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Power Supplies with Electron Tubes

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A.Bhatia



Continuing Education and Development, Inc.

P: (877) 322-5800

info@cedengineering.com

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CHAPTER 3

POWER SUPPLIES

LEARNING OBJECTIVES

Upon completion of this chapter you will be able to:

1. Identify the various sections of a power supply.
2. State the purpose of each section of a power supply.
3. Describe the operation of the power supply from both the whole unit standpoint and from the subunit standpoint.
4. Describe the purpose of the various types of rectifier circuits used in power supplies.
5. Describe the purpose of the various types of filter circuits used in power supplies.
6. Describe the operation of the various voltage and current regulators in a power supply.
7. Trace the flow of ac and dc in a power supply, from the ac input to the dc output on a schematic diagram.
8. Identify faulty components through visual checks.
9. Identify problems within specific areas of a power supply by using a logical isolation method of troubleshooting.
10. Apply safety precautions when working with electronic power supplies.

INTRODUCTION

In the early part of this century when electronics was first introduced, most electronic equipment was powered by batteries. While the use of batteries allowed the equipment to be portable (to some degree), it also placed several limitations on how the equipment could be used. Because of their general inefficiency, batteries had to be either replaced frequently or, if they were rechargeable, kept near a battery charger. Thus, the advantage of having portable equipment was more than offset by the need to replace or recharge the batteries frequently.

Users of electronic equipment needed a power supply that was reliable, convenient, and cost effective. Since batteries failed to satisfy these requirements, the "electronic power supply" was developed.

In today's Navy, all electronic equipment, both ashore and on board ship, require some type of power supply. Therefore, this chapter is of extreme importance to you. We will discuss the sections and individual components of the power supply and their purposes within the power supply. We will also discuss troubleshooting of each section and its components.

THE BASIC POWER SUPPLY

Figure 3-1 shows the block diagram of the basic power supply. Most power supplies are made up of four basic sections: a **TRANSFORMER**, a **RECTIFIER**, a **FILTER**, and a **REGULATOR**.



Figure 3-1.—Block diagram of a basic power supply.

As you can see, the first section is the **TRANSFORMER**. The transformer serves two primary purposes: (1) to step up or step down the input line voltage to the desired level and (2) to couple this voltage to the rectifier section. The **RECTIFIER** section converts the ac signal to a pulsating dc voltage. However, you will see later in this chapter that the pulsating dc voltage is not desirable. For this reason, a **FILTER** section is used to convert the pulsating dc voltage to filtered dc voltage. The final section, the **REGULATOR**, does just what the name implies. It maintains the output of the power supply at a constant level in spite of large changes in load current or in input line voltage. Depending upon the design of the equipment, the output of the regulator will maintain a constant dc voltage within certain limits.

Now that you know what each section does, let's trace a signal through the power supply and see what changes are made to the input signal. In figure 3-2, the input signal of 120 volts ac is applied to the primary of the transformer, which has a turns ratio of 1:3. We can calculate the output by multiplying the input voltage by the ratio of turns in the secondary winding to turns in the primary winding. Therefore, the output voltage of our example is: 120 volts ac \times 3, or 360 volts ac. Depending on the type of rectifier used (full-wave or half-wave), the output from the rectifier will be a portion of the input. Figure 3-2 shows the ripple waveform associated with a full-wave rectifier. The filter section contains a network of resistors, capacitors, or inductors that controls the rise and fall time of the varying signal so that the signal remains at a more constant dc level. You will see this more clearly in the discussion of the actual filter circuits. You can see that the output of the filter is at a 180-volt dc level with an ac **RIPPLE** voltage riding on it. (Ripple voltage is a small ac voltage riding at some dc voltage level. Normally, ripple voltage is an unwanted ac voltage created by the filter section of a power supply.) This signal now goes to the regulator where it will be maintained at approximately 180 volts dc to the load.

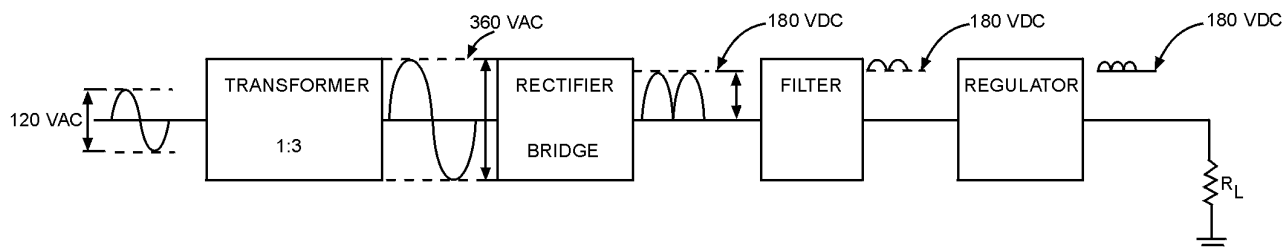


Figure 3-2.—Block diagram of a power supply.

Q1. What are the four basic sections to a power supply?

Q2. What is the purpose of the regulator?

THE TRANSFORMER

The transformer has several purposes: In addition to coupling the input ac signal to the power supply, it also isolates the electronic power supply from the external power source and either steps up or steps down the ac voltage to the desired level. Additionally, most input transformers have separate step-down windings to supply filament voltages to both power supply tubes and the tubes in the external equipment (load). Such a transformer is shown in figure 3-3. Because the input transformer is located in the power supply and is the ultimate source of power for both the load and the power supply, it is called the **POWER TRANSFORMER**. Notice that the transformer has the ability to deliver both 6.3 and 5 volts ac filament voltages to the electron tubes. The High-voltage winding is a 1:3 step-up winding and delivers 360 volts ac to the rectifier. This transformer also has what is called a *center tap*. This center tap provides the capability of developing two high-voltage outputs from one transformer.

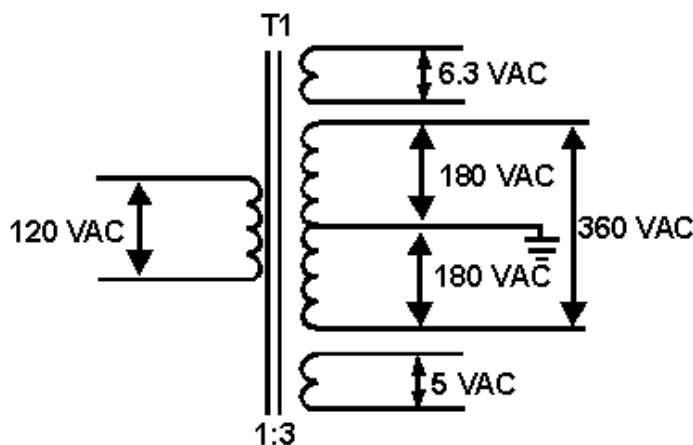


Figure 3-3.—Typical power transformer.

- Q3. What are the purposes of the transformer in a power supply?
- Q4. For what are the low voltage windings in a transformer used?
- Q5. For what is the center tap on a transformer used?

RECTIFIERS

From previous discussions, you know that rectification is the changing of an ac voltage to a pulsating dc voltage. Now let's discuss the process of rectification.

Since a diode vacuum tube will pass current in only one direction, it is ideally suited for converting alternating current to direct current. If an ac voltage is applied to a diode, the diode will conduct **ONLY DURING THE POSITIVE ALTERNATION OF VOLTAGE** when the plate of the diode is made positive with respect to the cathode.

Figure 3-4 shows a diode connected across the 120-volt ac line. During the positive alternation of the source voltage, the sine wave applied to the tube makes the plate positive with respect to the cathode. At this time the diode conducts and plate current flows from the negative supply lead, through the milliammeter, through the tube, and to the positive supply lead. This is indicated by the shaded area of the output waveform. This current exists during the entire period of time that the plate is positive with respect to the cathode (for the first 180 degrees of the input sine wave).

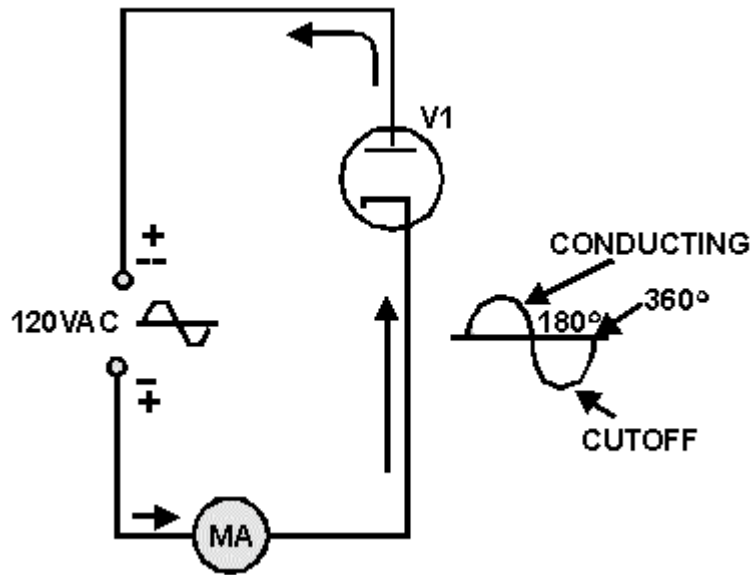


Figure 3-4.—Simple diode rectifier.

During the negative alternation of plate voltage (dotted polarity signs), the plate is driven negative and the tube cannot conduct. When conditions prevent the tube from conducting, the tube is said to be in **CUTOFF**. This is indicated by the dotted waveform. The tube will be in cutoff and no current will flow for the entire negative alternation.

For each 360-degree cycle of input voltage, the tube conducts for 180 degrees and is in cutoff for 180 degrees. The circuit current therefore has the appearance of a series of positive pulses, as shown by the shaded areas. Notice that although the current is in the form of pulses, the current always flows through the circuit in **THE SAME DIRECTION**. Current that flows in pulses in the same direction is called **PULSATING DC**. The diode has thus **RECTIFIED** the input voltage. Although the principle of rectification applies to all rectifier circuits, some rectifiers are more efficient than others. For this reason, we will explain the three rectifier circuits most commonly used in electronics today—the half-wave, full-wave, and bridge.

A Practical Half-Wave Rectifier

Figure 3-5 is a diagram of a complete half-wave rectifier circuit. For the diode to be used as a rectifier, it must be connected in series with a load device (R_L for this circuit), through which the direct current flows. Because Navy electronic equipment requires various input voltages, it is necessary to have a rectified voltage that is greater (or smaller in some cases) than the source voltage. The rectifier plate circuit is supplied power from a step-up (or step-down) transformer. Notice that the transformer has the two secondary windings mentioned earlier. The lower winding supplies high voltage to the plate and cathode of the diode, and the upper winding supplies a low ac voltage to the filaments of the diode. Notice also that the cathode of the diode is connected to the secondary winding of the transformer through the load resistor (R_L). Any current flowing through the tube also flows through the load resistor, causing a voltage to be developed across it. The magnitude of the voltage developed across the load resistor is directly proportional to the amount of current flowing through it (Ohm's law: $E = IR$).

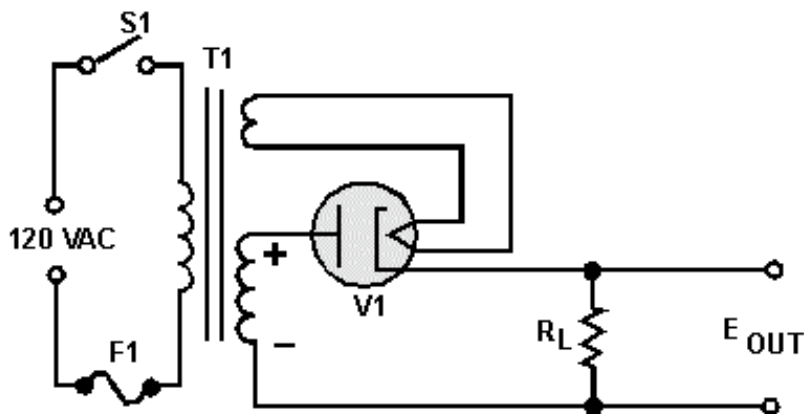


Figure 3-5.—Half-wave rectifier circuit.

You will better understand the operation of the half-wave rectifier circuit if it is redrawn in the form of a simplified series circuit. As you can see in figure 3-6, the diode (V1) and load resistor (R_L) are in series with the secondary winding of the transformer. During the positive alternation of the input, as the voltage in the secondary winding increases, the current through diode (V1) and load resistor (R_L) increases. Since the diode tube and the load resistor form a series circuit, the same current flows through both the tube and the resistor. This current produces a voltage drop across the tube and the load resistor, which have polarities as shown. Since the plate resistance of the tube is only about 500 ohms and the resistance of the load resistor is 10,000 ohms, approximately 95 percent of the applied 425 volts is dropped across the load resistor ($425 \times .95 = 404$ V) and 5 percent ($425 \times .05 = 21$ V) across the tube.

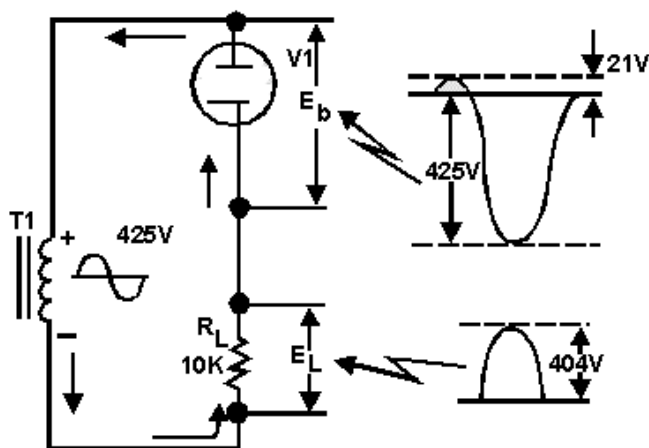


Figure 3-6.—Simplified half-wave rectifier circuit and waveforms.

During the negative half of the alternation of input voltage, the tube cannot conduct and no current flows in the circuit. Since there is no current flow through R_L , the load voltage remains at zero volts throughout the negative alternation. During this time the entire negative alternation is felt across the tube. The reason for this is derived from Kirchhoff's law, which states:

$$E_L + E_b = E_a$$

The sum of the load voltage and diode voltage equals the applied voltage.

Since a half-wave rectifier conducts once for each full cycle of input voltage, the frequency of the pulses is the same as the frequency of the input sine wave. The output pulse frequency is called **RIPPLE FREQUENCY**. If the rectifier circuit is supplied power from a 60-hertz ac line voltage, 60 pulses of load current will occur each second. Therefore, **THE RIPPLE FREQUENCY OF A HALF-WAVE RECTIFIER IS THE SAME AS THE LINE FREQUENCY**.

If a series of current pulses like those obtained from a half-wave rectifier is applied to a load resistance, an average amount of power will be dissipated over a given period of time. This average dc power is determined by the amplitude of the pulses and the time delay between pulses. The higher the peak amplitude of the pulses or the less the time between pulses, the greater the average dc power supplied to the load. To determine average dc voltage (E_{avg}), it is necessary to know the average value of the pulses and the peak value of load voltage. This is illustrated in figure 3-7.

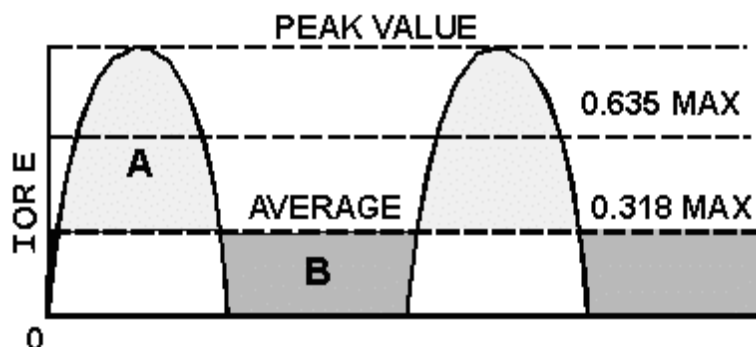


Figure 3-7.—Peak and average values for a half-wave rectifier.

Since current and voltage waveforms in a half-wave rectifier circuit are essentially half sine waves, we can develop a conversion factor. The formula for average value was discussed earlier in *NEETS*, module 2. By now you should know that the average value for a full sine wave is .637 times its peak or maximum value. Therefore, if you want the average value of a half-wave rectifier output, you should multiply half the value of .637 (.318) times the peak or maximum voltage, as expressed in the following equation:

$$E_{avg} \text{ (the average load voltage)} = .318 \times E_{max}$$

Where:

E_{max} = The peak value of the load voltage pulse

In most applications the drop across the rectifier tube is small compared to the load voltage, so we can assume E_{max} in our equation to be the same as the peak value of the input sine wave.

Since the load current has the same wave shape as the load voltage, we can modify the equation so that it applies to the load current. Thus,

$$I_{avg} \text{ (the average load current)} = .318 \times I_{max}$$

Where:

I_{max} = The peak load current

If a line is drawn through the rectified waveform at a point that is 0.318 of the distance from zero to maximum, the waveform will be divided so that area A is equal to area B (fig. 3-7). Therefore, current or

voltage pulses with a value of .318 of the peak value have the same effect on the load as a steady voltage or current.

The half-wave rectifier uses the transformer during only one-half of the cycle. Therefore, for any given size transformer, less power is developed than if the transformer were used on both halves of the cycle. In other words, to obtain large amounts of power, the half-wave transformer must be relatively large in comparison to what it would have to be if both halves of the cycle were used. This disadvantage limits the use of the half-wave rectifier to applications that require a very small current drain. The half-wave rectifier is widely used for commercial ac and dc radio receivers and other applications where inexpensive voltage supplies will suffice. As you can see from your study on half-wave rectifiers, this type of circuit placed many limitations on electronic equipment. For this reason another type of rectifier circuit had to be developed. One of the factors that had to be considered was how to use the full output from the transformer to obtain the highest average voltage and current. Thus, the **FULL-WAVE** rectifier was developed.

Q6. Does a rectifier tube conduct on the positive or negative alternation of the input signal?

Q7. What term is used to describe the period when the diode is not conducting?

Q8. Current that flows in pulses in the same direction is called ____.

Q9. For a diode to act as a rectifier, should it be connected in series or parallel with the load?

Q10. What is the Ripple frequency of a half-wave rectifier if the input frequency is 60 Hz?

Q11. What is the equation for determining average voltage in a half-wave rectifier?

The Conventional Full-Wave Rectifier

A full-wave rectifier is a device that has two or more diodes arranged so the load current flows in the same direction during each half cycle of the ac supply.

A schematic diagram of a simple full-wave rectifier is shown in figure 3-8. The transformer supplies the source voltage for two rectifier tubes (V1 and V2). This power transformer has a **CENTER-TAPPED** high-voltage secondary winding that is divided into two equal parts (W1 and W2). W1 provides the source voltage for V1 and the other winding (W2) provides the source voltage for V2. The connections to the diodes are arranged so that the diodes conduct on alternate half cycles.

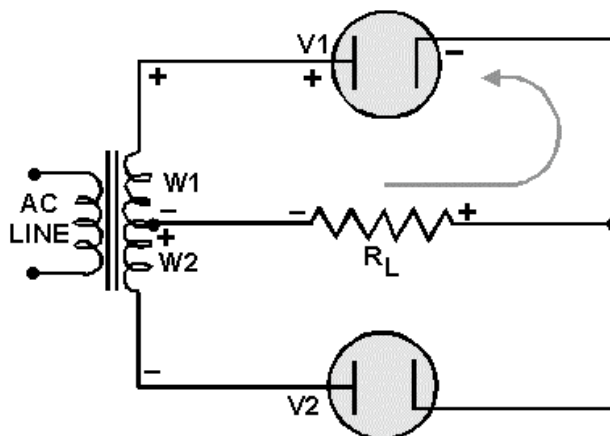


Figure 3-8.—Simple full-wave rectifier (first alternation).

During one alternation of the secondary voltage, the polarities will be as shown in figure 3-8. The source for diode V2 is the voltage induced into the lower half of the transformer secondary winding (W2). At the specific instant of time shown in the figure, the plate voltage on V2 is negative, and V2 cannot conduct.

Throughout the period of time during which the plate of V2 is negative, the plate of V1 is positive. This is illustrated by the polarity signs across W1, which indicate the source for V1. Since the plate of V1 is positive, it conducts, causing current to flow through the load resistor in the direction shown by the arrow.

