practical
POWER
SUPPLY
CIRCUITS

by JOHN POTTER SHIELDS

Practical Power-Supply Circuits

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Preface

Power supplies work behind the scenes in practically every piece of electronic equipment. Though they are essential if a circuit is to function, they do not have an active part in amplifying or generating the signals that are the end result. The proper functioning of the power supply is usually assumed or taken for granted, yet there must be an understanding of what the power supply should and can do if these other functions are to be performed efficiently.

There is a wide variety of components which can be arranged in many different circuits in order to provide sources of power. Vacuum tubes, gas-filled tubes, silicon rectifiers, silicon controlled rectifiers, and transistors make up only a partial list of the active elements that can be used. When assembled as half-wave rectifiers, full-wave rectifiers, bridges, or voltage multipliers, they are ready to fullfill their intended function. In most cases the basic task is to change the standard 117-volt alternating current into a form usable by an electronic circuit—usually direct current at potentials varying from 5 to 500 volts. To explain the circuits that perform this function is one of the major goals of this book.

Voltage regulation—the ability of a power supply to maintain a steady voltage and/or current under changing conditions of load and input—is essential if many electronic circuits are to give satisfactory service. An explanation of both open-loop and closed-loop methods of regulation is given in this book. Circuits involving both tubes and semiconductors are described and illustrated.

Silicon controlled rectifiers are being widely used where variable power supplies are essential, so an entire chapter is devoted to how they work and what they can do. The student in electronics will be anxious to try assembling a typical circuit in order to gain first-hand knowledge. All the information needed for the project is in this book.

Batteries are assuming increased importance in these days when portability of equipment is being stressed. There have been many

radical changes in their construction and potential applications in recent years. It is essential that the student and technician be familiar with the current trends in batteries, so a chapter on this subject has been included in this book.

It is the hope of the author that the reader will construct some or all of the power supplies described herein. Every effort has been made to provide all the essential information so this can be done. The name of a manufacturer or supplier has been indicated for transformers, chokes, and other parts that might be difficult to obtain.

While this book does not attempt to exhaust its subject, it is hoped that a careful study of its contents will provide a basic understanding of practical power-supply circuits.

JOHN POTTER SHIELDS

Dedicated to my mother

Contents

CHAPTER 1

Basic Power-Supply Circuits

The conventional electronic power supply is designed to provide a
d-c output voltage from an applied a-c input voltage. The job of con-
verting the alternating current to direct current is performed by the
power-supply rectifier. There are four basic power-supply rectifier
arrangements: half-wave, full-wave, bridge, and voltage multiplier.

THE HALF-WAVE RECTIFIER

Fig. 1-1 shows the basic operation of the half-wave rectifier. In Fig.
1-1A the a-c voltage is applied to the primary of transformer T1 so
that the top of the secondary is positive with respect to the bottom.
Under this condition the plate of rectifier tube V1 is positive with re-
spect to the cathode. Electrons flow from the cathode to the plate,
through the secondary winding of T1, and through the load, as indi-
cated by the arrows.

In Fig. 1-1B, the a-c voltage applied to the primary of T1 has re-
versed so that the top of the secondary is now negative with respect
to the bottom. The plate of V1 is now negative with respect to the
cathode, so no electrons flow from cathode to plate, and there is no
current in the secondary of T1 and the load. (Remember, the plate of
a vacuum tube must be positive with respect to the cathode for elec-
trons to be attracted to the plate from the cathode).

On the next half-cycle of the supply, the plate is again positive with
respect to the cathode, and electrons again flow through V1, the sec-
ondary of T1, and the load. From this you can see that a series of
current pulses is produced through the load. These pulses are of such
a polarity that the cathode end of the load is positive with respect to
the bottom end, as shown in Fig. 1-1A.

Fig. 1-2 shows another variation of the basic half-wave rectifier. In this circuit, rectifier V1 has been reversed so that its cathode is connected to the top of the secondary winding of T1. In Fig. 1-2A, the top of the secondary is negative with respect to the bottom, and as a result, the cathode is negative with respect to the plate. (This is the same as saying the plate is positive with respect to the cathode.) Electrons flow

(A) Top of secondary positive.

(B) Top of secondary negative.

