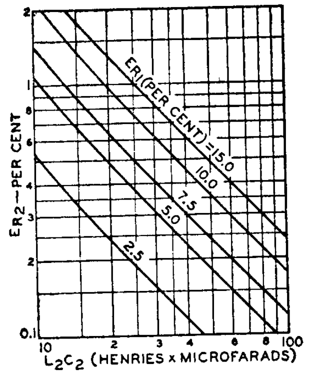

Fig. 66

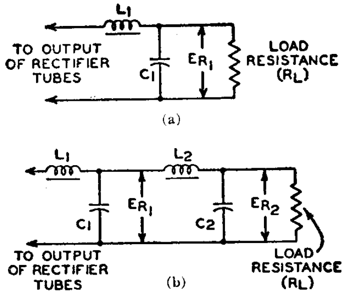

Fig. 67

For applications in which the load resistance (R_L) varies over a wide range, some means should be used to limit the resulting variation in output voltage. A bleeder resistor may be inserted across the filter output to restrict the range over which the effective load varies or an input choke having an inductance determined by the maximum load resistance attained may be used. The most economical method for minimizing output-voltage variations, however, is by the use of a "swinging" input choke.

The inductance of a well-designed swinging choke varies inversely with load current. The required minimum and maximum inductance for the choke can be determined from Fig. 65 at the intersections of the appropriate K curve with the curves for maximum and minimum R_L. It is generally most economical to select low values of swinging-choke inductance and obtain the required smoothing by the use of additional filter sections employing non-swinging ("smoothing") chokes.

Examples of Filter Design

Single-Section Filter

Problem: A full-wave rectifier operating from a 60-cycle source and employing two 872-A mercury-vapor tubes has a dc output voltage of 3200 volts. Design a single-section choke-input filter which will (*a*) limit output ripple to 5 per cent at a load current equal to the combined maximum dc load-current ratings of the tubes (2 × 1.25 = 2.5 amperes); (*b*) keep the peak anode current of each tube within its maximum peak-anode-current rating (5 amperes).

Procedure: R_L = 3200/2.5 = 1280 ohms. The value K = 3200/5 = 640. The curve for K = 640 in Fig. 62 would lie between the curves for K = 600 and K = 800 and, consequently, would be above the position where the curve for R_L = 1270 would be shown. Therefore, any combination of inductance and capacitance along the curve E_{R_1} = 5 per cent to the left of K = 640 will satisfy the requirements. A 5-henry choke and a 5-microfarad capacitor would be a suitable combination.

Two-Section Filter

Problem: A 60-cycle full-wave rectifier employing two 866-A mercury-vapor tubes delivers 2500 volts dc at full load to the input terminals of the filter. Design a two-section filter which will (*a*) limit the output ripple to 0.5 per cent at a load current equal to the combined maximum dc load-current ratings of the tubes (2 × 0.25 = 0.5 ampere); (*b*) keep the peak anode current of each tube within its maximum peak-anode-current rating (1.0 ampere). Because the voltage regulation must be good from no load to full load, the input choke shall be of the "swinging" type.

Procedure: At maximum load, R_L = 2500/0.5 = 5000 ohms. K = (2500 × 1.11)/1.0 = 2775. Because the curve in Fig. 62 for R_L = 5000 ohms would be completely below the curve for K = 2775, the maximum-load value of R_L (minimum R_L) need not be considered in the selection of constants for the first filter section. If an E_{R_1} of 10 per cent at the output of the first filter section is assumed to be satisfactory, the minimum swinging-choke inductance and the corresponding value for the first-section filter capacitor are selected along the curve E_{R_1} = 10 per cent to the left of the curve for K = 2775. Suitable values would be L_1 = 13.5 henries and C_1 = 1 microfarad. The maximum inductance of the swinging choke should be as high as practical. If a maximum value of 25 henries is chosen, the minimum-load value of R_L (maximum R_L) at which the regulating action of the choke will be effective is indicated by the point at which the 1-microfarad line intersects the line for 25 henries. This point corresponds to an R_L of 26000 ohms. Therefore, a bleeder having a resistance of not more than 26000 ohms should be used to prevent the dc output voltage from rising excessively when the load is removed. The bleeder draws a current of 2500/26000, or 0.096 ampere, and is required to dissipate 2500 × 0.096, or 240 watts. Because the maximum average current which can be supplied by two 866-A's in a full-wave circuit is 0.5 ampere, the useful load current available from the rectifier filter combination is 0.500 − 0.096 = 0.404 ampere, or 404 milliamperes.

The second filter section (L_2C_2) must reduce the ripple from the value of 10 per cent at the output of the first filter section to a value of 0.5 per cent. From Fig. 66, the value of the product L_2C_2 at the intersection of the curve for E_{R_1} = 10 per cent with the line for E_{R_2} = 0.5 per cent is 37. If C_2 is chosen to be 2 microfarads, then L_2 should have an inductance of 18.5 henries. The value chosen for L_2 should be checked to determine whether resonance effects will be present, *i.e.*, L_2 should be equal to, or greater than, $3 \times (1+2)/[2 \times (1 \times 2)] = 9/4 = 2.25$. Because the value of 18.5 henries selected for L_2 is considerably greater than 2.25, the filter design is satisfactory.