Figure 3-9 shows the next half cycle of secondary voltage. As you can see, the polarities across W1 and W2 are reversed. During this alternation the plate of V1 is driven negative and V1 cannot conduct.

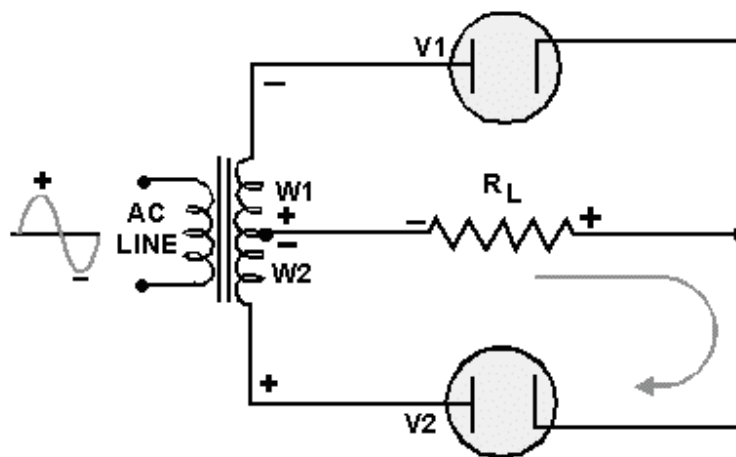


Figure 3-9.—Simple full-wave rectifier (second alternation).

For the period of time that V1 is negative, the plate of V2 is positive, permitting V2 to conduct. Notice that the plate current of V2 passes through the load resistor in the same direction as did the plate current of V1. In this circuit arrangement, a pulse of load current flows during each alternation of the input cycle. Since both alternations of the input voltage cycle are used, the circuit is called a **FULL-WAVE RECTIFIER**.

Now that you have a basic understanding of how a full-wave rectifier works, let's cover in detail a practical full-wave rectifier and its waveforms.

A Practical Full-Wave Rectifier

A practical full-wave rectifier circuit is shown in figure 3-10. It uses two diodes (V1 and V2) and a center-tapped transformer (T1). When the center tap is grounded, the voltages at the opposite ends of the secondary windings are 180 degrees out of phase with each other. Thus, when the voltage at point A is positive with respect to ground, the voltage at point B is negative with respect to ground. Let's examine the operation of the circuit during one complete cycle.

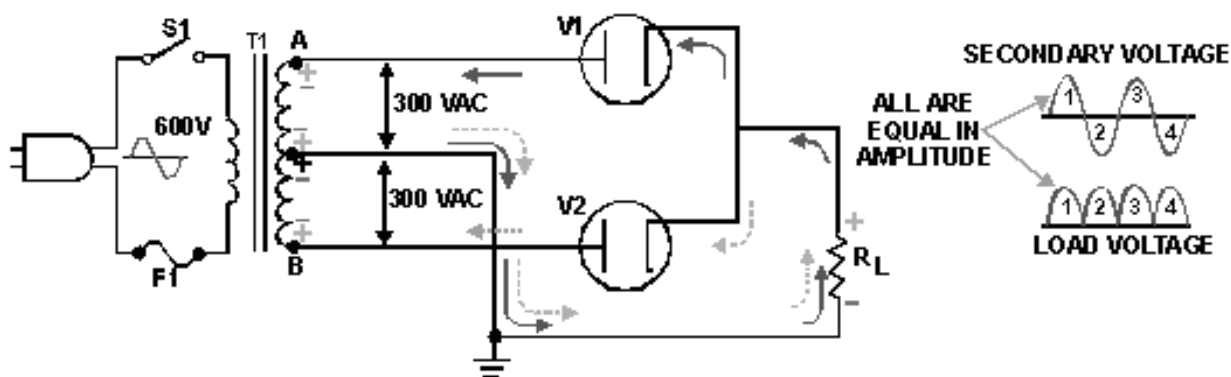


Figure 3-10.—Complete full-wave rectifier.

During the first half-cycle (as indicated by solid arrows) the plate of V1 is positive with respect to ground and the plate of V2 is negative. As shown, current flows from ground (center tap), up through the load resistor (R_L), through diode V1 to point A. In the transformer, current flows from point A, through the upper winding and back to ground (center tap). When V1 conducts, it acts like a closed switch so that the positive half-cycle is felt across the load.

During the second half-cycle (broken lines), the polarity of the applied voltage has reversed. Now the plate of V2 is positive with respect to ground and the plate of V1 is negative. Only V2 can conduct. Current now flows, as shown, from ground (center tap), up through the load resistor (R_L), through diode V2 to point B of T1. In the transformer, current flows from point B up through the lower windings and back to ground (center tap). Notice that the current flows across the load resistor (R_L) in the **SAME DIRECTION** for both halves of the input cycles.

The output waveform from the full-wave rectifier consists of two pulses of current (or voltage) for each cycle of input voltage. The ripple frequency at the output of the full-wave rectifier is therefore **TWICE THE LINE FREQUENCY**.

The higher ripple frequency at the output of a full-wave rectifier has a distinct advantage: Because of the higher pulse frequency, the output is closely approximate to pure dc. This higher frequency also makes filtering much easier than the output of the half-wave rectifier.

In terms of peak value, the average value of current and voltage at the output of the full-wave rectifier is twice as great as the average current or voltage at the output of the half-wave rectifier. The relationship between peak and average values is illustrated in figure 3-11.

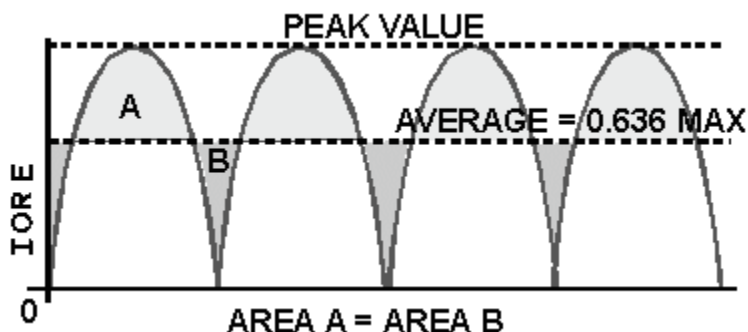


Figure 3-11.—Peak and average values for a full-wave rectifier.

Since the output waveform is essentially a sine wave with both alternations at the same polarity, the average current or voltage is 63.7 percent (or .637) of the peak current or voltage.

As an equation:

$$E_{\text{avg}} \text{ (the average load voltage)} = .637 \times E_{\text{max}}$$

Where

E_{max} = The peak value of the load voltage pulse

And

$$I_{\text{avg}} \text{ (the average load current)} = .637 \times I_{\text{max}}$$

Where:

I_{max} = The peak value of the load current pulse

Example: The total voltage across the high-voltage secondary of a transformer used to supply a full-wave rectifier is 600 volts. Find the average load voltage. (Ignore the drop across the rectifier tube.)

Solution: Since the total secondary voltage is 600 volts, each diode is supplied one-half of this value, or 300 volts. As the secondary voltage is an rms value, the peak load voltage is:

$$E_{\text{max}} = 1.414 \times E_s$$

$$E_{\text{max}} = 1.414 \times 300$$

$$E_{\text{max}} = 424 \text{ volts}$$

The average load voltage is:

$$E_{\text{avg}} = .637 \times E_{\text{max}}$$

$$E_{\text{avg}} = .637 \times 424$$

$$E_{\text{avg}} = 270 \text{ volts}$$

NOTE: If you have problems with this equation, review *NEETS*, module 2, pertaining to this area.

As you may recall from your past studies in electricity, there are advantages and disadvantages in every circuit. The full-wave rectifier is no exception. In studying the full-wave rectifier, you have found that when the output frequency is doubled, the average voltage is also doubled, and the resulting signal is much easier to filter because of the high-ripple frequency. The only disadvantage is that the peak voltage in a full-wave rectifier is only half the peak voltage in a half-wave rectifier. This is because the secondary of the power transformer in a full-wave rectifier is center tapped; therefore only half the source voltage goes to each diode.

Fortunately, there is a rectifier that produces the same peak voltage as a half-wave rectifier and the same ripple frequency as a full-wave rectifier. This circuit, called the **BRIDGE RECTIFIER**, will be the chapter of our next discussion.

Q12. What is the ripple frequency of a full-wave rectifier with an input frequency of 60 Hz?

Q13. What is the average voltage (E_{avg}) output of a full-wave rectifier that has an output of 100 volts peak?

The Bridge Rectifier

When four diodes are connected as shown in figure 3-12, the circuit is called a **BRIDGE RECTIFIER**. The input to the circuit is applied to the diagonally opposite corners of the network, and the output is taken from the remaining two corners.

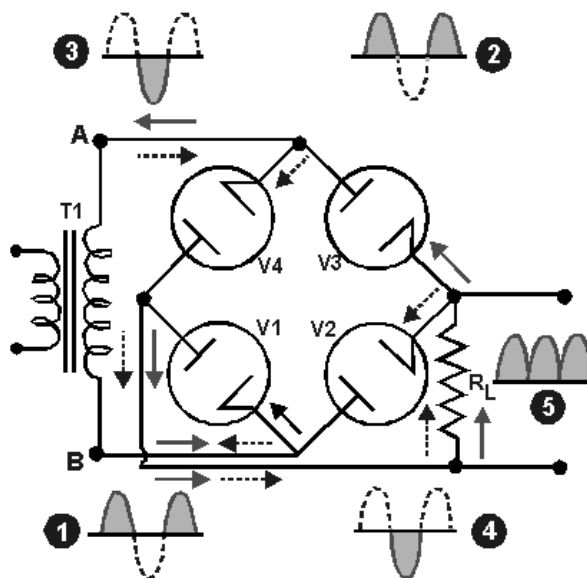


Figure 3-12.—Bridge rectifier circuit.

During one half-cycle of the applied voltage, point A becomes positive with respect to point B by the amount of voltage induced into the secondary of the transformer. During this time, the voltage between points A and B may be considered to be impressed across V1, the load resistor R_L , and V3, in series. The voltage applied across these tubes makes their plates more positive than their cathodes, and current flows from point B through tube V1 in an upward direction across the load resistor, through tube V3, to point A. This path is indicated by the solid arrows. The waveform is shown as numbers (1) and (2).

One half-cycle later, the polarity across the secondary reverses, making the plates of V1 and V3 negative with respect to their cathodes. At the same time, the plates of V2 and V4 become positive with respect to their cathodes, and current flows in the direction indicated by the dashed arrows. The current through R_L is always in the same direction. This current, in flowing through R_L , develops a voltage corresponding to that shown in waveform (5) of the figure. The bridge rectifier is a full-wave rectifier since current flows through the load during both half cycles of the applied alternating voltage.

One advantage of a bridge rectifier over a conventional full-wave rectifier is that with a given transformer, the bridge rectifier produces a voltage output that is nearly twice that of the conventional full-wave circuit. We can show this by assigning values to some of the components as shown in figure 3-13, views (A) and (B). Assume that the same transformer is used in both circuits. The peak voltage developed between points X and Y is 1,000 volts in both circuits. In the conventional full-wave circuit,

view (A), the peak voltage from the center tap to either X or Y is 500 volts. Since only one diode can conduct at any instant, the maximum voltage that can be rectified at any instant is 500 volts. Therefore, the maximum voltage that appears across the load resistor is nearly, but never exceeds, 500 volts (because of the small voltage drop across the tube). In the bridge rectifier of view (B), the maximum voltage that can be rectified is the full secondary voltage, 1,000 volts. Therefore, the peak output voltage across the load resistor is nearly 1,000 volts. Thus, with both circuits using the same transformer, the full-wave bridge circuit produces a higher output voltage than the conventional full-wave rectifier.

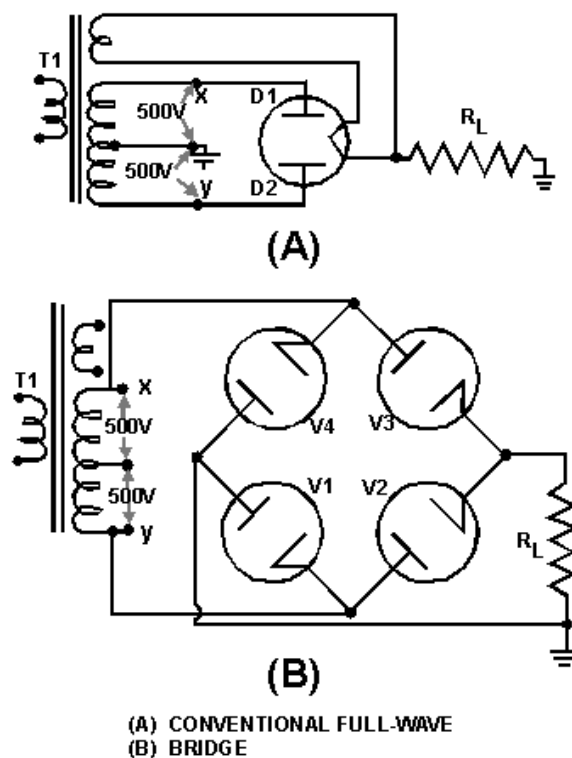


Figure 3-13.—Comparison of conventional full-wave and bridge rectifiers: A. Conventional full-wave circuit

A second advantage of the bridge rectifier is the low ratio of peak inverse voltage to average output voltage. For this reason bridge rectifiers that use vacuum tubes are widely used in high-voltage power supply applications.

If directly heated diodes are used in a bridge rectifier, three separate filament transformers are required. This is due to the different potentials existing at the filaments of the diodes. The filaments of V2 and V3 in figure 3-14 are at the same potential, but the filament of V1 is at a different potential from either V2 or V4. The three filament transformers must be well insulated from each other, and from ground, because of the high potentials to which they are subjected. The use of indirectly heated diodes would solve the filament transformer problem, but the high potential difference between cathode and heater would be likely to result in arcing.

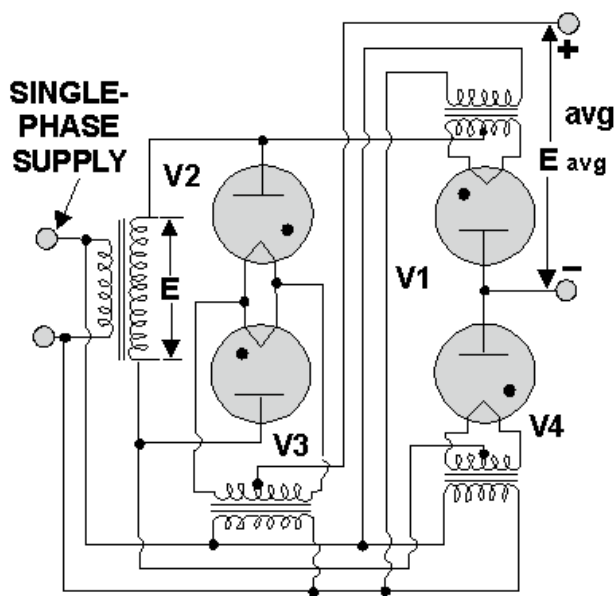


Figure 3-14.—Bridge rectifier with filament transformers.

Q14. What is the main disadvantage of the conventional full-wave rectifier?

Q15. What main advantage does a bridge rectifier have over a conventional full-wave rectifier?

FILTERS

While the output of a rectifier is a pulsating dc, most electronic circuits require a substantially pure dc for proper operation. This type of output may be provided by placing single or multisection filter circuits between the output of the rectifier and the load.

There are four basic types of filter circuits:

- Simple capacitor filter
- LC choke-input filter
- LC capacitor-input filter (pi-type)
- RC capacitor-input filter (pi-type)

We will cover the function of each of these filters in detail later in this chapter.

Filtering is done by using various combinations of capacitors, inductors, and resistors. Inductors are used as series impedances to oppose the change in flow of alternating (pulsating dc) current. Capacitors are used as shunt elements to bypass the alternating components of the signal around the load (to ground). Resistors are used in place of inductors in low current applications.

Let's briefly review the properties of a capacitor. First, a capacitor opposes any change in voltage. The opposition to a change in voltage is called capacitive reactance (X_C) and is measured in ohms. The capacitive reactance is determined by the frequency (f) of the applied voltage and capacitance (C) of the capacitor.

$$X_C = \frac{1}{2\pi fC} \text{ or } \frac{.159}{fC}$$

From the formula, you can see that if frequency or capacitance is increased, the X_C will decrease. Since filter capacitors are placed in parallel with the load, a low X_C will provide better filtering than a high X_C . This is done by providing a better shunting effect of the ac around the load, as shown in figure 3-15.

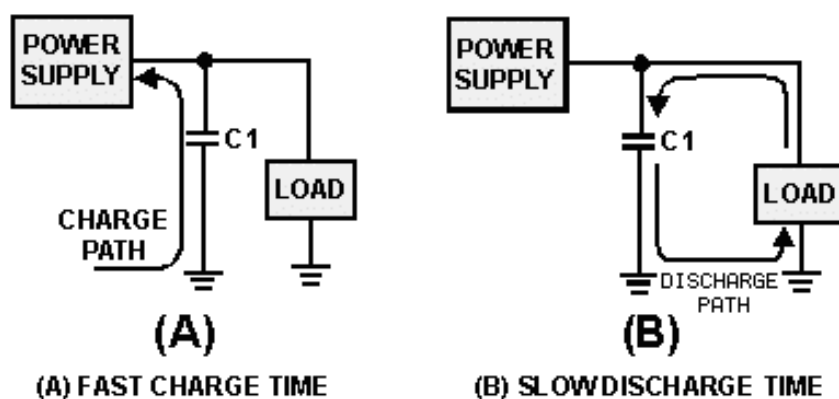


Figure 3-15.—Capacitor filter. Fast charge time

To obtain a steady dc output, the capacitor must charge almost instantaneously to the value of applied voltage. Once charged, the capacitor must retain the charge as long as possible. The capacitor must have a short charge time constant (view A) and a long discharge time constant (view B). This can be done by keeping the internal resistance of the power supply as small as possible (fast charge time) and the resistance of the load as large as possible (slow discharge time).

From your earlier studies in basic electricity, you may remember that one capacitor time constant is defined as the time it takes a capacitor to charge to 63.2 percent of the applied voltage or to discharge to 36.8 percent of its total charge. This can be expressed by the following equation:

$$t = R \times C$$

Where: R represents the resistance of the charge or discharge path

And: C represents the capacitance of the capacitor

You should also recall that a capacitor is considered fully charged after five RC time constants. Referring to figure 3-16, you should see that to obtain a steady dc output voltage, the capacitor should charge rapidly and discharge as slowly as possible.

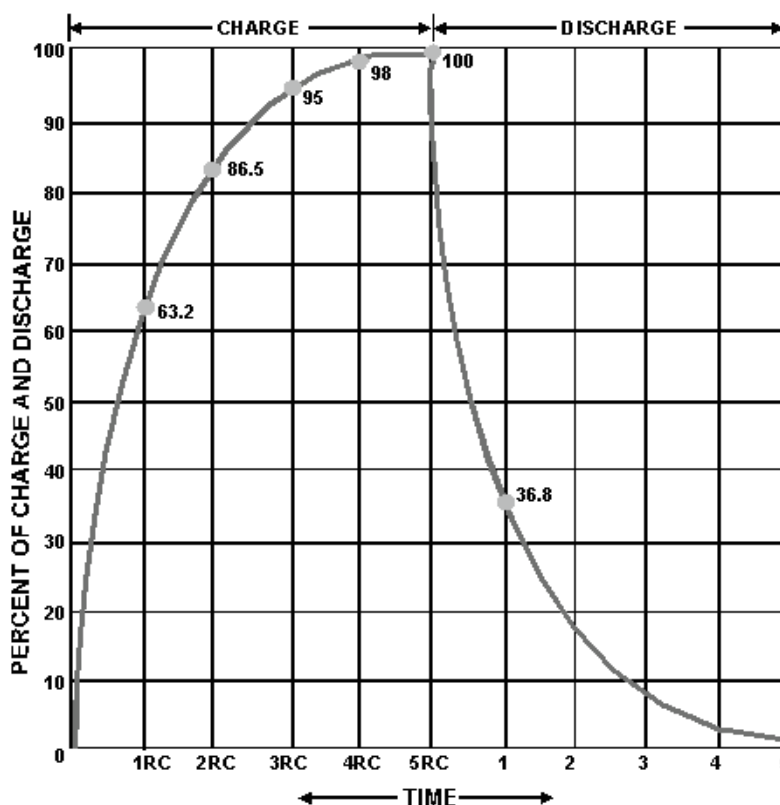


Figure 3-16.—RC time constant chart.