(C) Positive output pulses.
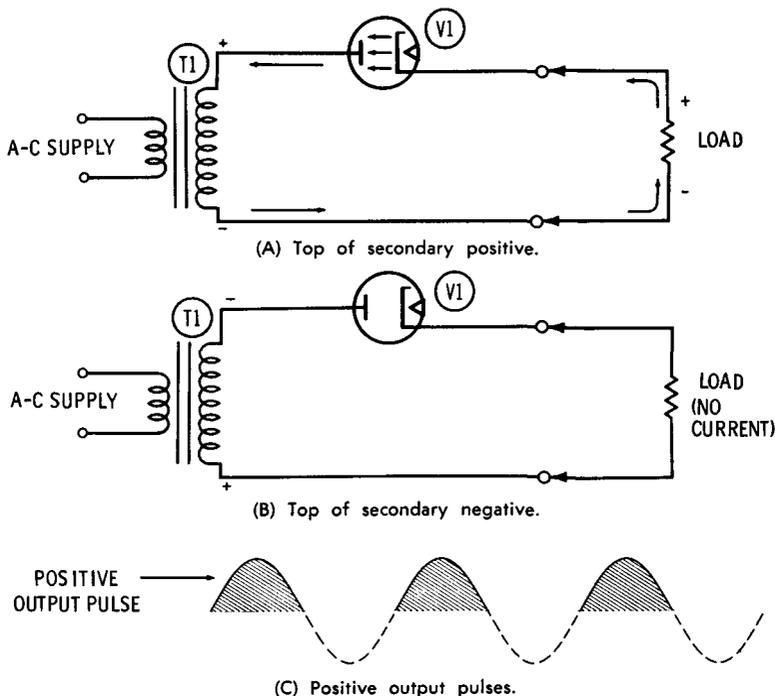
Fig. 1-1. Operation of half-wave rectifier (positive output).

from the cathode to the plate; the resulting current in the circuit is indicated by the arrows. Note that the bottom of the load is now positive with respect to the top—just the reverse of Fig. 1-1A.

In Fig. 1-2B, the upper end of the secondary is positive with respect to the bottom end, so the cathode is positive with respect to the plate. No electrons flow from cathode to plate, and there will be no current in the circuit. Fig. 1-2C shows the series of negative pulses developed across the load.

THE FULL-WAVE RECTIFIER

Fig. 1-3 shows the basic operation of the full-wave rectifier. Notice that the full-wave rectifier differs from the half-wave rectifier in that

8

two rectifier tubes are required and that the secondary of T1 is center-tapped.

In Fig. 1-3A, the a-c voltage applied to the primary of T1 is such that the top of the secondary is positive with respect to the center tap, and the bottom of T1 is negative. Under these conditions, the plate of V1 is positive with respect to the cathode, and electrons flow through V1, the top half of the T1 secondary, and the load. Since the plate of V2 is negative with respect to the cathode, there is no current in V2.
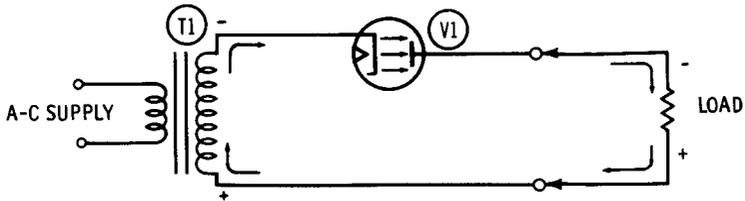
(A) Top of secondary negative.

(B) Top of secondary positive.

(C) Negative output pulses.

Fig. 1-2. Operation of half-wave rectifier (negative output).

In Fig. 1-3B, the a-c voltage applied to the primary has reversed so that the top of the T1 secondary is now negative with respect to its center tap, and the bottom is positive with respect to the center tap. Now the V2 p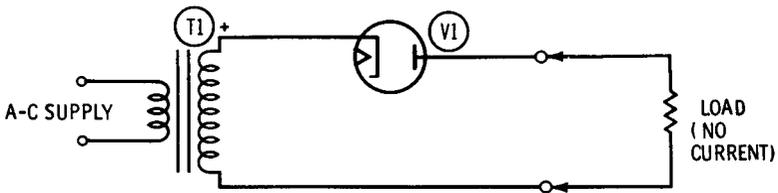late is positive with respect to the cathode. Electrons flow through V2, the bottom half of the secondary, and the load, as indicated by the arrows.

Fig. 1-3C shows the resulting series of current pulses in the load. Note that the "gaps" in the pulses produced by the half-wave rectifier (Fig. 1-1C) are filled in by the full-wave rectifier. This results in a smoother current through the load, because the full-wave rectifier produces an output for both alternations of applied voltage, while the

9

half-wave rectifier produces an output for only the positive or the negative half-cycles.