In filter circuits the capacitor is the common element to both the charge and discharge paths. Therefore, to obtain the longest possible discharge time, you want the capacitor to be as large as possible. Another way to look at this is: The capacitor acts as a short circuit around the load (as far as the ac component is concerned), and since

$$X_C = \frac{1}{2\pi fC}$$

the larger the value of the capacitor (C), the smaller the opposition (X_C) or resistance to ac.

Now let's look at inductors and their application in filter circuits. Remember, **AN INDUCTOR OPPOSES ANY CHANGE IN CURRENT**. In case you have forgotten, a change in current through an inductor produces a changing electromagnetic field. The changing field, in turn, cuts the windings of the wire in the inductor and thereby produces a counterelectromotive force (cemf). It is the cemf that opposes the change in circuit current. Opposition to a change in current at a given frequency is called inductive reactance (X_L) and is measured in ohms. The inductive reactance (X_L) of an inductor is determined by the applied frequency and the inductance of the inductor. Mathematically,

$$X_L = 2\pi fL$$

From the preceding formula, you know that if either frequency or inductance is increased, the X_L will increase. Since inductors are placed in series with the load (fig. 3-17), the larger the X_L , the larger the ac voltage developed across the inductor and the smaller the ac voltage developed across the load.

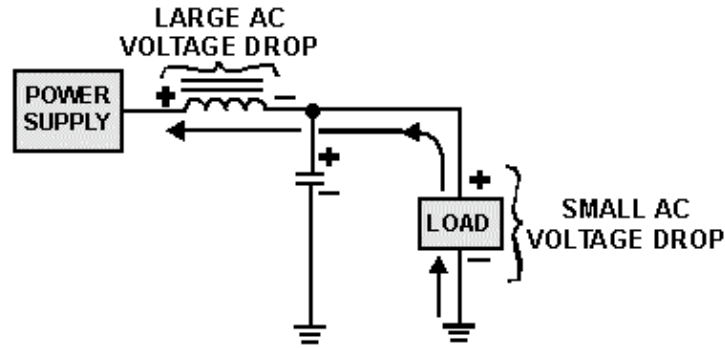


Figure 3-17.—Voltage drops in an inductive filter.

Now back to our circuit. As illustrated in figure 3-18, when the current starts to flow through the coil, an expanding magnetic field builds up around the inductor. This magnetic field around the coil develops the cemf that opposes the change in current. When the rectifier current decreases as shown in figure 3-19, the magnetic field collapses and again cuts the turns (windings) of wire, thus inducing current into the coil. This additional current adds to the rectifier current and attempts to keep it at its original level.

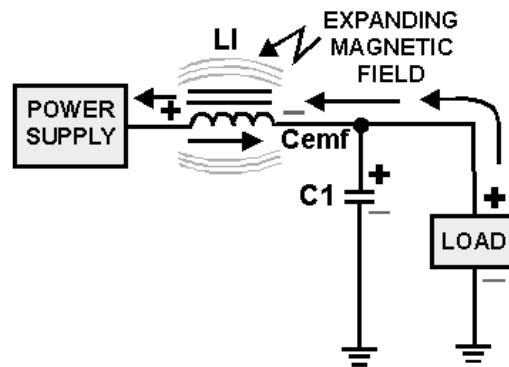


Figure 3-18.—Inductive filter (expanding field).

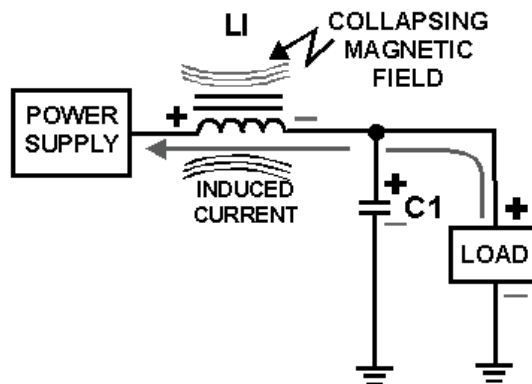


Figure 3-19.—Inductive filter (collapsing field).

Now that you have learned how the components in the filter circuits react to current flow from the rectifier, let's discuss the different types of filter circuits in use today.

Q16. If you increase the value of the capacitor will the X_C increase or decrease? Why?

The Capacitor Filter

The simple capacitor filter is the most basic type of power supply filter. The use of this filter is very limited. It is sometimes used on extremely high-voltage, low-current power supplies for cathode-ray and similar electron tubes that require very little load current from the supply. This filter is also used in circuits where the power-supply ripple frequency is not critical and can be relatively high.

The simple capacitor filter shown in figure 3-20 consists of a single-filter element. This capacitor (C1) is connected across the output of the rectifier in parallel with the load. The RC charge time of the filter capacitor (C1) must be short and the RC discharge time must be long to eliminate ripple action when using this filter. In other words, the capacitor must charge up fast with preferably no discharge at all. Better filtering also results when the frequency is high; therefore, the full-wave rectifier output is easier to filter than the half-wave rectifier because of its higher frequency.

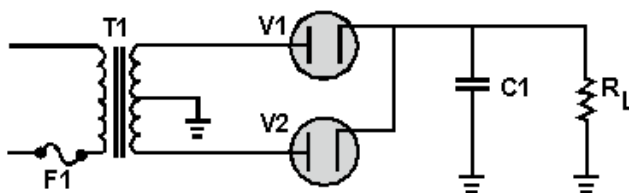


Figure 3-20.—Full-wave rectifier with a capacitor filter.

To understand better the effect that filtering has on E_{avg} , compare the rectifier circuits without filters in figure 3-21 to those with filters in figure 3-22. The output waveforms in figure 3-21 represent the unfiltered outputs of the half-wave and full-wave rectifier circuits. Current pulses flow through the load resistance (R_L) each time a diode conducts. The dashed line indicates the average value of output voltage. For the half-wave rectifier, E_{avg} is less than half the peak output voltage (or approximately 0.318 of the peak output voltage). For the full-wave rectifier, E_{avg} is approximately 0.637. This value is still much less than the applied voltage. With no capacitor connected across the output of the rectifier circuit, the waveform has a large pulsating component (ripple) compared with the average or dc component. Now refer to figure 3-22. When a capacitor is connected across the output (in parallel with R_L), the average value of output voltage (E_{avg}) is increased due to the filtering action of capacitor C1.

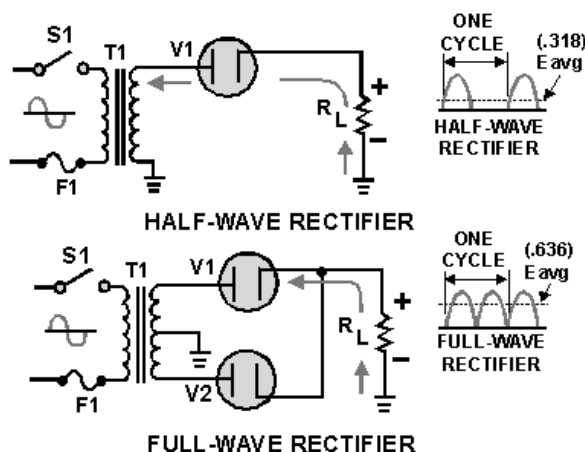


Figure 3-21.—Half-wave/full-wave rectifiers (without filters).

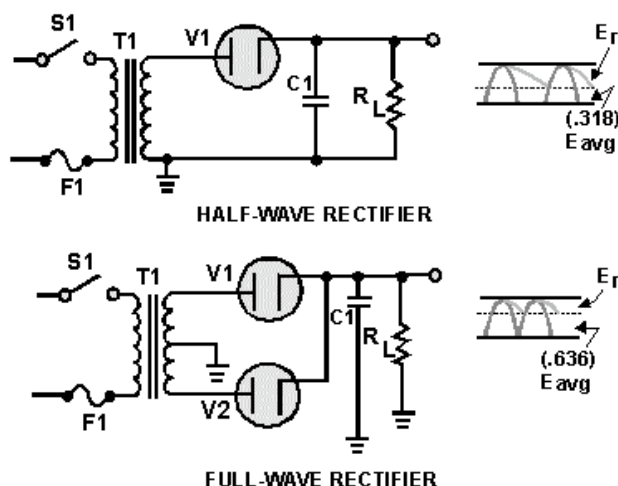


Figure 3-22.—Half-wave/full-wave rectifiers (with capacitor filters).

The value of the capacitor is fairly large (several microfarads); it thus presents a relatively low reactance to the pulsating current and stores a substantial charge. The rate of charge for the capacitor is limited only by the relatively low resistance of the conducting diode. The RC charge time of the circuit is, therefore, relatively short. As a result, when the pulsating voltage is first applied to the circuit, the capacitor charges rapidly and almost reaches the peak value of the rectified voltage within the first few cycles. The capacitor attempts to charge to the peak value of the rectified voltage anytime a diode is conducting, and tends to retain its charge when the rectifier output falls to zero. (The capacitor cannot discharge immediately). The capacitor slowly discharges through the load resistance (R_L) during the time the rectifier is nonconducting.

The rate of discharge of the capacitor is determined by the value of capacitance and the value of the load resistance. If the capacitance and load resistance values are large, the RC discharge time for the circuit is relatively long.

From the waveforms shown in figure 3-22, you should see that the addition of C_1 to the circuit results in an increase in the average value of output voltage (E_{avg}) and a reduction in the amplitude of the ripple component (E_r) present across the load resistance.

Now, let's consider a complete cycle of operation using a half-wave rectifier, a capacitive filter (C_1), and a load resistor (R_L).

As shown in figure 3-23, C_1 is assumed to be large enough to ensure a small reactance to the pulsating rectified current. The resistance of R_L is assumed to be much greater than the reactance of C_1 at the input frequency.

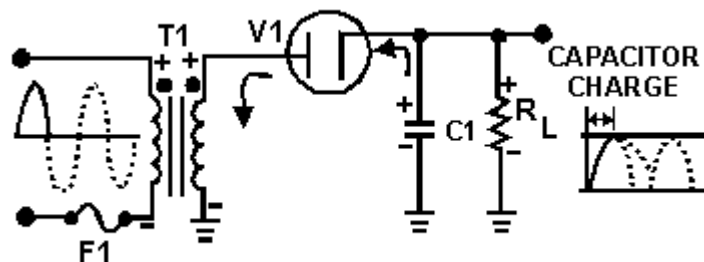


Figure 3-23.—Half-wave rectifier capacitor filter (positive input cycle).

When the circuit is energized, the diode conducts on the positive half cycle and current flows through the circuit allowing C1 to charge. C1 will charge to approximately the peak value of the input voltage. The charge is less than the peak value because of the voltage drop across diode V1. The charge on C1 is indicated by the heavy, solid line on the waveform.

As illustrated in figure 3-24, the diode (V1) cannot conduct on the negative half cycle because the plate of V1 is negative in respect to the cathode. During this interval, C1 discharges through load resistance R_L . The discharge of C1 produces the downward slope indicated by the solid line on the waveform in the figure.

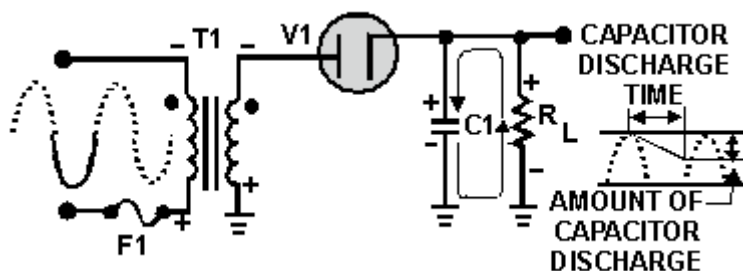


Figure 3-24.—Half-wave rectifier capacitor filter (negative input cycle).

During the discharge period, in contrast to the abrupt fall of the applied ac voltage from peak value to zero, the voltage across C1 (and thus across R_L) gradually decreases until the time of the next half cycle of rectifier operation. Keep in mind that for good filtering, the filter capacitor should charge as fast as possible and discharge as little as possible.

Since practical values of C1 and R_L ensure a more or less gradual decrease of the discharge voltage, a substantial charge remains on the capacitor at the time of the next half cycle of operation. As a result, no current can flow through the diode until the rising ac input voltage at the plate of the diode exceeds the voltage of the charge remaining on C1. The charge on C1 is the cathode potential of the diode. When the potential on the plate exceeds the potential on the cathode (the charge on C1), the diode again conducts, and C1 commences to charge to approximately the peak value of the applied voltage.

After the capacitor has charged to its peak value, it begins to discharge. Since the fall of the ac input voltage on the plate is considerably more rapid than the decrease on the capacitor voltage, the cathode quickly becomes more positive than the plate, and the diode ceases to conduct.

The operation of the simple capacitor filter using a full-wave rectifier is basically the same as the operation we discussed for the half-wave rectifier. Notice in figure 3-25 that because one of the diodes is always conducting on either alternation, the filter capacitor charges and discharges during each half cycle. (Note that each diode conducts only for that portion of time when the peak secondary voltage is greater than the charge across the capacitor.)

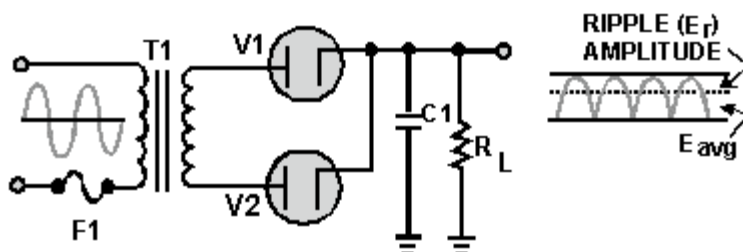


Figure 3-25.—Full-wave rectifier (with capacitor filter).

We stated before that a major advantage of full-wave and bridge rectifiers over half-wave rectifiers is the ease of filtering their output voltages. You can now see the reason for this. The ripple frequency is doubled; therefore, the time period the capacitor is allowed to discharge is cut in half. This means that the capacitor discharges less. Thus, ripple amplitude is less, and a smoother output voltage occurs.

Another thing to keep in mind is that the ripple component (E_r) of the output voltage is an ac voltage and the average output voltage (E_{avg}) is the dc component of the output. Since the filter capacitor offers a relatively low impedance to ac, the majority of the ac component flows through the filter capacitor. The ac component is therefore bypassed (shunted) around the load resistance and the entire dc component (or E_{avg}) flows through the load resistance. To clarify this statement, let's take a look at the formula for X_C in a half-wave and full-wave rectifier. First, you must establish some values for the circuit.

HALFWAVE RECTIFIER

FREQUENCY AT
RECTIFIER OUTPUT: 60 Hz

VALUE OF FILTER
CAPACITOR: 30 μ F

LOAD RESISTANCE: 10k Ω

$$X_C = \frac{1}{2\pi fC}$$

$$X_C = \frac{.159}{fC}$$

$$X_C = \frac{.159}{60 \times .000030}$$

$$X_C = \frac{.159}{.0018}$$

$$X_C = 88.3\Omega$$

FULLWAVE RECTIFIER

FREQUENCY AT
RECTIFIER OUTPUT: 120z

VALUE OF FILTER
CAPACITOR: 30 μ F

LOAD RESISTANCE: 10k

$$X_C = \frac{1}{2\pi fC}$$

$$X_C = \frac{.159}{fC}$$

$$X_C = \frac{.159}{120 \times .000030}$$

$$X_C = \frac{.159}{.0036}$$

$$X_C = 44.16\Omega$$

As you can see from the calculations, when the output frequency of the rectifier is doubled, the impedance of the capacitor is reduced by one-half. Therefore, when the simple capacitor filter is used in

conjunction with a full-wave or bridge rectifier, improved filtering is provided because the increased ripple frequency decreases the capacitive reactance of the filter capacitor. This allows the ac component to be passed through the capacitor more easily. Therefore, the output of a full-wave rectifier is much easier to filter than that of a half-wave rectifier.

It should be obvious that the smaller the X_C of the filter capacitor in respect to the load resistance, the better the filtering action. By using the largest possible capacitor, we achieve the best filtering. The load resistance is also an important consideration. If load resistance is made small, the load current increases, and the average value of output voltage (E_{avg}) decreases. The RC discharge time constant is a direct function of the value of the load resistance; therefore, the rate of capacitor voltage discharge is a direct function of the current through the load. The greater the load current, the more rapid the discharge of the capacitor, and the lower the average value of output voltage. For this reason, the simple capacitor filter is seldom used with rectifier circuits that must supply a relatively large load current.

Q17. What is the most basic type of filter?

Q18. In a capacitor filter, is the capacitor in series or parallel with the load?

Q19. Is better filtering achieved at a high frequency or at a low frequency at the input of the filter?

Q20. Does a filter circuit increase or decrease the average output voltage?

Q21. What determines the rate of discharge of the capacitor in a filter circuit?

Q22. Does low ripple voltage indicate good or bad filtering?

Q23. Is a full-wave rectifier output easier to filter than that of a half-wave rectifier?

In general, with the supply voltage removed from the input to the filter circuit, one terminal of the filter capacitor can be disconnected from the circuit.

CAUTION

REMEMBER-AN UNDISCHARGED CAPACITOR RETAINS ITS POLARITY AND HOLDS ITS CHARGE FOR LONG PERIODS OF TIME. TO BE SAFE, USE A PROPER SAFETY SHORTING PROBE TO DISCHARGE THE CAPACITOR TO BE TESTED WITH THE POWER OFF BEFORE CONNECTING TEST EQUIPMENT OR DISCONNECTING THE CAPACITOR.

You can check the capacitor by using a capacitance analyzer to determine its effective capacitance and leakage resistance. During these checks it is very important that you observe correct polarity if the capacitor is an electrolytic. A decrease in capacitance or losses within the capacitor can cause the output to be below normal and also cause excessive ripple amplitude.

If a suitable capacitance analyzer is not available, you can get an indication of leakage resistance by using an ohmmeter. You can make resistance measurements across the terminals of the capacitor to determine whether it is shorted, leaky, or open. When you test electrolytic capacitors, set the ohmmeter to the high range, and connect the test probes across the capacitor. Be careful to observe polarity. This is important because current flows through an electrolytic capacitor with less opposition in one direction than in the other. If you do not observe the correct polarity, you will get an incorrect reading and you may damage the meter. When you first connect the test probes, a large deflection of the meter should take place, and then the pointer should return slowly toward the infinite-ohms position as the capacitor charges. For a good capacitor with a rated working voltage of 450 volts dc, the final reading on the

ohmmeter should be over 500,000 ohms. (A rough rule of thumb for high-voltage capacitors is at least 1000 ohms per volt.) Low-voltage electrolytic capacitors (below 100 volts rating) should indicate approximately 100,000 ohms.

If the ohmmeter does not deflect when you make the resistance check explained above, you have found an open-circuit capacitor.

A steady full-scale deflection of the pointer at zero ohms indicates that the capacitor being tested is shorted.

An indication of a leaky capacitor is a steady reading on the scale somewhere between zero and the minimum acceptable value. (Be certain this reading is not caused by an in-circuit shunting part.) To be valid, these capacitor checks should be made with the capacitor completely disconnected from the circuit in which it operates.

In high-voltage filter capacitor applications, paper and oil-filled capacitors are used in addition to mica and ceramic capacitors (for low-capacitance values). In this case, polarity is of no importance unless the capacitor terminals are marked plus or minus. It is, however, good maintenance practice to use the output polarity of the circuit as a guide, connecting positive to positive, and negative to negative. Thus, any adverse effects of polarity on circuit tests are minimized and the possibility of damage to components or to test equipment is eliminated.

The LC Choke-Input Filter

The LC choke-input filter is used primarily in power supplies where good voltage regulation is important and where the output current is relatively high and subject to varying load conditions. This filter is used in high-power applications such as those found in radar and communication transmitter power supplies.

In figure 3-26 you can see that this filter consists of an input inductor or filter-choke (L1) and an output filter capacitor (C1).

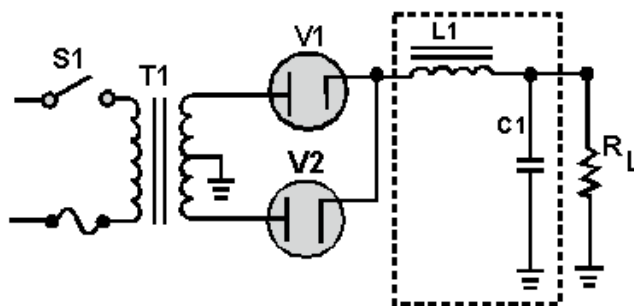


Figure 3-26.—Full-wave rectifier LC choke-input filter.