One disadvantage of the full-wave rectifier is that the transformer secondary, being center-tapped, must generally have twice as many turns as a half-wave rectifier transformer giving the same voltage output. However, the output of the full-wave rectifier is much easier to filter (smooth out) because both alternations are used.
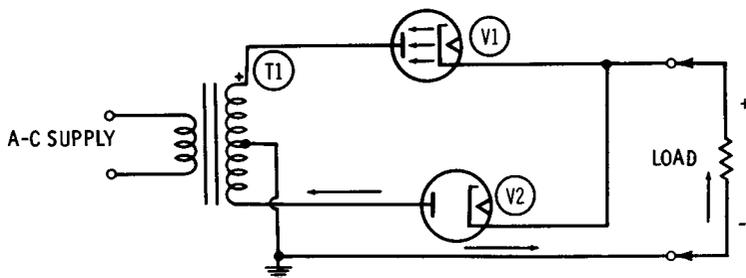
(A) Top of secondary positive.
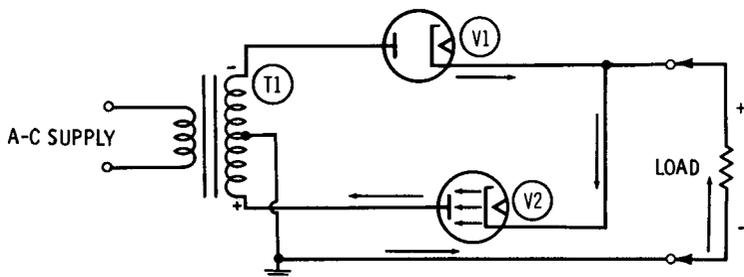
(B) Bottom of secondary positive.

(C) Positive output pulses.

Fig. 1-3. Operation of full-wave rectifier.

THE BRIDGE RECTIFIER

The bridge rectifier is similar to the full-wave rectifier in that it provides a d-c output for both half-cycles of the applied a-c input. However, the full-wave rectifier requires only two rectifier tubes, whereas the bridge requires four. Also, the bridge rectifier does not use a center-tapped secondary winding, and the full-wave rectifier does. The entire secondary is used on both alternations in the bridge circuit.

10

Fig. 1-4 explains the operation of the bridge rectifier. In Fig. 1-4A, the a-c input to transformer T1 makes the top of the secondary positive with respect to the bottom. Since the plate of V1 is positive with respect to the cathode, electrons are attracted from the cathode to the plate. This causes a current in the T1 secondary, V2, the load, and finally, V1, as indicated by the arrows.
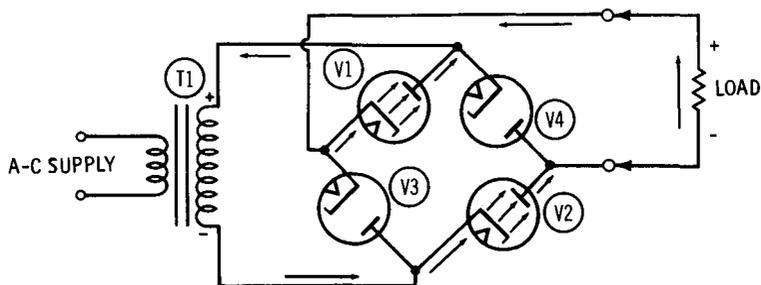
(A) Top of secondary positive.

(B) Bottom of secondary positive.

(C) Positive output voltage.

Fig. 1-4. Operation of bridge rectifier.

On the following half-cycle (Fig. 1-4B), the top of the T1 secondary becomes negative with respect to the bottom. Since the plate of V3 is now positive with respect to the cathode, electrons are attracted to the plate, and there is current in the secondary of T1, V4, and the load, finally returning to the cathode of V3, as shown by the arrows. Notice that for a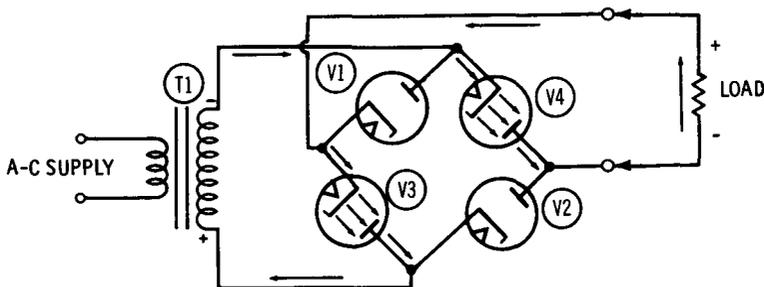n entire cycle of alternating current the polarity of the voltage across the load is the same. Fig. 1-4C shows the resulting voltage waveform developed across the load. As you can see, it is identical to that produced by the full-wave rectifier.

11

(A) V1 conducts.   (B) V2 conducts.
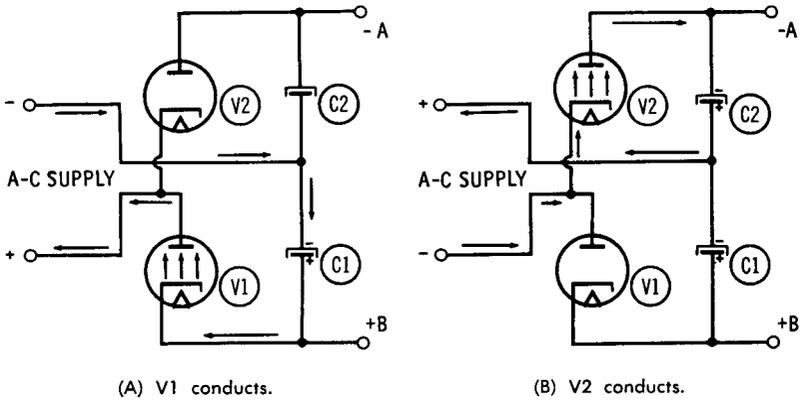
Fig. 1-5. Operation of voltage-doubler rectifier.

THE VOLTAGE MULTIPLIER

The voltage multiplier represents another basic type of power-supply configuration. It can provide an output voltage greater than the applied voltage without the use of a step-up transformer.

Fig. 1-5 shows one form of voltage multiplier known as a voltage doubler. During one half-cycle of the applied a-c input, the plate of V1 is positive with respect to the cathode. Electrons then flow through V1, charging C1 to the polarity shown.

On the following half-cycle (Fig. 1-5B), the plate of V2 is positive with respect to the cathode, and electrons flow through V2, charging C2. Since the voltages across C1 and C2 are in series, the voltage at the output terminals (points A and B) is the sum of the individual voltages across each capacitor.

Fig. 1-6 shows another voltage-doubler arrangement. During the a-c input when the plate of V1 is positive with respect to the cathode, V1 conducts, charging C1. On the following half-cycle, the voltage on

(A) V1 conducts.   (B) V2 conducts.
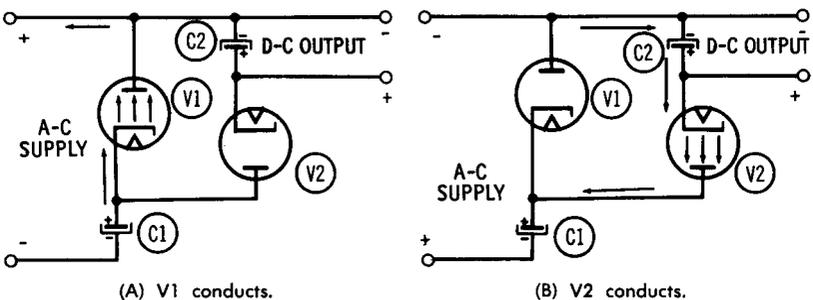
Fig. 1-6. Modified voltage doubler.

C1 adds to the supply voltage so twice the supply voltage is applied to V2 and C2. Since its plate is now positive, V2 conducts and C2 charges. Thus, the d-c output is approximately twice the value of the a-c input.

Fig. 1-7A is the circuit of a voltage tripler, and Fig. 1-7B is the circuit of a voltage quadrupler. Their basic operation is the same as that of the voltage multiplier shown in Fig. 1-6, except for the use of additional rectifiers and capacitors.

(A) Tripler.

(B) Quadrupler.
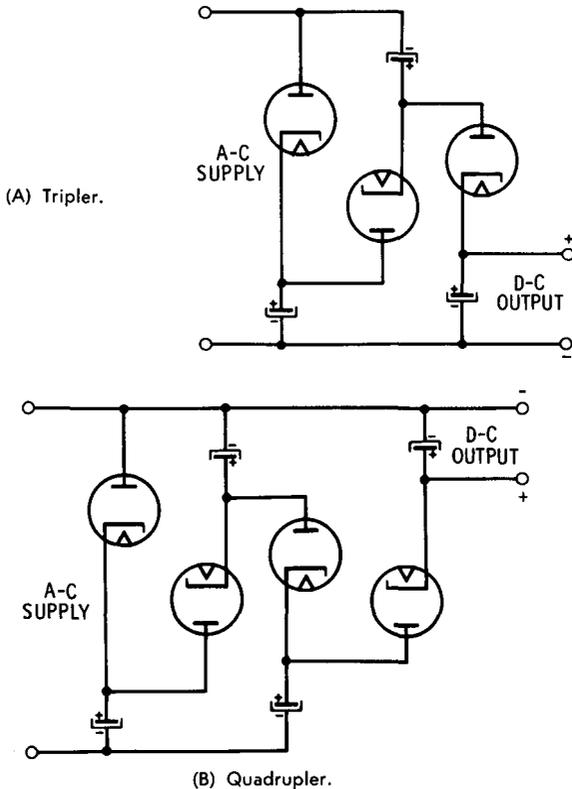
Fig. 1-7. Voltage-multiplier circuits.