Inductor L1 is placed at the input to the filter and is in series with the output of the rectifier circuit. Since the action of an inductor is to oppose any change in current flow, the inductor tends to keep a constant current flowing to the load throughout the complete cycle of the applied voltage. As a result, the output voltage never reaches the peak value of the applied voltage; instead, the output voltage approximates the average value of the rectified input to the filter, as shown in figure 3-27.

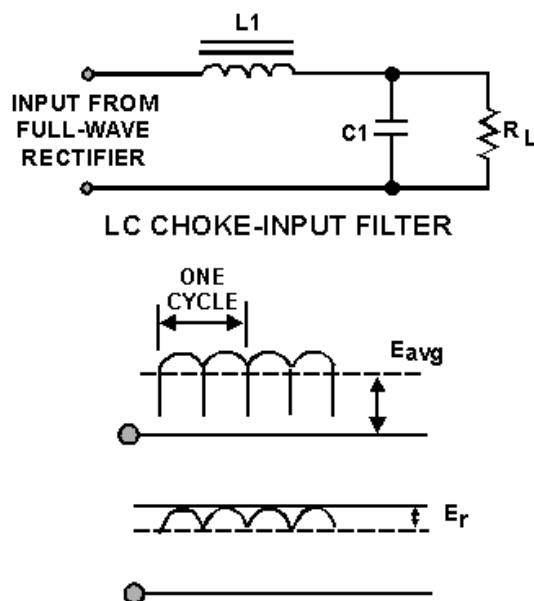


Figure 3-27.—Waveforms for a LC choke-input filter.

The reactance of the inductor (X_L) reduces the amplitude of ripple voltage without reducing the dc output voltage by an appreciable amount. (The dc resistance of the inductor is just a few ohms.)

The shunt capacitor (C_1) charges and discharges at the ripple frequency rate, but the amplitude of the ripple voltage (E_r) is relatively small because the inductor (L_1) tends to keep a constant current flowing from the rectifier circuit to the load. In addition, the reactance of the shunt capacitor (X_C) presents a low impedance to the ripple component existing at the output of the filter, and thus shunts the ripple component around the load. The capacitor attempts to hold the output voltage relatively constant at the average value of the voltage.

The value of the filter capacitor (C_1) must be relatively large to present a low opposition (X_C) to the pulsating current and to store a substantial charge. The rate of the charge for the capacitor is limited by the low impedance of the ac source (transformer), the small resistance of the diode, and the counter emf developed by the coil. Therefore, the RC charge time constant (fig. 3-28) is short compared to its discharge time.

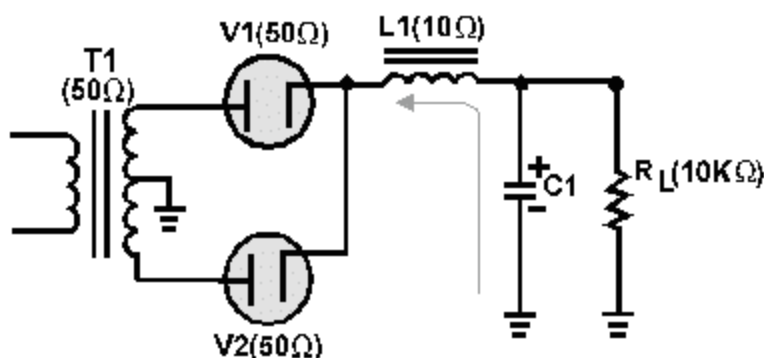


Figure 3-28.—LC choke-input filter (circuit resistance).

As a result, when the pulsating voltage is first applied to the LC choke-input filter, the inductor or filter choke (L1) produces a counter emf that opposes the constantly increasing input voltage. The net result is to effectively prevent the rapid charging of the filter capacitor (C1). Thus, instead of reaching the peak value of the input voltage, C1 only charges to the average value of the input voltage. After the input voltage reaches its peak and decreases sufficiently, the capacitor (C1) attempts to discharge through the load resistance (R_L). C1 will attempt to discharge as indicated in figure 3-29. Because of its relatively long discharge time constant, C1 can only partially discharge.

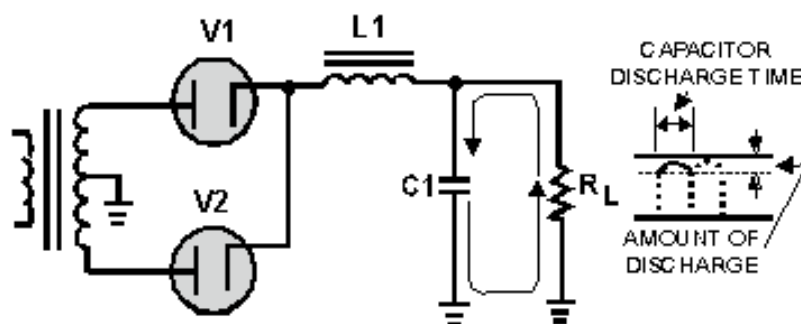


Figure 3-29.—LC choke-input filter (discharge path).

The larger the value of the filter capacitor, the better the filtering action. However, due to the physical size, there is a practical limitation to the maximum value of the capacitor.

The inductor or filter choke (L1) maintains the current flow to the filter output (capacitor C1 and load resistance R_L) at a nearly constant level during the charge and discharge periods of the filter capacitor.

The series inductor (L1) and the capacitor (C1) form a voltage divider for the ac component (ripple) of the applied input voltage. This is shown in figure 3-30. As far as the ripple component is concerned, the inductor offers a high impedance (Z) and the capacitor offers a low impedance. As a result, the ripple component (E_r) appearing across the load resistance is greatly attenuated (reduced). Since the inductance of the filter choke opposes changes in the value of the current flowing through it, the average value of the voltage produced across the capacitor contains a much smaller value of ripple component (E_r), as compared with the value of ripple produced across the coil.

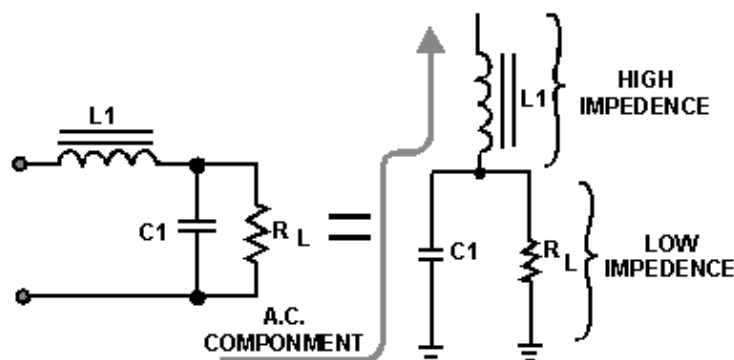


Figure 3-30.—LC choke-input filter (as voltage divider).

Now look at figure 3-31, which illustrates a complete cycle of operation where a full-wave rectifier circuit is used to supply the input voltage to the filter. The rectifier voltage is developed across capacitor C1. The ripple voltage in the output of the filter is the alternating component of the input voltage reduced in amplitude by the filter section.

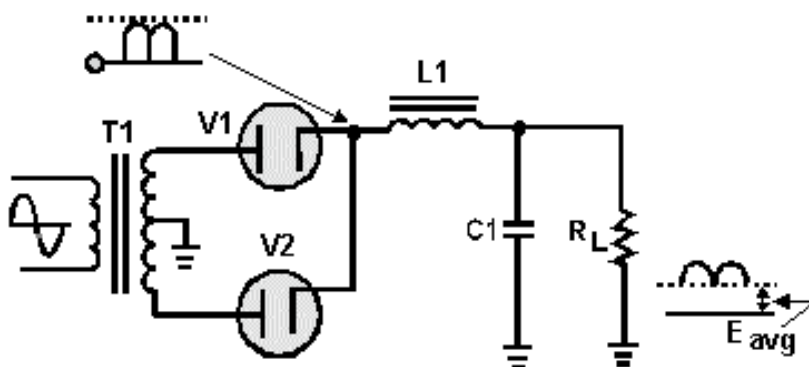


Figure 3-31.—Filtering action of an LC choke-input filter.

Each time the plate of a diode goes positive with respect to the cathode, the diode conducts and C1 charges. Conduction occurs twice during each cycle for a full-wave rectifier. For a 60-hertz supply, this produces a ripple frequency of 120 hertz. Although the diodes alternate (one conducts while the other is nonconducting), the filter input voltage is not steady. As the plate voltage of the conducting diode increases (on the positive half of the cycle), capacitor C1 charges—the charge being limited by the impedance of the secondary transformer winding, the diode's forward (cathode-to-plate) resistance, and the counter emf developed by the choke. During the nonconducting interval, (when the plate voltage drops below the capacitor charge voltage), C1 discharges through the load resistance R_L . The components in the discharge path cause a long time constant; thus C1 discharges slower than it charges.

The choke (L1) is usually of a large value, on the order of 1 to 20 henries, and offers a large inductive reactance to the 120-hertz ripple component produced by the rectifier. Therefore, the effect that L1 has on the charging of the capacitor (C1) must be considered. Since L1 is connected in series with the parallel branch consisting of C1 and R_L , a division of the ripple ac voltage and the output dc voltage occurs. The greater the impedance of the choke, the less the ripple voltage that appears across C1 and the output. The dc output voltage is fixed mainly by the dc resistance of the choke.

Now that you have read how the LC choke-input filter functions, let's take a look at it using actual component values. For simplicity, the input frequency at the primary of the transformer will be 117 volts 60 hertz. We will use both half-wave and full-wave rectifier circuits to provide the input to the filter.

Starting with the half-wave configuration as shown in figure 3-32, the basic parameters are: with 117 volts ac rms applied to the T1 primary, 165 volts ac peak-to-peak is available at the secondary $[(117 \text{ V}) \times (1.414) = 165 \text{ V}]$. You should recall that the ripple frequency of this half-wave rectifier is 60 hertz. Therefore, the capacitive reactance of C1 is:

$$X_C = \frac{1}{2\pi fC}$$

$$X_C = \frac{1}{(2)(3.14)(60)(10)(10^{-6})}$$

$$X_C = \frac{(1)(10^6)}{3768}$$

$$X_C = 265\Omega$$

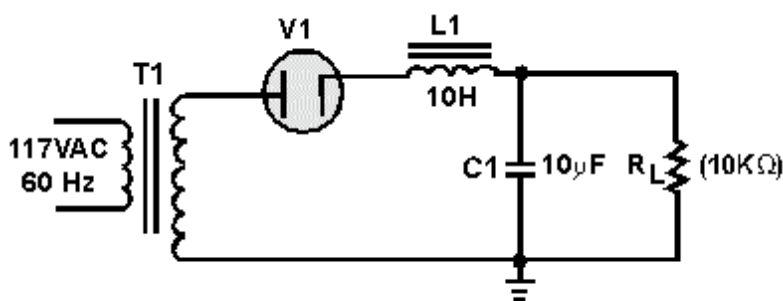


Figure 3-32.—Half-wave rectifier with an LC choke-input filter.

This means that the capacitor (C1) offers 265 ohms of opposition to the ripple current. Note, however, that the capacitor offers an infinite impedance to direct current. The inductive reactance of L1 is:

$$X_L = 2\pi fL$$

$$X_L = (2)(3.14)(60)(10)$$

$$X_L = 3.8 \text{ Kilohms}$$

This shows that L1 offers a relatively high opposition (3.8 kilohms) to the ripple in comparison to the opposition offered by C1 (265 ohms). Thus, more ripple voltage will be dropped across L1 than across C1. In addition, the impedance of C1 (265 ohms) is relatively low in respect to the resistance of the load (10 kilohms). Therefore, more ripple current flows through C1 than the load. In other words, C1 shunts most of the ac component around the load.

Let's go a step further and redraw the filter circuit so that you can see the voltage divider action. (Refer to figure 3-33.) Remember, the 165 volts peak-to-peak 60 hertz provided by the rectifier consist of both an ac and a dc component. The first discussion will be about the ac component. Looking at figure 3-33, you see that the capacitor (C1) offers the least opposition (265 ohms) to the ac component; therefore, the greatest amount of ac will flow through C1. (The heavy line indicates current flow through the capacitor.) Thus the capacitor bypasses, or shunts, most of the ac around the load.

By combining the X_C of C1 and the resistance of R_L into an equivalent circuit, you will have an equivalent impedance of 265 ohms.

$$Z = \frac{R \times X_c}{\sqrt{(R^2 + X_c^2)}}$$

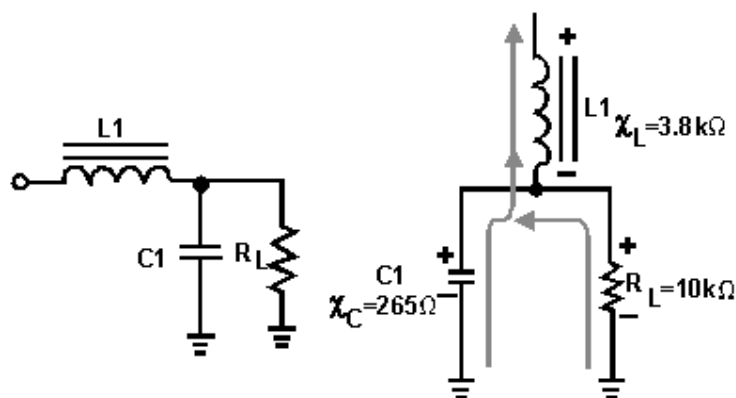


Figure 3-33.—AC component in an LC choke-input filter.

You now have a voltage divider as illustrated in figure 3-34. You should see that because of the impedance ratios, a large amount of ripple voltage is dropped across L1, and a substantially smaller amount is dropped across C1 and RL. You can further increase the ripple voltage across L1 by increasing the inductance:

$$X_L = 2\pi fL$$

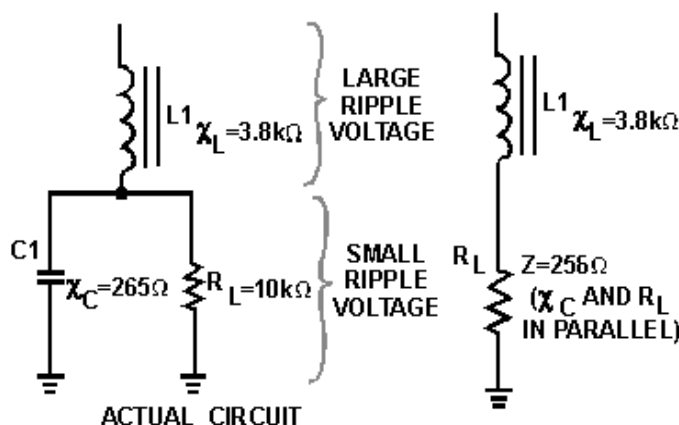


Figure 3-34.—Actual and equivalent circuits.

Now let's discuss the dc component of the applied voltage. Remember, a capacitor offers an infinite (∞) impedance to the flow of direct current. The dc component, therefore, must flow through RL and L1. As far as the dc is concerned, the capacitor does not exist. The coil and the load are, therefore, in series with each other. The dc resistance of a filter choke is very low (50 ohms average). Therefore, most of the dc component is developed across the load and a very small amount of the dc voltage is dropped across the coil, as shown in figure 3-35.

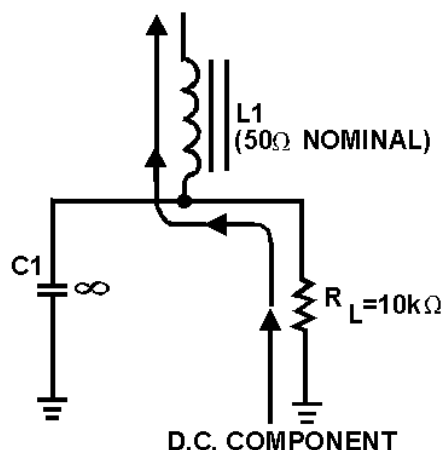


Figure 3-35.—DC component in an LC choke-input filter.

As you may have noticed, both the ac and the dc components flow through L1, and because the coil is frequency sensitive, it provides a large resistance to ac and a small resistance to dc. In other words, the coil opposes any change in current. This property makes the coil a highly desirable filter component. Note that the filtering action of the LC capacitor input filter is improved when the filter is used in conjunction with a full-wave rectifier as shown in figure 3-36. This is due to the decrease in the X_C of the filter capacitor and the increase in the X_L of the choke. Remember, the ripple frequency of a full-wave rectifier is twice that of a half-wave rectifier. For a 60-hertz input, the ripple will be 120 Hertz. Let's briefly calculate the X_C of C1 and the X_L of L1:

$$X_C = \frac{1}{2\pi fC}$$

$$X_C = \frac{1}{(2)(3.14)(120)(10)(10^{-6})}$$

$$X_C = \frac{(1)(10^6)}{7536}$$

$$X_C = 132.5\Omega$$

$$X_L = 2\pi fL$$

$$X_L = (2)(3.14)(120)(10)$$

$$X_L = 7.5 \text{ kilohms}$$

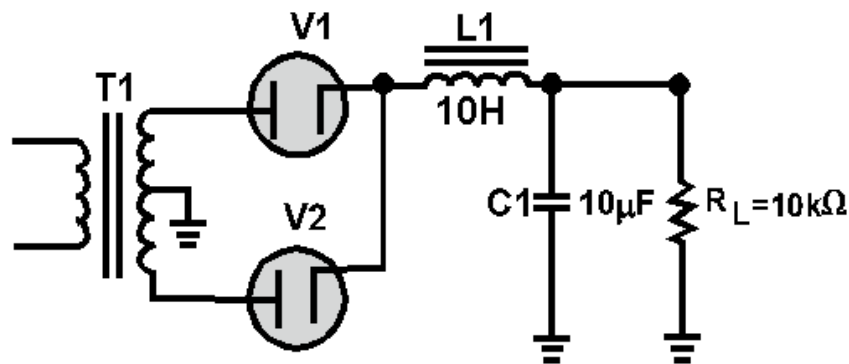


Figure 3-36.—Full-wave rectifier with an LC choke-input filter.

It should be apparent that when the X_C of a filter capacitor is decreased, it provides less opposition to the flow of ac. The greater the ac flow through the capacitor, the lower the flow through the load. Conversely, the larger the X_L of the choke, the greater the amount of ac ripple developed across the choke; consequently, less ripple is developed across the load. This condition provides better filtering.

Q24. In an LC choke-input filter, what prevents the rapid charging of the capacitor?

Q25. What is the value usually chosen for a filter choke?

Q26. If the inductance of a choke-input filter is increased, will the output ripple voltage amplitude (E_r) increase or decrease?

An LC choke-input filter is subject to several problems that can cause it to fail. The filter capacitors are subject to open circuits, short circuits, and excessive leakage. The series inductor is subject to open windings and, occasionally, shorted turns or a short circuit to the core.

The filter capacitor in the choke-input filter circuit is not subject to extreme voltage surges because of the protection offered by the inductor; however, the capacitor can become open, leaky, or shorted.

Shorted turns in the choke may reduce the value of inductance below the critical value. This will result in excessive peak-rectifier current, accompanied by an abnormally high output voltage, excessive ripple amplitude, and poor voltage regulation. A choke winding that is open, or a choke winding that is shorted to the core will result in a no-output condition. A choke winding that is shorted to the core may cause overheating of the rectifier element(s), blown fuses, and so forth.

To check the capacitor, first remove the supply voltage from the input to the filter circuit. Then disconnect one terminal of the capacitor from the circuit. Check the capacitor with a capacitance analyzer to determine its capacitance and leakage resistance. When the capacitor is electrolytic, be sure to use the correct polarity at all times. A decrease in capacitance or losses within the capacitor can decrease the efficiency of the filter and produce excessive ripple amplitude. If a suitable capacitance analyzer is not available, you can use an ohmmeter to check for leakage resistance. The test procedure is the same as that described for the input capacitor filter.

So far, this section has discussed in detail the operation and troubleshooting of the basic inductive and capacitive filter circuits. For the two remaining types of filters, we will discuss only the differences between them and the other basic filters.

Resistor-Capacitor (RC) Filters

The RC capacitor-input filter is limited to applications in which the load current is small. This type of filter is used in power supplies where the load current is constant and voltage regulation is not necessary. For example, RC filters are used in high-voltage power supplies for cathode-ray tubes and as part of decoupling networks for multistage amplifiers.

Figure 3-37 shows an RC capacitor-input filter and its associated waveforms. Both half-wave and full-wave rectifiers are used to provide the inputs.

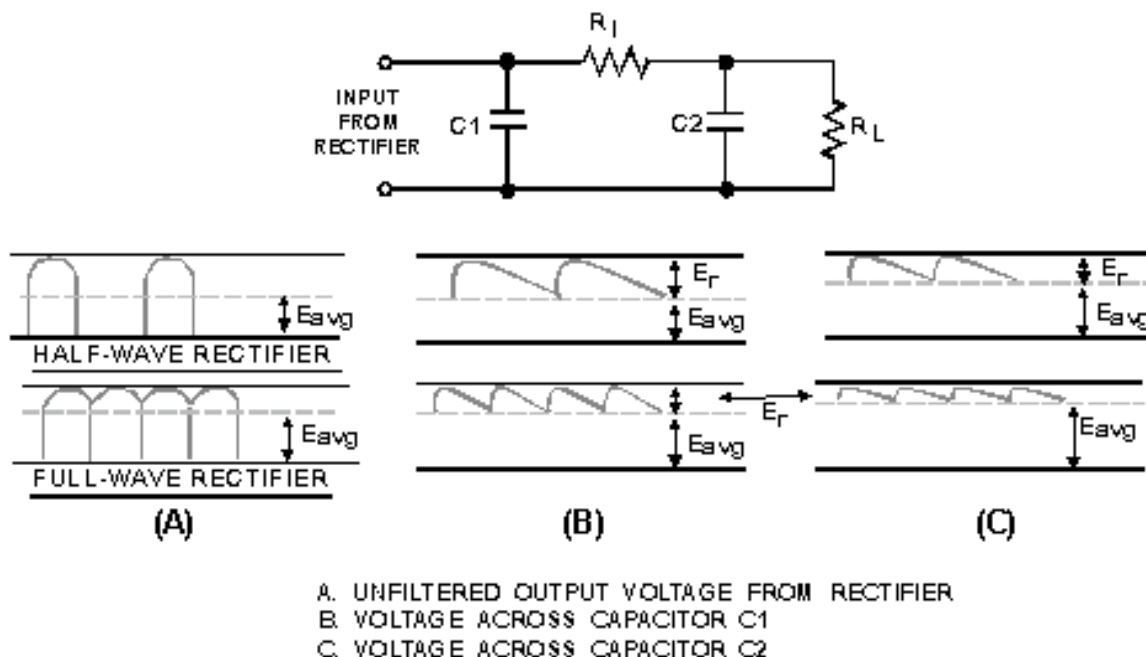


Figure 3-37.—RC filter and waveforms.

The RC filter in figure 3-37 consists of an input filter capacitor (C1), a series resistor (R1), and an output filter capacitor (C2). Although not part of the RC filter, R_L is shown to help explain the circuit. This filter is sometimes referred to as an RC *pi-section filter* because its schematic symbol resembles the Greek letter π .

Although the single capacitor filter is suitable for many noncritical, low-current applications, when the load resistance is very low or when the percent of ripple must be held to an absolute minimum, the capacitor must have an extremely large value. While electrolytic capacitors are available in sizes up to 10,000 μF or greater, the larger sizes are quite expensive. A more practical approach is to use a more sophisticated filter that can do the same job but that has lower capacitor values, such as the RC filter.

The waveforms shown in the figure represent the unfiltered output from a typical rectifier circuit. Note that the dashed line, which indicates the average value of output voltage (E_{avg}) for the half-wave rectifier, is less than half the amplitude of the voltage peaks (approximately 0.318). The average value of output voltage (E_{avg}) for the full-wave rectifier is greater than half (approximately 0.637), but is still much less than the peak amplitude of the rectifier-output waveform. With no filter circuit connected across the output of the rectifier circuit (unfiltered), the waveform has a large value of pulsating component (ripple) as compared to the average (or dc) component.

An RC filter, such as a pi-section filter, does a much better job than a single capacitor filter.

Figure 3-37 illustrates an RC filter connected across the output of a rectifier. C1 performs the same function that it did in the single capacitor filter. It is used to reduce the percentage of ripple to a relatively low value. Thus, the voltage across C1 might consist of an average dc value of +100 volts with a ripple voltage of 10 volts. This voltage is passed on to the R1-C2 network, which reduces the ripple even further (view C).

C2 offers an infinite impedance (resistance) to the dc component of the output voltage. Thus, the dc voltage is passed to the load, but reduced in value by the amount of the voltage drop across R1. However, R1 is generally small compared to the load resistance. Therefore, the drop in the dc voltage by R1 is not a drawback.

Component values are designed so that the resistance of R1 is much greater than the reactance of C2 at the ripple frequency. C2 offers a very low impedance to the ac ripple frequency. Thus, the ac ripple senses a voltage divider consisting of R1 and C2 between the output of the rectifier and ground. Therefore, most of the ripple voltage is dropped across R1. Only a trace of the ripple voltage can be seen across C2 and the load.

In extreme cases where the ripple must be held to an absolute minimum, a second stage of RC filtering can be added. In practice, the second stage is rarely required. The RC filter is extremely popular because smaller capacitors can be used with good results.

The RC filter has some disadvantages, however. First, the voltage drop across R1 takes voltage away from the load. Second, power is wasted in R1 and is dissipated in the form of unwanted heat.

Finally, if the load resistance changes, the voltage across the load will change. Even so, the advantages of the RC filter overshadow these disadvantages in many cases.

Q27. Is an RC filter used when a large current or a small current demand is required?

Q28. Why is the use of large value capacitors in filter circuits discouraged?

Q29. When is a second RC filter stage used?

The resistor-capacitor (RC) filter is also subject to problems that can cause it to fail. The shunt capacitors (C1 and C2) are subject to an open circuit, a short circuit, or excessive leakage. The series filter resistor (R1) is subject to changes in value and occasionally opens. Any of these troubles can be easily detected.

The input capacitor (C1) has the greatest pulsating voltage applied to it and is the most susceptible to voltage surges. As a result, it is frequently subject to voltage breakdown and shorting. The remaining shunt capacitor (C2) in the filter circuit is not subject to voltage surges because of the protection offered by the series filter resistor (R1). However, a shunt capacitor can become open, leaky, or shorted.

A shorted capacitor or an open filter resistor results in a no-output indication. An open filter resistor results in an abnormally high dc voltage at the input to the filter and no voltage at the output of the filter. Leaky capacitors or filter resistors that have lost their effectiveness, or filter resistors that have decreased in value, result in an excessive ripple amplitude in the output of the supply.

LC Capacitor-Input Filter

The LC input filter is one of the most commonly used filters. This type of filter is used primarily in radio receivers, small audio amplifier power supplies, and in any type of power supply where the output current is low and the load current is relatively constant.

Figure 3-38 shows an LC capacitor-input filter and its associated waveforms. Both half-wave and full-wave rectifier circuits are used to provide the inputs.

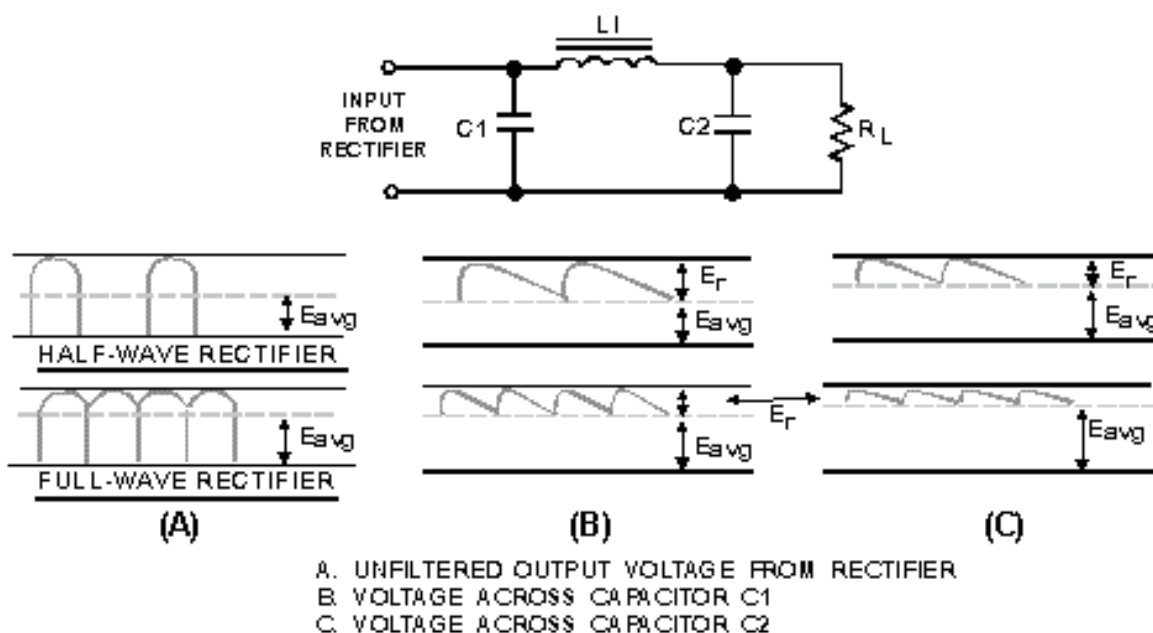


Figure 3-38.—LC capacitor-input filter and waveforms.

The waveforms shown in the figure represent the unfiltered output from a typical rectifier circuit. Note again, that the average value of output voltage (E_{avg}) for the half-wave rectifier is less than half the amplitude of the voltage peaks. This is indicated by the dashed line. The average value of output voltage (E_{avg}) for the full-wave rectifier is greater than half, but is still much less than the peak amplitude of the rectifier-output waveform. With no filter circuit connected across the output of the rectifier circuit (unfiltered), the waveform has a large value of pulsating component (ripple) as compared to the average (or dc) component.

A common type of LC filter is shown in figure 3-38. C1 performs the same functions as discussed earlier by reducing the ripple to a relatively low level. L1 and C2 form the LC filter, which reduces the ripple even further (view C).

L1 is a large value iron-core inductor (choke.) It has a high value of inductance and, therefore, a high value of X_L , which offers a high reactance to the ripple frequency. At the same time, C2 offers a very low reactance to the ac ripple. L1 and C2 form an ac voltage divider and, because the reactance of L1 is much higher than that of C2, most of the ripple voltage is dropped across L1. Only a slight trace of the ripple appears across C2 and the load.

While the L1-C2 network greatly reduces the ac ripple, it has little effect on the dc. You should recall that an inductor offers no reactance to dc. The only opposition to current flow is the resistance of

the wire in the choke. Generally, this resistance is very low and the dc voltage drop across the coil is minimal. Thus, the LC filter overcomes the disadvantages of the RC filter.

Aside from the voltage divider effect, the inductor improves filtering in another way. You should recall that an inductor resists changes in the magnitude of the current flowing through it. Consequently, when the inductor is placed in series with the load, the inductor tends to hold the current steady. This, in turn, helps to hold the voltage across the load constant.

The LC filter provides good filtering action over a wide range of currents. The capacitor filters best when the load is drawing little current. Thus, the capacitor discharges very slowly and the output voltage remains almost constant. On the other hand, the inductor filters best when the current is highest. The complementary nature of these components ensures good filtering over a wide range of current when size of components is a factor.

The LC filter has two disadvantages. The first is cost. The LC filter is more expensive than the RC filter because its iron-core choke costs more than the resistor of the RC filter. The second disadvantage is size, since the iron-core choke is bulky and heavy. Thus, the LC filter may be unsuitable for some applications but is still one of the most widely used.

Q30. What is the most commonly used filter in use today?

Q31. What are the two main disadvantages of an LC capacitor filter?

Several problems may cause the LC capacitor filter to fail. Shunt capacitors are subject to open circuits, short circuits, and excessive leakage; series inductors are subject to open windings and occasionally shorted turns or a short circuit to the core.

The input capacitor (C1) has the greatest pulsating voltage applied to it, is the most susceptible to voltage surges, and has a generally higher average voltage applied. As a result, the input capacitor is frequently subject to voltage breakdown and shorting. The output capacitor (C2) is not as susceptible to voltage surges because of the series protection offered by the series inductor (L1), but the capacitor can become open, leaky, or shorted.

A shorted capacitor, an open filter choke, or a choke winding that is shorted to the core, results in a no-output indication. A shorted capacitor, depending on the magnitude of the short, may cause a shorted rectifier, transformer, or filter choke and result in a blown fuse in the primary of the transformer. An open filter choke results in an abnormally high dc voltage at the input to the filter and no voltage at the output of the filter. A leaky or open capacitor in the filter circuit results in a low dc output voltage. This condition is generally accompanied by an excessive ripple amplitude. Shorted turns in the winding of a filter choke reduce the effective inductance of the choke and decrease its filtering efficiency. As a result, the ripple amplitude increases.

VOLTAGE REGULATION

Ideally, the output of most power supplies should be a constant voltage. Unfortunately, this is difficult to achieve. There are two factors that can cause the output voltage to change. First, the ac line voltage is not constant. The so-called *115 volts ac* can vary from about 105 volts ac to 125 volts ac. This means that the peak ac voltage to which the rectifier responds can vary from about 148 volts to 177 volts. The ac line voltage alone can be responsible for nearly a 20 percent change in the dc output voltage.

The second factor that can change the dc output voltage is a change in the load resistance. In complex electronic equipment, the load can change as circuits are switched in and out. In a television

receiver, the load on a particular power supply may depend on the brightness of the screen, the control settings, or even the channel selected.

These variations in load resistance tend to change the applied dc voltage because the power supply has a fixed internal resistance. If the load resistance decreases, the internal resistance of the power supply drops more voltage. This causes a decrease in the voltage across the load.

Many circuits are designed to operate with a particular supply voltage. When the supply voltage changes, the operation of the circuit may be adversely affected. Consequently, some types of equipment must have power supplies that produce the same output voltage regardless of changes in the load resistance or changes in the ac line voltage. This constant supply of power may be achieved by adding a circuit called the **VOLTAGE REGULATOR** at the output of the filter.

LOAD REGULATION

A commonly used **FIGURE OF MERIT** for a power supply is its **PERCENT OF REGULATION**. The figure of merit gives us an indication of how much the output voltage changes over a range of load resistance values. The percent of regulation aids us in determining of the type of load regulation needed. Percent of regulation is determined by the equation:

$$\text{Percent of regulation} = \frac{(E_{nL} - E_{fL})}{E_{fL}} \times 100$$

This equation compares the change in output voltage at the two loading extremes to the voltage produced at full loading. For example, assume that a power supply produces 12 volts when the load current is zero. If the output voltage drops to 10 volts when full load current flows, then the percent of regulation is:

$$\text{Percent of regulation} = \frac{(E_{nL} - E_{fL})}{E_{fL}} \times 100$$

$$\text{Percent of regulation} = \frac{(12 - 10V)}{10V} \times 100$$

$$\text{Percent of regulation} = \frac{2V}{10V} \times 100$$

$$\text{Percent of regulation} = 20\%$$

Ideally, the output voltage should not change over the full range of operation. That is, a 12-volt power supply should produce 12 volts at no load, at full load, and at all points in between. In this case, the percent of regulation would be:

$$\text{Percent of regulation} = \frac{(E_{nL} - E_{fL})}{E_{fL}} \times 100$$

$$\text{Percent of regulation} = \frac{(12 - 12V)}{12V} \times 100$$

$$\text{Percent of regulation} = \frac{0V}{12V} \times 100$$

$$\text{Percent of regulation} = 0\%$$

Thus, zero-percent load regulation is the ideal situation. It means that the output voltage is constant under all load conditions. While you should strive for zero percent load regulation, in practical circuits you must settle for something less. Even so, by using a voltage regulator, you can hold the percent of regulation to a very low value.

If you are interested in reading more on this subject, refer to the *Electronic Installation and Maintenance Book (EIMB)* series or other similar books from your technical library.

Q32. What two factors can cause output dc voltage to change?

Q33. What is the commonly used figure of merit for a power supply?

Q34. If a power supply produces 20 volts with no load and 15 volts under full load, what is the percent of regulation?

Q35. What percent of regulation would be ideal?

REGULATORS

You know that the output of a power supply varies with changes in input voltage and circuit load current requirements. Because many military electronic equipments require operating voltages and currents that must remain constant, some form of regulation is necessary. The circuits that maintain power supply voltage or current outputs within specified limits, or tolerances, are called regulators. They are designated as dc voltage or dc current regulators, depending on their specific application.

Voltage regulator circuits are additions to basic power supply circuits and are made up of rectifier and filter sections. The purpose of the voltage regulator is to provide an output voltage with little or no variation. Regulator circuits sense changes in output voltages and compensate for the changes. Regulators that maintain voltages within plus or minus (\pm) 0.1 percent are quite common. The diagram in figure 3-39 clearly illustrates the purpose of the voltage regulator.

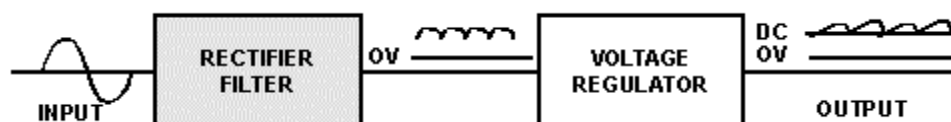


Figure 3-39.—Block diagram of a power supply and regulators

There are two basic types of voltage regulators, series and shunt. Whether a voltage regulator is classified as series or shunt depends on the location or position of the regulating element(s) in relation to the circuit load resistance.

Figure 3-40 illustrates the two basic types of voltage regulators. In actual practice the circuitry of regulating devices may be quite complex. We use the simplified drawings in the figure to emphasize that there are two basic types of voltage regulators. Broken lines highlight the differences between the series and shunt regulators.

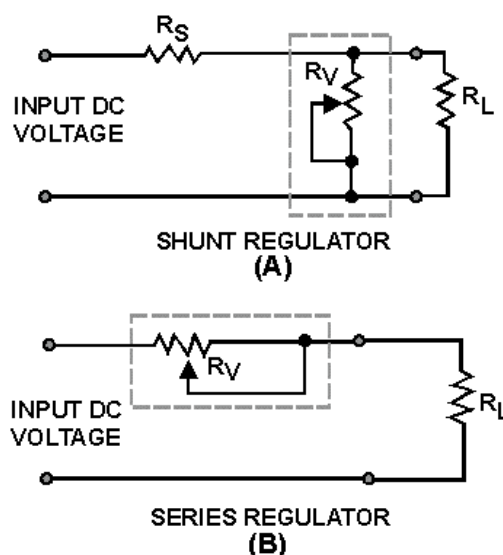


Figure 3-40.—Series and shunt regulators.

The schematic in view (A) is that of a shunt-type regulator. It is called a shunt-type regulator because the regulating device is connected in parallel with the load resistance. This is a characteristic of all shunt-type regulators. The schematic in view (B) is that of a series regulator. It is called a series regulator because the regulating device is connected in series with the load resistance.

Series Voltage Regulator

Figure 3-41 illustrates the principle of series voltage regulation. As you study the figure, notice that the regulator is in series with the load resistance and that all current passes through the regulator. In this example, variable resistor R_V is used for regulation. Examine the circuit to determine how the regulator functions. When the input voltage increases, the output voltage also increases. However, since the voltage regulator device (R_V) senses this change, the resistance of the regulating device increases and results in a greater voltage drop through R_V . This causes the output voltage to decrease to normal or, for all practical purposes, to remain constant.

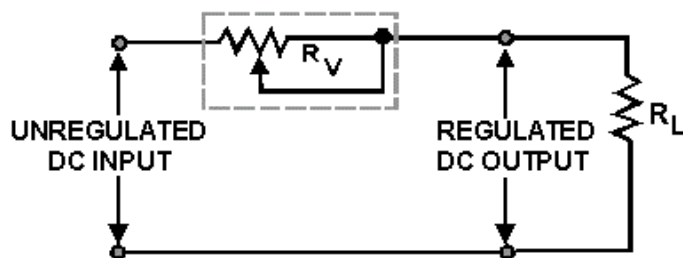


Figure 3-41.—Series voltage regulator.

You should be able to see that as the input voltage decreases, the resistance of the variable resistor R_v decreases almost simultaneously, thereby compensating for the voltage drop. Since there is a smaller voltage drop across R_v , the output voltage remains almost constant. Voltage fluctuations within the circuit occur in microseconds.

Shunt Voltage Regulator

The diagram in figure 3-42 represents a shunter voltage regulator. Notice that variable resistor R_v is in parallel with the load resistance R_L and that fixed resistor R_s is in series with the load resistance. You already know the voltage drop across a fixed resistor remains constant unless there is a variation (increase or decrease) in the current through it.

In a shunt regulator as shown in figure 3-42, output voltage regulation is determined by the current through the parallel resistances of the regulating device (R_v), the load resistance (R_L), and the series resistor (R_s). For now, assume that the circuit in figure 3-42 is operating under normal conditions, that the input is 120 volts dc, and that the desired regulated output is 100 volts dc. For a 100-volt output to be maintained, 20 volts must be dropped across the series resistor (R_s). If you assume that the value of R_s is 2 ohms, then you must have 10 amperes of current through R_v and R_L . (Remember: $E = IR$.) If the values of the resistance of R_v and R_L are equal, then 5 amperes of current will flow through each resistance (R_v and R_L).

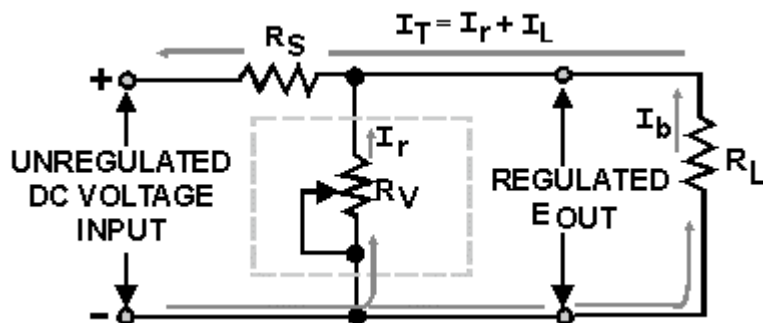


Figure 3-42.—Shunt voltage regulator.

Now, if the load resistance (R_L) increases, the current through R_L will decrease. For example, assume that the current through R_L is now 4 amperes and that the total current through R_s is 9 amperes. With this drop in current, the voltage drop across R_s is 18 volts; consequently, the output of the regulator has increased to 102 volts. At this time, the regulating device (R_v) decreases in resistance, and 6 amperes of current flows through this resistance (R_v). Thus, the total current through R_s is once again 10 amperes (6 amperes across R_v , 4 amperes through R_L); therefore, 20 volts will be dropped across R_s causing the output to decrease back to 100 volts.

You should know by now that if the load resistance (R_L) increases, the regulating device (R_v) decreases its resistance to compensate for the change. If R_L decreases, the opposite effect will occur and R_v will increase. Now take a look at the circuit when a decrease in load resistance takes place.

When R_L decreases, the current through R_L subsequently increases to 6 amperes. This action causes a total of 11 amperes to flow through R_s which now drops 22 volts. As a result, the output is now 98 volts. However, the regulating device (R_v) senses this change and increases its resistance so that less current (4 amperes) flows through R_v . The total current again becomes 10 amperes, and the output is again 100 volts.

From these examples, you should now understand that the shunt regulator maintains the desired output voltage by sensing the current change that occurs in the parallel resistance of the circuit.

Again refer to the schematic shown in figure 3-42 and consider how the voltage regulator operates to compensate for changes in input voltages. You know, of course, that the input voltage may vary and that any variation must be compensated for by the regulating device. Consider an increase in input voltage. When this happens the resistance of R_v automatically decreases to maintain the correct voltage division between R_v and R_s . You should see, therefore, that the regulator operates in the opposite way to compensate for a decrease in input voltage.

So far we have explained the operation of voltage regulators that use variable resistors; however, this type of regulation has limitations. Obviously, the variable resistor cannot be adjusted rapidly enough to compensate for frequent fluctuations in voltage. Since input voltages fluctuate frequently and rapidly, the variable resistor is not a practical method for voltage regulation. A voltage regulator that operates continuously and automatically to regulate the output voltage without external manipulation is required.

Q36. The purpose of a voltage regulator is to provide an output voltage with little or no ____.

Q37. The two basic types of voltage regulators are _____ and _____.

Q38. When a series voltage regulator is used to control output voltages, any increase in the input voltage results in an increase/a decrease in the resistance of the regulating device.

Q39. A shunt type voltage regulator is connected in series/parallel with the load resistance.

Basic VR Tube Regulator Circuit

Although we covered the electrical characteristics of the VR tube in chapter 2 of this module, we now need to cover the capabilities and limitations of the VR tube itself.

Figure 3-43 shows a basic VR tube regulating circuit. The voltage produced by the source is 150 volts. The VR 90 will provide a constant 90 volts across the load resistance (R_L) if the tube is operated in the normal glow discharge region. This means that 60 volts is dropped across R_s , which is the series limiting resistance used to limit the current through the VR tube.

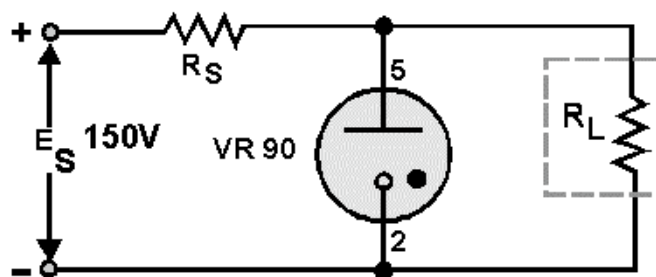


Figure 3-43.—Basic VR tube regulator.

Since the operating limits of a VR tube are determined by its maximum and minimum currents, circuits using such tubes should be designed to allow maximum variations in current above and below the normal point of operation. The normal point of operation, which allows maximum variation in current, must be midway between the current limits of the tube. This median current is called I_{mean} , and can be calculated by the use of the following equation:

$$I_{\text{mean}} = \frac{I_{\text{max}} + I_{\text{min}}}{2}$$

We can determine the mean current for the VR90-40 as shown in figure 3-44 by using the following values:

$$I_{\text{mean}} = \frac{40 + 5}{2} = \frac{45}{2} = 22.5\text{mA}$$

To calculate the value of series dropping resistance R_S , we use the following equation:

$$R_S = \frac{\text{Source Voltage} - \text{Regulated Voltage}}{I_{\text{mean}} + I_{\text{load}}(\text{average})}$$

If the average current flowing through the load of figure 3-44 is 100 milliamperes, we can find the series dropping resistance in the following manner:

$$R_S = \frac{150 - 90}{22.5 + 100} = \frac{60 \text{ volts}}{122.5\text{mA}} = 490 \text{ ohms}$$

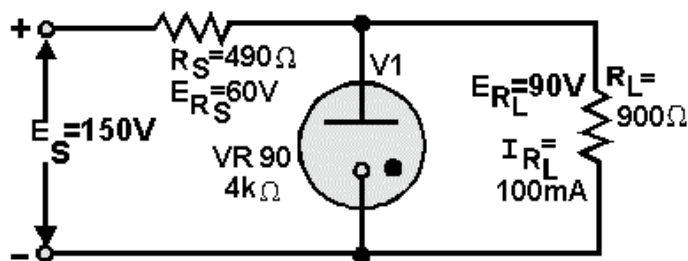


Figure 3-44.—Simplified VR tube regulator.

According to Ohm's law, the value of the load resistance for this circuit figure will be 900 ohms if a current of 100 milliamperes flows through R_L . The internal resistance of the VR tube can be calculated in a similar manner. With 22.5 milliamperes flowing and 90 volts dropped across the VR tube, its resistance is 4 kilohms.

To determine the voltage regulation in the circuit for figure 3-44, assume a constant supply voltage of 150 volts and a variable load resistance. If the value of R_L were to decrease to 857 ohms, the load current would increase to approximately 105 milliamperes to maintain 90 volts across the load resistance. R_S must drop 60 volts. To do so requires a current of 122.5 milliamperes flowing through the series resistance. Since 105 milliamperes is now flowing through the load, the current through the VR tube must decrease from 22.5 milliamperes to 17.5 milliamperes. We will discuss the sequence of events in more detail to help you better understand how the tube current is made to vary.

The original load resistance was 900 ohms. Changes in this resistance will not occur instantaneously, but will require some time to vary from 900 ohms to a new value. As resistance of the load begins to decrease, load current begins to increase. The minute increase in load current will flow through the series resistance R_S causing a slight increase in E_{RS} . This slight increase in voltage across R_S will result in the VR tube voltage dropping slightly. This slight drop in tube voltage will cause a decrease in the ionization of the tube gas, which in turn increases the resistance of the tube. As a result, less current flows through the tube.

Note that tube current can decrease only to a value of 5 milliamperes before deionization occurs. Therefore, the load current cannot exceed 117.5 milliamperes, for beyond this value, tube current becomes less than 5 milliamperes and regulation ceases.

If load resistance were to increase, load current would decrease. This would result in the VR tube current increasing to maintain a current of 122.5 milliamperes. The VR tube current can only increase to 40 milliamperes. Beyond this value of current, the tube enters the abnormal glow region and tube voltage increases.

The upper limit of the VR tube current will occur when load current decreases to a value of 82.5 milliamperes. When load current drops below this value, the VR tube ceases to regulate the load voltage. Therefore, with a constant source voltage but variable load resistance, the limits of regulation will be reached when current in the load exceeds 117.5 milliamperes or drops below 82.5 milliamperes.

The VR tube regulator can also compensate for changes in power supply voltage. Under these conditions, the load resistance will remain constant while the power supply voltage will be variable. Refer to figure 3-44 for the following discussion.

Assume that the source voltage begins to increase from an original value of 150 volts toward 155 volts. As this voltage increases, current through R_S increases from its original value of 122.5 milliamperes. Initially, this additional current is drawn from the load, causing a slight increase in load voltage. This increase in load voltage is felt across the VR tube and causes an increase in tube ionization. This decreases the internal resistance of the VR tube with a resultant increase in tube current. When source voltage reaches 155 volts, current through R_S is approximately 133 milliamperes ($R_S = 490$ ohms). Most of the additional current through R_S flows through the VR tube. As a result, approximately 33 milliamperes flows through the VR tube, maintaining the load voltage at 90 volts.

Since VR tube current decreases as source voltage decreases, tube current will drop below its lower limit of 5 milliamperes at some point. When source voltage drops below 141.4 volts, tube current will be less than 5 milliamperes and regulation will cease. The upper and lower limits of the supply voltage variations that can be allowed and still provide regulation in the circuit are 158.6 volts and 141.4 volts,

respectively. Remember that tube voltage varies slightly through its operating range, but this voltage change is less than that which would exist without the use of a VR tube.

As the source voltage increases, the current through the VR tube increases. Since the upper limit of tube current is 40 milliamperes, there is a limit in the ability of the tube to regulate increasing voltage. When the supply voltage exceeds 158.6 volts, tube current will be greater than 40 milliamperes and regulation will cease.

If the source voltage decreases from 150 volts to 145 volts, only 55 volts must be dropped across the 490-ohm series resistance (R_S) to maintain the load voltage at 90 volts. Current through R_S for a 55 volt drop is 112 milliamperes. Since load current is 100 milliamperes, the remaining 12 milliamperes must flow through the VR tube. This represents a decrease in the ionization level of the VR tube, with a resultant increase in tube resistance. Under these conditions, 90 volts will be maintained across the load resistance.

VR Tubes Connected in Series

In applications where a regulated voltage in excess of the maximum rating of one tube is required, two or more tubes may be placed in series as shown in figure 3-45.

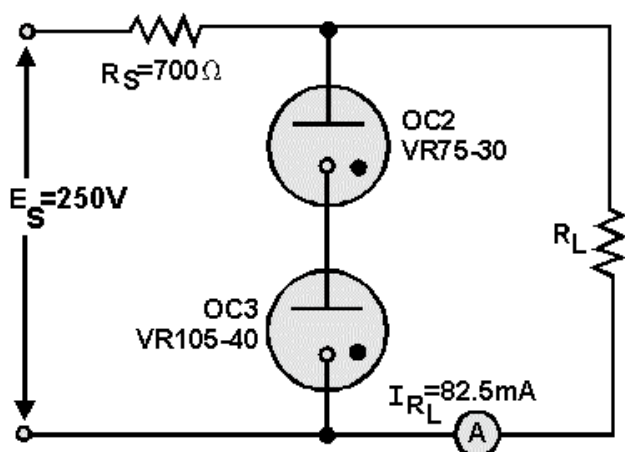


Figure 3-45.—VR tubes as voltage dividers.

In the figure, a VR75-30 and a VR105-40 are shown connected in series. The source voltage is 250 volts, and 82.5 milliamperes flows through the load resistance. Since current through the two VR tubes is common, the limits of regulation are determined by the tube having the smaller current limitations. (In this case, the VR 75-30). In computing I_{mean} for this circuit, I_{max} and I_{min} will be 30 milliamperes and 5 milliamperes, respectively. Therefore, the mean current will be 17.5 milliamperes.

The value of R_S in the figure can be computed using the source voltage of 250 volts and the total current through R_S (load current + I_{mean}). Using these values, $R_S = 700$ ohms. Note that the regulated voltage to the load is 180 volts. This provides a regulated voltage greater than would be possible using either VR tube by itself.

Another advantage of using VR tubes in series is illustrated in figure 3-46. In this circuit, several values of regulated voltages are obtained from a single power supply.

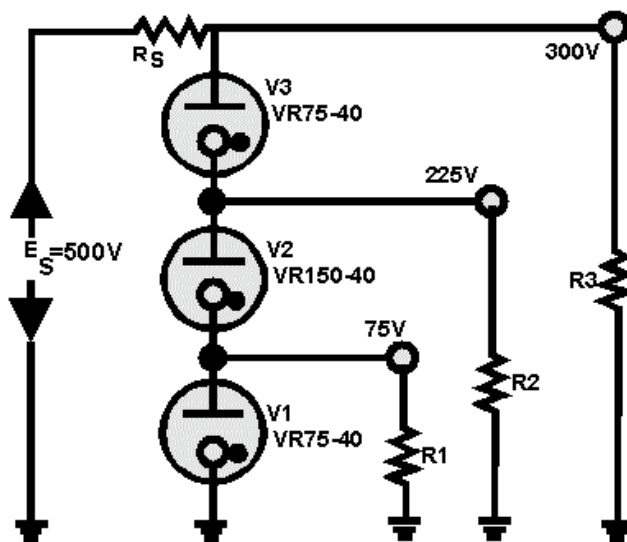


Figure 3-46.—VR tubes as voltage dividers

The current flowing through V2 in the figure is a combination of the current through R1 and the current through V1. The current through V3, on the other hand, is the sum of the currents through V2 and R2. Since V3 has more current flowing through it than any of the other VR tubes, it places or determines the limit on the maximum current in the VR tube circuit. Since the maximum rating of V3 is 40 milliamperes, the currents through R1 and R2 must be limited to only a few milliamperes, or the rating of V3 will be exceeded and regulation will cease.

The obvious advantage in using VR tubes in series is to provide several regulated voltages from a single power supply. The primary disadvantage is in the current limitations. Since it is impossible to have all VR tubes operating about their mean current values, this limits the ability of the circuit to regulate over wide ranges of variations in load resistance or source voltage.

VR Tubes Connected in Parallel

One might expect that connecting VR tubes in parallel as shown in figure 3-47 would increase the current handling capacity of the network. Although this is true for some gas-filled tubes, it is not true for VR tubes. In figure 3-47, two VR tubes are constructed in exactly the same way. The only difference will be a slight variation in their ionization potential. For the purpose of this discussion, VR tube VR1 will have a lower ionization potential than VR2. The potential that must be reached before a VR tube ionizes is considerably higher than its normal operating voltage.

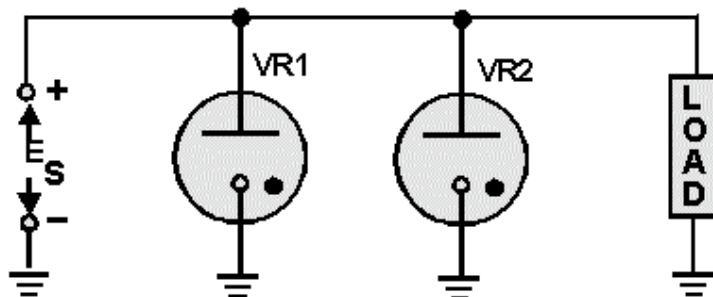


Figure 3-47.—VR tubes connected in parallel.

When voltage is applied to the circuit of figure 3-47, as soon as the correct potential is reached, VR1 begins to conduct and the potential across it decreases to its operating voltage. The potential across VR2 never becomes high enough to cause it to ionize. Therefore, placing the VR tubes in parallel accomplishes no useful purpose. When greater current handling capacity and better regulation are desired, electronic (vacuum tube) regulator circuits are used.

Several conditions may either indicate or cause problems with a VR tube regulator. Initially, you can get some indication of the trouble associated with a gas-tube regulator circuit by visually inspecting it to determine the presence of the characteristic glow from the ionized gas within the tube. When current through the tube is near its maximum rating, the tube is highly ionized. When the current is near its minimum rating, the tube is lightly ionized. Therefore, the intensity of the gaseous discharge within the tube is an indication of tube conduction. If the tube is not ionized, however, this does not necessarily mean that the tube is defective. The same indication (lack of characteristic glow) may also result from the following conditions: the series resistor (R_S) has increased in value, the dc input voltage (E_S) is below normal, the load current is below normal, or the load current is excessive. You therefore need to make dc voltage measurements at the input and output terminals of the voltage regulator circuit to determine whether the problem is inside the regulator circuit or outside of it.

You can check value of the series resistor (R_S) by using ohmmeter measurements to determine whether any change in resistance has occurred. If the maximum current rating of the regulator tube is exceeded for a considerable length of time, the tube may be damaged and lose its regulation characteristics; therefore, you can suspect the regulator tube itself as a possible source of trouble.

Although VR tubes are used extensively in electronic equipment, there are circuits that require a greater degree of regulation than a VR tube can provide. For these circuits, an electron tube voltage regulator is used.

Electron Tube Voltage Regulator

An electron tube may be considered a variable resistance. When the tube is passing a direct current, this resistance is simply the plate-to-cathode voltage divided by the current through the tube and is called the dc plate resistance (R_p). For a given plate voltage, the value of R_p depends upon the tube current, and the tube current depends upon the grid bias.

Refer to figure 3-48, view (A). The resistance of V1 is established initially by the bias on the tube. Assume that the voltage across the load is at the desired value. Then the cathode is positive with respect to ground by some voltage (E_L). The grid can be made positive relative to ground by a voltage (E_2) that is less than E_1 . The potentiometer R2 is adjusted until the bias (grid-to-cathode voltage), which is $E_2 - E_1$, is sufficient to allow V1 to pass a current equal to the desired load current. With this bias, the resistance of V1 is established at the proper value to reduce the rectifier output voltage to the desired load voltage.

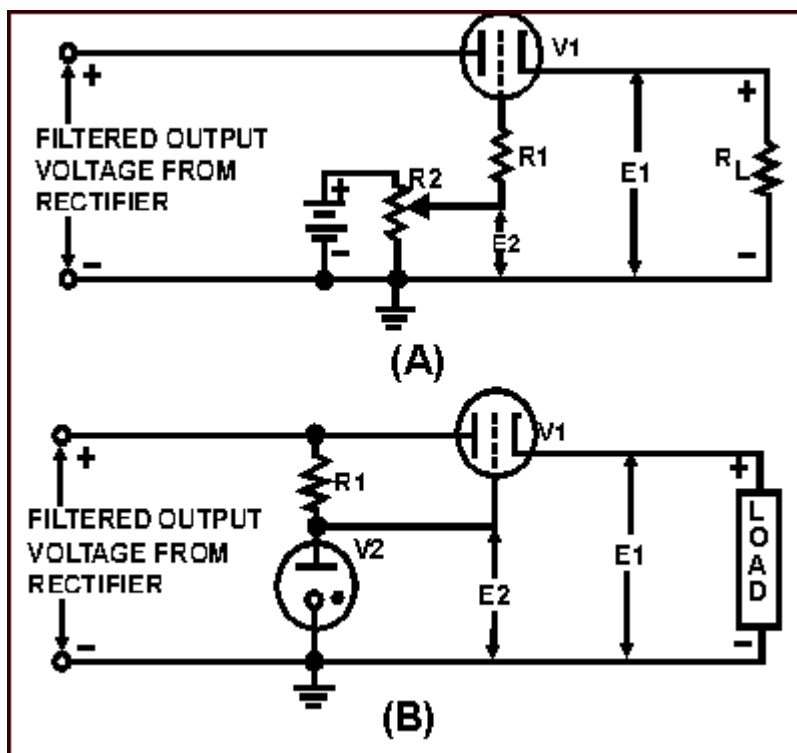


Figure 3-48.—Electron tube voltage regulator using a battery for the fixed bias

If the rectifier output voltage increases, the voltage at the cathode of V1 tends to increase. As E_1 increases, the negative bias on the tube increases and the plate resistance of the tube becomes greater. Consequently, the voltage drop across V1 increases with the rise in input voltage. If the circuit is designed properly, the increased voltage drop across V1 is approximately equal to the increase in voltage at the input. Thus the load voltage remains essentially constant.

The resistor (R_1) is used to limit the grid current. This is necessary in this particular circuit because the battery is not disconnected when the power is turned off. However, the battery can be eliminated from the circuit by the use of a glow tube (V2), as shown in view (B) of the figure, to supply a fixed bias for the grid of the tube. The action of the circuit in view (B) is the same as the action of the circuit in view (A). The output voltage of the simple voltage regulators shown in the figure cannot remain absolutely constant. As the rectifier output voltage increases, the voltages on the cathode of V1 must rise slightly if the regulator is to function.

The voltage regulators shown in the figure compensate not only for changes in the output voltage from the rectifier, but also for changes in the load. For example, in view (B) if the load resistance decreases, the load current will increase. The load voltage will tend to fall because of the increased drop across V1. The decrease in load voltage is accompanied by a decrease in bias voltage on V1. The bias voltage on V1 is equal to $E_1 - E_2$. Thus the effective resistance of V1 is reduced at the same time the load current is increased. The IR drop across V1 increases only a slight amount because R decreases about as much as I increases. Therefore, the tendency for the load voltage to drop when the load is increased is checked by the decrease in resistance of the series triode.

Q40. In an electron tube regulator, the electron tube replaces what component?

CURRENT REGULATION

Before we go to the next section, there is one type of regulation that we should discuss—current regulation. In most power supplies, current is not regulated directly. Fuses and other circuit protection devices are used to set an upper limit on the amount of current that can flow in a power supply. Once this limit is exceeded, the fuse simply opens and the power supply is deenergized. Beyond this, current is usually left unregulated because the load will draw from the power supply only the amount of current that it needs. Decreases and increases in the power supply voltage caused by the variations in load current are usually controlled by the voltage regulator.

The Amperite Regulator

There are some cases in which current must be regulated or kept at a relatively constant value. The best example of this is the filament supply of a power transformer located in a power supply that is designed to supply filament power to many tubes. You can see this in view (A) of figure 3-49, which is a portion of a power supply designed to supply 50 vacuum tubes with both plate and filament voltages. Under normal conditions, circuit current will not exceed 2.5 amperes. For this reason, the power supply has been fused at 3 amperes. Because you are only interested in current regulation at this time, only the portion of the power supply that deals with current regulation is shown; namely, the power transformer and four of the 50 parallel connected vacuum-tube filaments. At operating temperatures, the resistance of each filament is 1 kilohm. Because the filaments are connected in parallel, the total filament resistance at operating temperature is 20 ohms. Ohm's law,

$$I = \frac{E}{R}$$

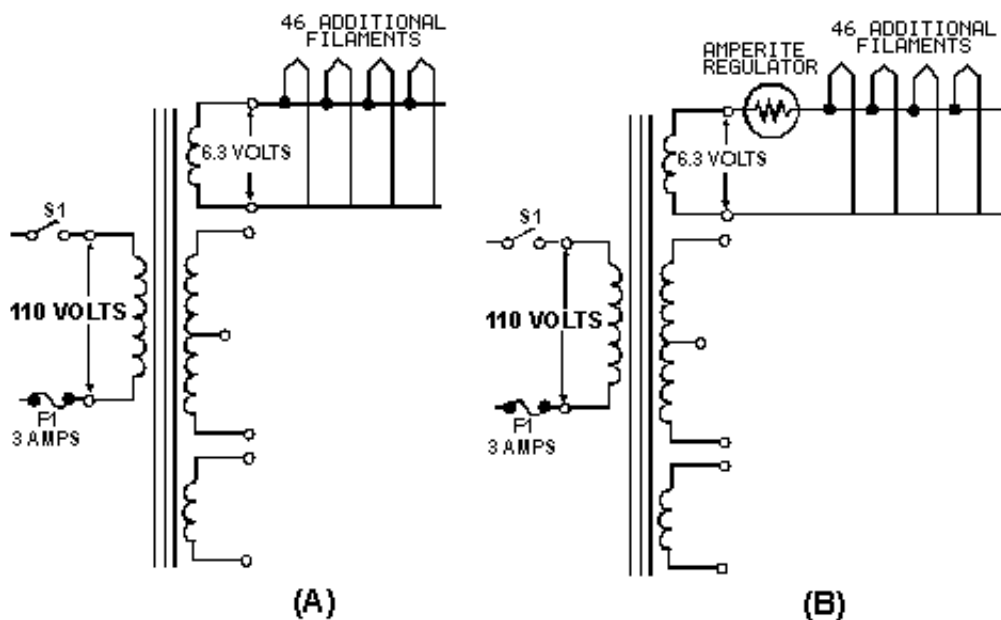


Figure 3-49.—Amperite regulator.

tells you that the filaments draw .315 amperes. You should know from your previous study that as conductors are heated, their resistance increases. Therefore, the cold resistance of the filaments is considerably lower than the hot resistance. In this case, assume 100 ohms per filament. The total resistance of the 50 parallel filaments is then 2 ohms when the power supply is first energized, and the filaments draw 3.15 amperes of current. If the current for the rest of the power supply is added to the filament current, the surge current will cause the power supply to draw 5 amperes when it is first energized. Unfortunately, the power supply is fused at 3 amperes. Under these conditions, it would be impossible to keep the power supply on the line long enough to get the filaments up to operating temperature.

There are three possible solutions to this problem. The first is simply to fuse the power supply at 5 amperes, but this could allow excessive current to flow in the power supply. Another solution is to use a slow-blow fuse. Unfortunately, the duration of the current surge may exceed the time limit that a slow-blow fuse can handle. Therefore, current regulation is the best solution to this problem.

Because of its quick-heating ability, the amperite tube is ideal as a current regulator. The amperite regulator is nothing more than an iron wire enclosed in a hydrogen-filled envelope. Because of its construction, the iron filament will heat quickly when current is applied to it.

View (B) of figure 3-49 shows the amperite regulator connected in series with the filaments of the load. When the power supply is first energized, the iron wire of the amperite gets hot quickly and presents a large resistance connected in series with the 2 ohms of filament resistance. As a result, most of the voltage is dropped across the amperite. Because of the large resistance of the amperite regulator, current in the circuit is held to an acceptable level in accordance with Ohm's law:

$$I = \frac{E}{R}$$

As the filaments warm up, their resistance increases, which causes circuit current to decrease. The decreasing circuit current allows the iron wire of the amperite to cool. As it cools, its resistance decreases until it reaches the approximate resistance of the circuit wiring. You might think that decreasing the resistance of the amperite would allow circuit current to increase again, but this does not happen. As the iron wire of the amperite cools and its resistance decreases, the resistance of the warming tube filaments increases. Throughout the entire heating cycle of the filaments, the total resistance of the series circuit, consisting of the amperite and tube filaments, remains fairly constant. When power is first applied, most of the resistance is in the amperite. Therefore, most of the voltage is dropped across the resistance of the amperite. Halfway through the cycle, the resistance of the amperite and the resistance of the filaments are approximately equal, and the voltage drops across the two series elements are equal. Finally, when the filaments have reached their operating temperature, most of the resistance is in the filaments of the tube. Therefore, most of the voltage is dropped across the tube filaments.

The important thing to note is that the total circuit resistance remains approximately the same throughout the heating cycle. As the cycle progresses, the resistance of the amperite decreases as the resistance of the tube filaments increases. Because resistance and voltage (6.3 volts) remain constant, current remains constant, except for the slight surge in the beginning of the heating cycle, which is necessary to heat up the iron wire of the amperite.

Now that we have discussed the different types of regulators, you should be able to see that there are many variables that affect good regulation.

Although you may not be required to design regulators, you will be required to maintain them because your electronic equipment depends upon good regulation to operate properly.

Up to this point we have discussed only the individual sections of the electron tube power supply. In the next section, we will discuss the techniques of troubleshooting these individual sections and the total power supply.

Q41. What is the purpose of the amperite regulator?

Q42. As the tube filaments in the load heat up, will the circuit current increase or decrease?

TROUBLESHOOTING POWER SUPPLIES

Whenever you work with electricity, you **must** follow all the appropriate safety precautions. In the front of all electronic technical manuals, you will always find a section on safety precautions. You should also find posted on each piece of equipment a sign listing the specific precautions for that equipment. One hazardous area that is sometimes overlooked, especially on board ship, is grounding of equipment. By grounding the return side of the power transformer to the metal chassis, manufacturers can wire the cathodes of the tubes in both the power supply and the load being supplied by the power supply directly to the metal chassis. This eliminates the necessity of wiring each tube directly to the return side of the transformer, saving wire, and reducing the cost of building the equipment. While this solves one of the problems of the manufacturer, it creates a problem for you, the technician. Unless the chassis is physically grounded to the ship's ground (the hull), the chassis can be charged (or can float) several hundred volts above ship's ground. If you come in contact with the metal chassis at the same time you are in contact with the ship's hull, the current from the chassis can use your body as a low resistance path back to the ship's ac generators. At best this can be an unpleasant experience; at worst it can be fatal. For this reason Navy electronic equipment is always grounded to the ship's hull, and approved rubber mats are required in all spaces where electronic equipment is present. Therefore, before you start to work on any electronic or electrical equipment ALWAYS ENSURE THAT THE EQUIPMENT AND ANY TEST EQUIPMENT YOU ARE USING IS PROPERLY GROUNDED AND THAT THE RUBBER MAT YOU ARE STANDING ON IS IN GOOD CONDITION. As long as you follow these simple rules, you should be able to avoid the possibility of becoming an electrical conductor.

TESTING

There are two widely used checks in testing electronic equipment. The first is the **VISUAL CHECK**. Do not underestimate the importance of this check. Many technicians find defects right away simply by looking for them. A visual check does not take long; in fact you should be able to see the problem in about 2 minutes if it is the kind of problem that can be seen. You should learn the following procedure. You will find yourself using it quite often, as it is good not only for power supplies but also for any other type of electronic equipment you may be troubleshooting.

1. BEFORE YOU PLUG IN THE EQUIPMENT, LOOK FOR:

- a. LOOSE TUBES—A tube that is not properly seated in its socket may not be making proper contact with the rest of the circuit. It may very well be the source of your problem. Push the tube completely into place.
- b. SHORTS—Examine any terminal or connection that is close to the chassis or to any other terminal for the possibility of a short. A short in any part of the power supply can cause considerable damage. Look for and remove any stray drops of solder, bits of wire, nuts, or screws. It sometimes helps to shake the chassis and listen for any tell-tale rattles. Remember to correct any problem that may cause a short circuit. If it is not causing trouble now, it may cause problems in the future.

- c. DISCOLORED OR LEAKING TRANSFORMER—This is a sure sign that there is a short somewhere. Locate it. If the equipment has a fuse, find out why the fuse did not blow; too large a size may have been installed, or there may be a short across the fuse holder.
- d. LOOSE, BROKEN, OR CORRODED CONNECTIONS—Any connection that is not in good condition is a trouble spot. If it is not causing problems now, it probably will in the future. Fix it.
- e. DAMAGED RESISTORS OR CAPACITORS—A resistor that is discolored or charred has been subjected to an overload. An electrolytic capacitor will show a whitish deposit at the seal around the terminals. Check for a short whenever you notice a damaged resistor or capacitor. If there is no short, the trouble may be that the power supply has been overloaded in some way. Make a note to replace the part after signal tracing. There is no sense in risking a new part until you have located the trouble.

2. PLUG IN THE POWER SUPPLY AND LOOK FOR:

- a. SMOKING PARTS—If any part smokes or if you hear any boiling or sputtering sounds, pull the plug immediately. There is a short circuit somewhere that you have missed in your first inspection. Use an ohmmeter to check the part again; begin in neighborhood of the smoking part.
- b. COLD TUBES—After allowing the equipment about two minutes for warm-up, touch all the tubes. If a tube is cold, it is either burned out or there is a break in the heater connections and the tube is not receiving proper heater voltage. Remove the tube and connect an ohmmeter across the heater terminals to see if the filament is open (reads almost infinite resistance). If the filament reads open, it is burned out. Replace the bad tube with a good one. If the filament reads a low resistance, this indicates that the filament is all right. Use an ac voltmeter to find the break between the filament and the output of the transformer.
- c. SPARKING—Tap or shake the chassis. If you see or hear sparking, you have located a loose connection or a short. Check and repair the problem.

If you locate and repair any of the defects listed under the visual check, make a note of what you find and what you do to correct it. It is quite probable you have found the trouble. However, a good technician takes nothing for granted. You must prove to yourself that the equipment is operating properly and that no other troubles exist.

If you find none of the defects listed under the visual check, go ahead with the signal tracing procedure. The trouble is probably of such a nature that you cannot see it directly with your eye—you must see it through the eye of the oscilloscope.

The second type of testing is signal tracing. Tracing the ac signal through the equipment is the most rapid method of locating a trouble that you cannot find by a visual check. It also serves as a check on any repairs you may have made. The idea is to trace the ac voltage from the transformer, to see it change to pulsating dc at the rectifier tube filament, and then to see the pulsations smoothed out by the filter. The point where the signal stops or becomes distorted is the place to look for the trouble.

Before you begin signal tracing, it is a good idea to measure the dc voltage. The dc output voltage should be in the neighborhood of 340 volts. If you have no dc output voltage, you should look for an open or a short in your signal tracing. If you have a low dc voltage, you should look for a defective part and keep your eyes open for the place where the signal becomes distorted.

Signal tracing is done by observing the waveform at the input and output of each part of a circuit. It is the method used to localize trouble in a circuit.

Let's review what each part of a good power supply does to the signal, as shown in figure 3-50. The ac voltage is brought in from the power line through the line cord. This voltage is connected to the primary of the transformer through the **ON-OFF** switch (S1). At the secondary winding of the transformer (points 1 and 2), the scope shows you a picture of the stepped-up voltage developed across each half of the secondary winding—the picture is that of a complete sine wave. Each of the two stepped-up voltages is connected between ground and one of the two plates of the rectifier tube. At the two rectifier plates (points 4 and 5) there is still no change in the shape of the stepped-up voltage the scope picture still shows a complete sine wave.

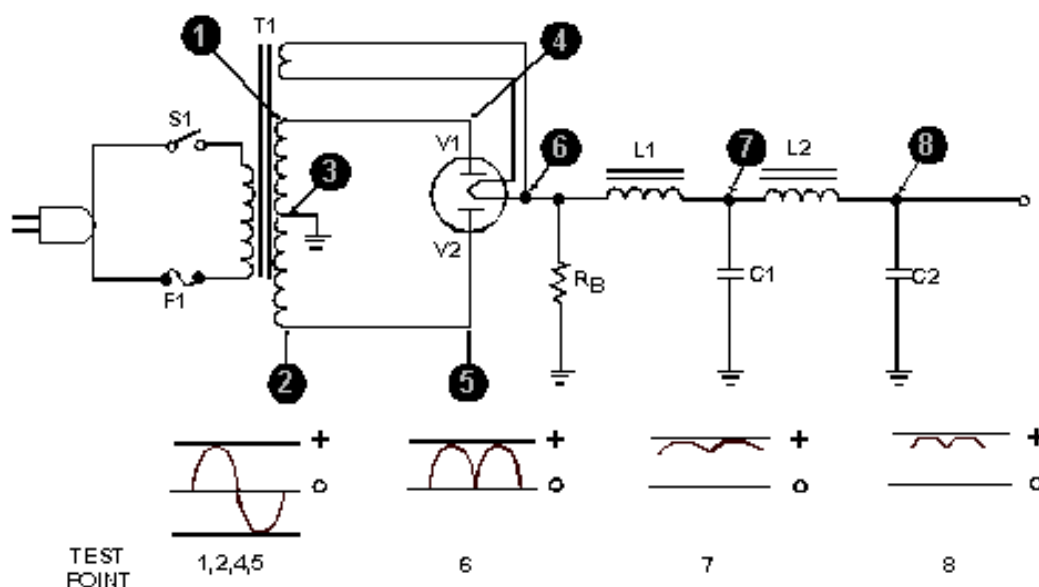


Figure 3-50.—Complete power supply (without regulator).

However, when you look at the scope pattern for point 6 (the voltage at the rectifier heater), you see the wave shape for pulsating direct current. This pulsating dc is fed through the first choke (L1) and filter capacitor (C1), which remove a large part of the ripple or "hum," as shown by the waveform for point 7. Finally, the dc voltage is fed through the second choke (L2) and filter capacitor (C2), which remove nearly all of the remaining ripple. See the waveform for point 8, which shows almost no visible ripple. You now have almost pure dc.

No matter what power supplies you may encounter in the future, they all do the same thing—they change ac voltage into dc voltage.

COMPONENT PROBLEMS

The following paragraphs will give you an indication of troubles that occur with many different electronic circuit components.

Tube Troubles

The symptoms of tube trouble will vary with every type of circuit and each type of tube. However, the problems that can develop with a tube are common to every tube. Here are the five possible tube

troubles that you should keep in mind. The meaning of each trouble will be clear by the time you end your study of vacuum tubes, even though you may not quite understand them now.

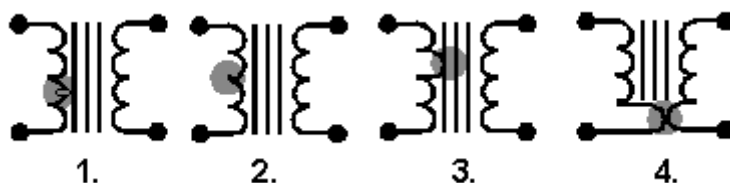
1. The filament, after long service, may be unable to emit as many electrons as are required for proper operation.
2. The filament may burn out.
3. A tube element—the plate, for instance—may break its connection with the tube base pin.
4. Two elements, such as filament and plate, may short together.
5. The tube may become gassy.

The symptoms you will come across in signal tracing will be many and varied. You will need to combine your "know-how" of the circuit and your knowledge of these five possible tube troubles to determine if the tube could in some way be causing the symptoms. If you suspect the tube of causing trouble, either try another tube in its place or check it on a tube tester. But remember, the final check of whether or not the old tube was bad is whether or not the equipment works properly when a good tube is put in its place. Therefore, putting in a good tube and then trying out the equipment is the best check.

Transformer and Choke Troubles

As you should know by now, the transformer and choke are quite similar in construction. Therefore, it is no coincidence that the basic troubles they can develop are the same.

1. A winding can open.
2. Two or more turns of one winding can short together.
3. A winding can short to the casing, which is usually grounded.
4. Two windings can short together. This trouble is possible, of course, only in transformers.



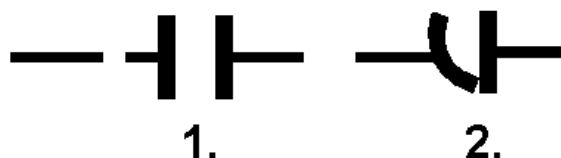
As with the tube, the symptoms of these troubles will vary with the type of circuit. However, when you have decided that one of these four possible troubles could be causing the symptoms, there are definite steps to take. If you surmise that there is an open winding or windings shorted together or to ground, an ohmmeter continuity check will locate the trouble. If the turns of a winding are shorted together, you may not be able to detect a difference in winding resistance. Therefore, you need to connect a good transformer in the place of the old one and see if the symptoms are eliminated; but keep in mind that transformers are difficult to replace. Make absolutely sure that the trouble is not elsewhere in the circuit before you change the transformer.

Occasionally, shorts will appear only when operating voltages are applied to the transformer. In this case you might find the trouble with a megger—an instrument that applies a high voltage as it reads resistance.

Capacitor and Resistor Troubles

Only two things can happen to a capacitor:

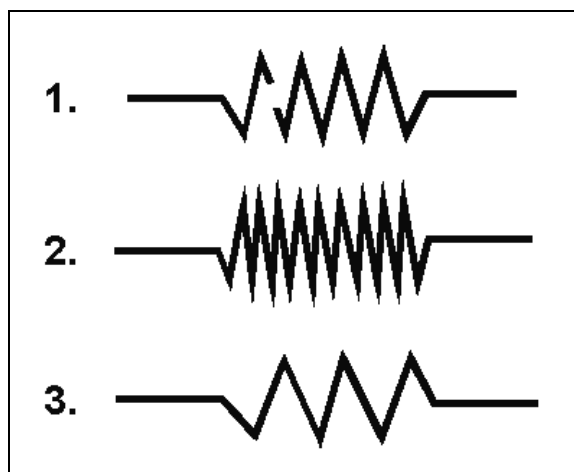
1. It may open up, removing itself completely from the circuit.
2. It may develop an internal short circuit. This means that it begins to pass current as though it were a resistor or a direct short.



You can check a capacitor you suspect of being open by disconnecting it from the circuit and checking it with a capacitor analyzer. You can check a capacitor you suspect of being leaky with an ohmmeter; if it reads less than 500 kilohms, it is more than likely bad. However, capacitor troubles are difficult to find since they may appear intermittently or only under operating voltages. Therefore, the best check for a faulty capacitor is to replace it with one you know to be good. If this restores proper operation, the fault was in the capacitor.

Resistor troubles are the simplest; but like the rest, you must keep them in mind.

1. A resistor can open up.
2. A resistor can increase in value.
3. A resistor can decrease in value.



You already know how to check possible resistor troubles. Just use an ohmmeter after making sure no parallel circuit is connected across the resistor you wish to measure. When you know a parallel circuit is connected across the resistor or when you are in doubt, disconnect one end of the resistor before measuring it. The ohmmeter check will usually be adequate. However, never forget that intermittent troubles may develop in resistors as well as in any other electronic parts. Also remember that the final

proof that a resistor is bad is when you replace it with another resistor and the equipment operates satisfactorily.

Although you may observe problems that we have not covered specifically in this chapter, you should have gained enough knowledge to localize and repair any problem that may occur.

Q43. What is the most important thing to remember when troubleshooting?

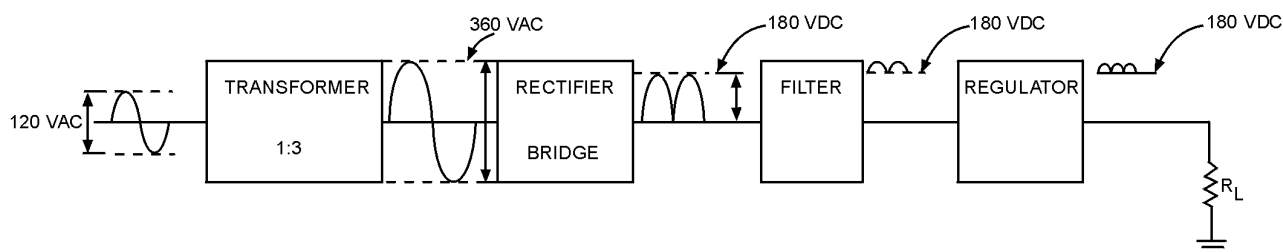
Q44. What is the main reason for grounding the return side of the transformer to the chassis?

Q45. What are two types of checks used in troubleshooting power supplies?

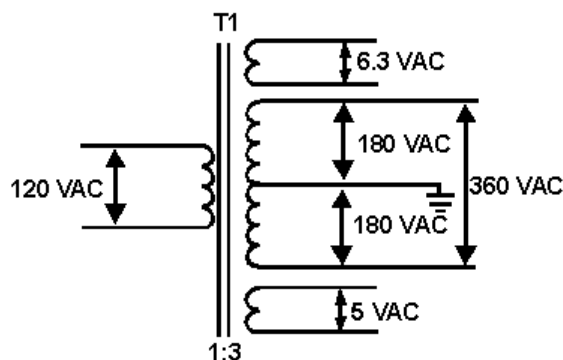
SUMMARY

In this chapter, we have presented you a basic description of the theory and operation of a basic power supply and its components. The following summary should enhance your understanding of power supplies.

POWER SUPPLIES are electronic circuits designed to convert ac to dc at any desired level. Almost all power supplies are composed of four sections: transformer, rectifier, filter, and regulator.

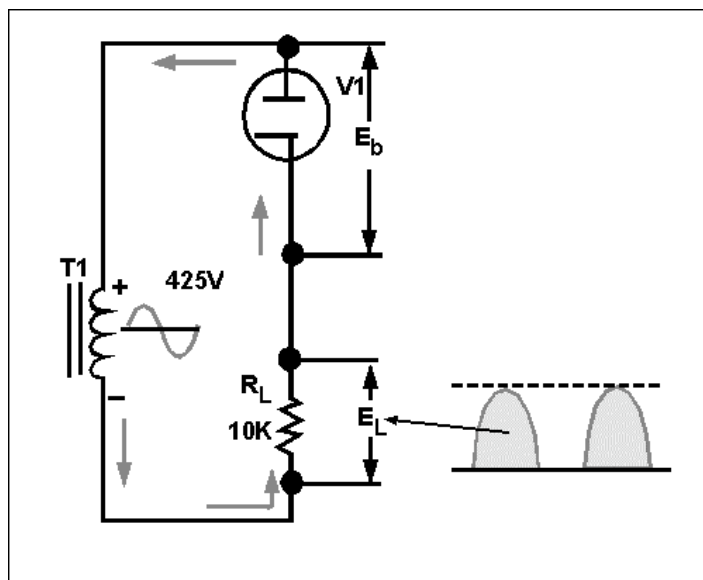


The **POWER TRANSFORMER** is the input transformer for the power supply. In addition to the high voltage, the power transformer also supplies filament voltage.

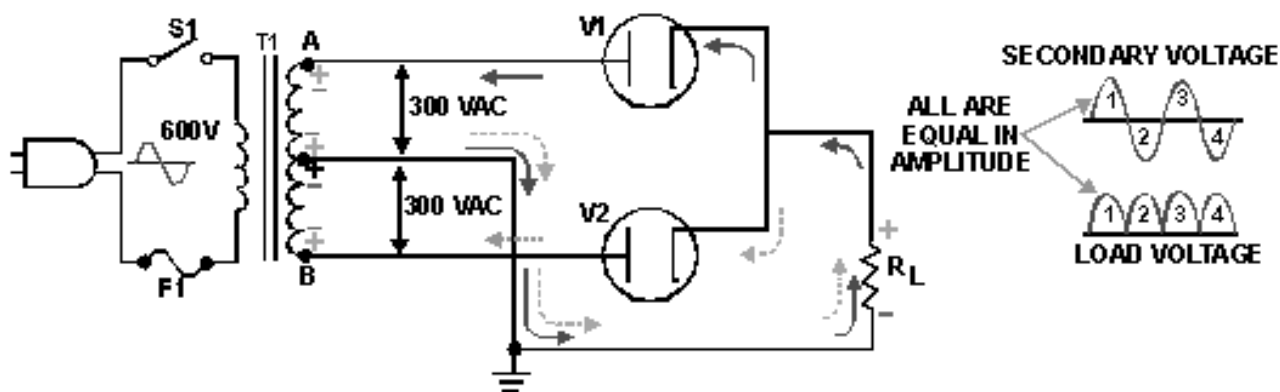


The **RECTIFIER** is the section of the power supply that contains the secondary windings of the power transformer and the rectifier circuit. The rectifier uses the ability of a diode to conduct during one half cycle of ac to convert ac to dc.

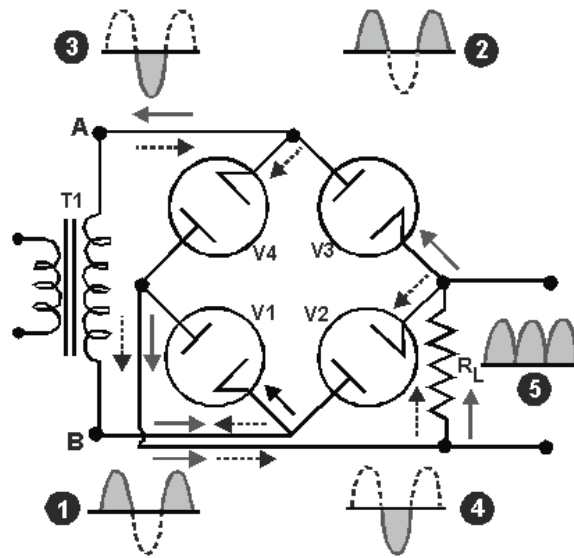
HALF-WAVE RECTIFIERS give an output on only one half cycle of the input ac. For this reason, the pulses of dc are separated by a period of one half cycle of zero potential voltage.



FULL-WAVE RECTIFIERS conduct on both halves of the input ac cycles. As a result, the dc pulses are not separated from each other. A characteristic of full-wave rectifiers is the use of a center-tapped, high-voltage secondary. Because of the center tap, the output of the rectifier is limited to one-half of the input voltage of the high-voltage secondary.

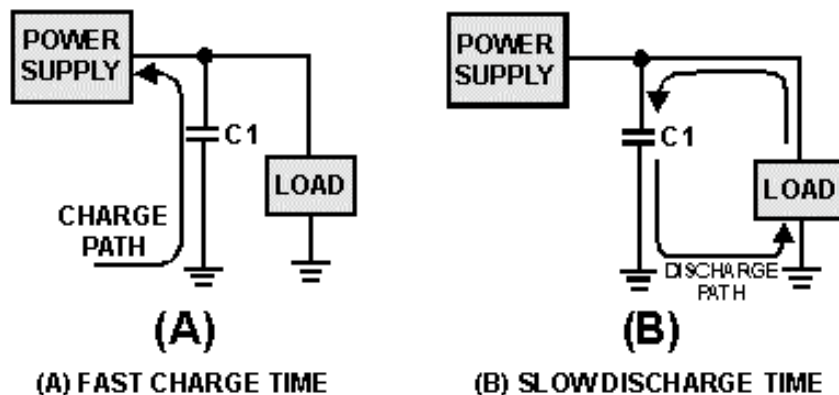


BRIDGE RECTIFIERS are full-wave rectifiers that do not use a center-tapped, high-voltage secondary. Because of this their dc output voltage is equal to the input voltage from the high-voltage secondary of the power transformer. Bridge rectifiers use four diodes connected in a bridge network. Tubes conduct in diagonal pairs to give a full-wave pulsating dc output.

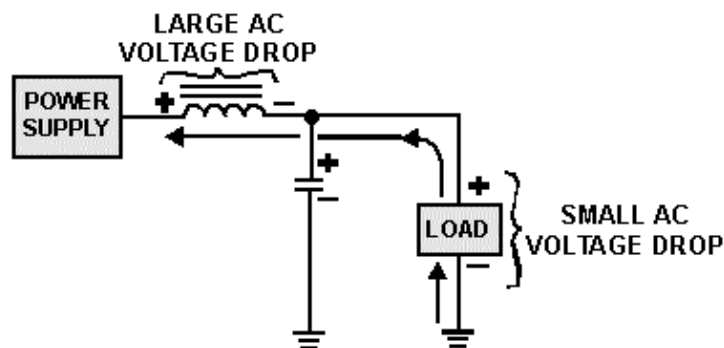


FILTER CIRCUITS are designed to smooth, or filter, the ripple voltage present on the pulsating dc output of the rectifier. This is done by an electrical device that has the ability to store energy and to release the stored energy.

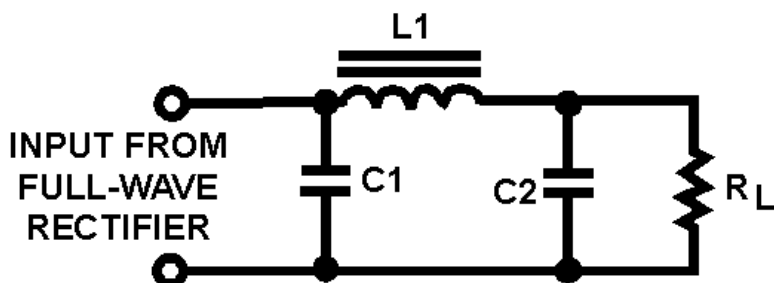
CAPACITANCE FILTERS are nothing more than large capacitors placed across the output of the rectifier section. Because of the large size of the capacitors, fast charge paths, and slow discharge paths, the capacitor will charge to average value, which will keep the pulsating dc output from reaching zero volts.



INDUCTOR FILTERS use an inductor called a choke to filter the pulsating dc input. Because of the impedance offered to circuit current, the output of the filter is at a lower amplitude than the input.

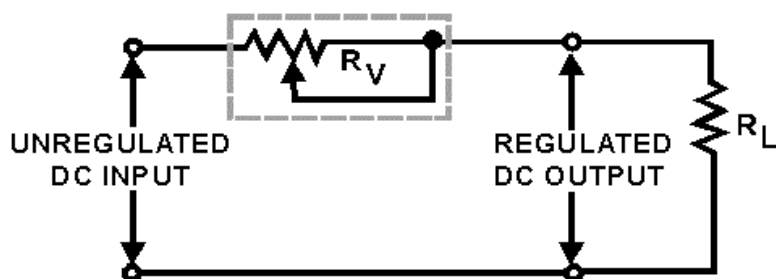


PI-TYPE FILTERS use both capacitive and inductive filters connected in a pi-type configuration. Because of the combination of filtering devices, the ability of the pi filter to remove ripple voltage is superior to that of either the capacitance or inductance filter.

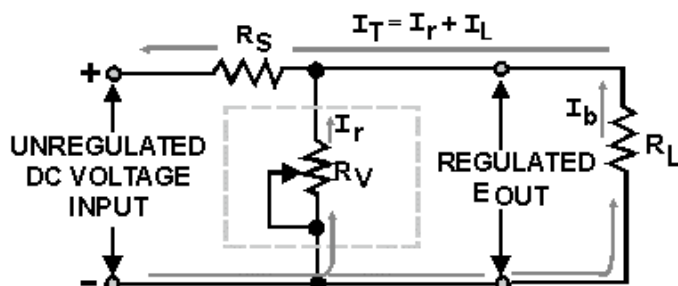


VOLTAGE REGULATORS are circuits designed to maintain the output of power supplies at a constant amplitude despite variations of the ac source voltage or changes of the resistance of the load. This is done by creating a voltage divider of a resistive element in the regulator and the resistance of the load. Regulation is achieved by varying the resistance of the resistive element in the regulator.

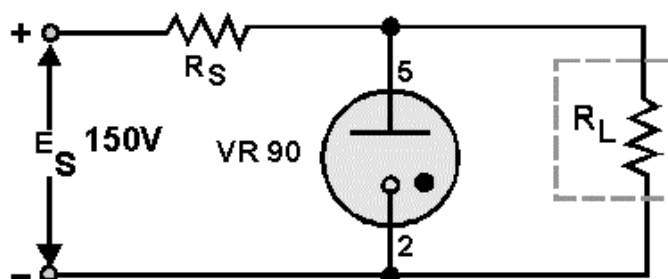
A **SERIES REGULATOR** uses a variable resistance in series with the load. Regulation is achieved by varying this resistance either to increase or decrease the voltage drop across the resistive element of the regulator. Characteristically, the resistance of the variable resistance moves in the same direction as the load. When the resistance of the load increases, the variable resistance of the regulator increases; when load resistance decreases, the variable resistance of the regulator decreases.



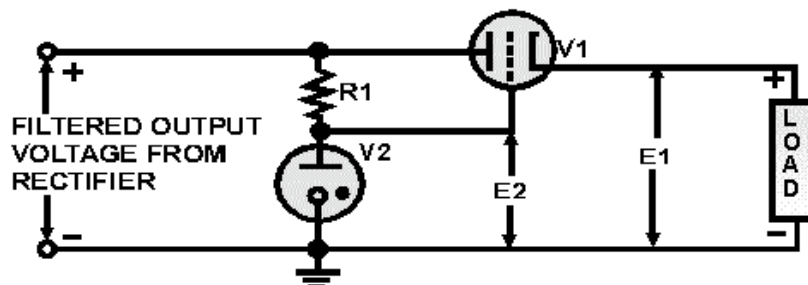
SHUNT REGULATORS use a variable resistance placed in parallel with the load. Regulation is achieved by keeping the resistance of the load constant. Characteristically, the resistance of the shunt moves in the opposite direction of the resistance of the load.



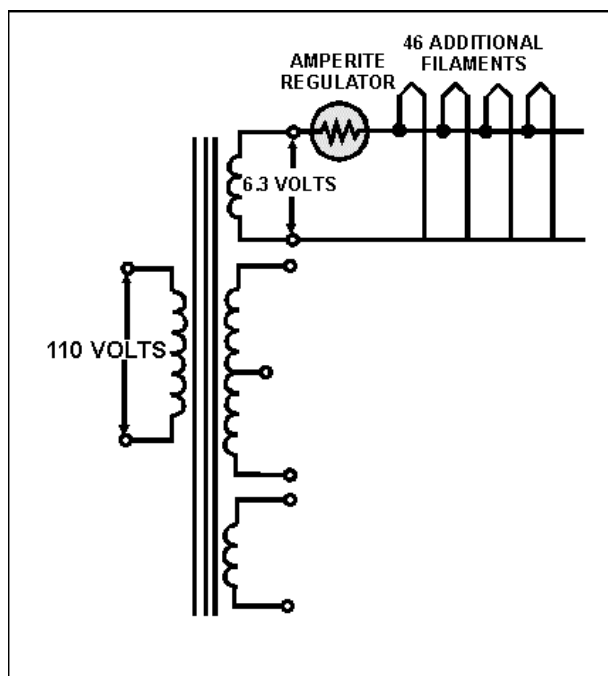
VR-TUBE REGULATORS are shunt regulators that use a cold cathode as a variable resistance in parallel with the load. Because of their ability to maintain a constant voltage potential between their plates and cathode, glow tubes can be connected in series to regulate any voltage. Additionally, glow tubes can be used to deliver different voltages to different loads.



SIMPLE ELECTRON TUBE REGULATORS use the dc plate resistance of a triode as a variable resistance in series with the load. The resistance of the vacuum tube is varied by changing the amount of conduction of the tube. This is done by holding the control grid voltage at a constant level and allowing the cathode voltage to vary with the output voltage.



The **AMPERITE VOLTAGE REGULATOR** or **BALLAST TUBE** is normally used to control current surges. This is done by heating an iron wire in a hydrogen-filled envelope. The hot iron will present a large resistance to current flow.



ANSWERS TO QUESTIONS Q1. THROUGH Q45.

- A1. Transformer, rectifier, filter, regulator.
- A2. To maintain a constant voltage to the load.
- A3. It couples the power supply to the ac line voltage, isolates the ac line voltage from the load, and steps this voltage up or down to the desired level.
- A4. Filament voltage to the electron tubes.
- A5. Provides capability of developing two high-voltage outputs.
- A6. Positive.
- A7. Cutoff.
- A8. Pulsating dc.
- A9. Series.
- A10. 60 hertz.
- A11. $E_{avg} = 0.318 \times E_{max}$.
- A12. 120 hertz.
- A13. 63.6 volts.
- A14. The peak voltage is half that of a half-wave rectifier.

A15. The bridge rectifier can produce double the voltage with the same size transformer.

A16. Decrease-Capacitance is inversely proportional to X_C .

A17. Capacitor.

A18. Parallel.

A19. High.

A20. Increase.

A21. Value of capacitance and load resistance.

A22. Good.

A23. Yes.

A24. Counter electro-motive force of the inductor.

A25. 1 to 20 henries.

A26. Decrease.

A27. Small.

A28. Expense.

A29. When ripple must be held at an absolute minimum.

A30. LC capacitor-input filter.

A31. Cost of the inductor and size of the inductor.

A32. Ac line voltage and a change in load resistance.

A33. Percent of regulator.

A34. 33.33%

A35. 0%.

A36. Variation.

A37. Series and shunt.

A38. Increase.

A39. Parallel.

A40. Variable resistor.

A41. Current regulation.

A42. Decrease.

A43. Safety precautions.

A44. Reduce the cost of manufacturing equipment.

A45. Visual and signal tracing.