COMPARISON OF THE BASIC RECTIFIER SYSTEMS

Each of the four basic types of power-supply rectifier configurations has its merits and disadvantages. The half-wave rectifier is used primarily where only a relatively modest d-c output current is required—up to about 50 ma. It is generally not used to deliver higher currents because of its inefficiency and because of the difficulty in filtering (smoothing out) its pulsating output.

The full-wave rectifier is the most common of all power-supply con-figurations. It is more efficient, and its output is more easily filtered than that of the half-wave rectifier. The full-wave rectifier does, how-ever, require a center-tapped transformer winding to supply its oper-ating power, and this can be a disadvantage in some applications.

The bridge rectifier is on a par with the full-wave rectifier in regard to efficiency and ease of filtering the output; it has the advantage of not requiring a center-tapped transformer. On the other hand, the bridge rectifier requires four rectifier diodes, whereas the full-wave rectifier requires only two. The bridge rectifier has become increasingly popu-lar with the development of semiconductor diodes.

Voltage-multiplier circuits are chiefly used where the d-c output voltage must be higher than the a-c supply voltage, but where the use of a voltage step-up transformer is not desirable. Voltage-multiplier circuits are used typically on portable tv receivers, electronic photo-flash units, etc.
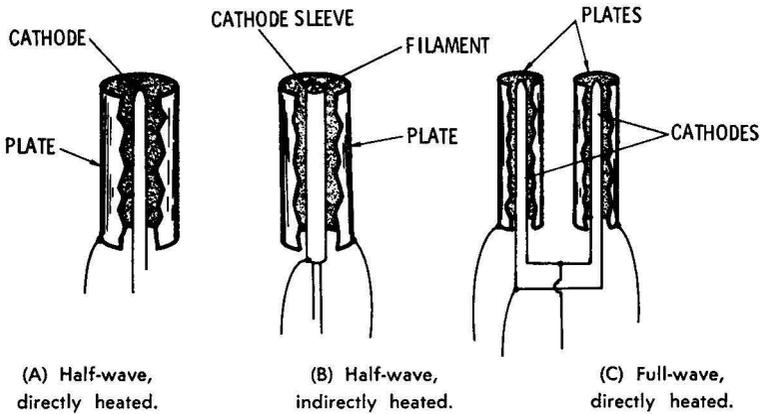
TYPES OF RECTIFIERS

Rectifiers come in a wide variety of sizes, shapes, and methods of construction. Among the first to be developed were the vacuum tubes which featured large glass bulbs. Refinements in manufacturing tech-niques soon reduced the size and increased the current-carrying capa-bilities. Gas-filled tubes were developed to fill the need for more pow-erful units. Although these were used in industrial and commercial applications for the most part, some found places in portable radios, car radios, etc. The cold-cathode tubes resulted from efforts to limit the power lost in tube heaters and filaments.

The introduction of semiconductor rectifiers has created an entirely new field. They are rapidly replacing tubes in many of the conventional rectifier circuits. Their small size makes them particularly attractive in miniaturized equipment.

High-Vacuum Rectifiers

One of the most common rectifiers is the high-vacuum rectifier shown in Fig. 1-8. The half-wave high-vacuum diode rectifier (Fig. 1-8A) consists of a single cylinder-shaped plate that surrounds a heated cathode. The cathode may be either directly or indirectly heated. The directly heated cathode is simply a wire coated with a metallic oxide that emits electrons when heated. The indirectly heated cathode consists of a "cathode sleeve" upon which is deposited an electron-emitting metallic oxide. The sleeve is raised to the proper operating temperature by a coil of heater wire placed inside the cath-ode and electrically insulated from it. The wire is heated by passing current through it. Half-wave high-vacuum diodes are primarily used

| (A) Half-wave, directly heated. | (B) Half-wave, indirectly heated. | (C) Full-wave, directly heated. |

Fig. 1-8. Construction of rectifier tubes.

as damper diodes (in tv receivers) and as high-voltage rectifiers (in tv receivers and specialized industrial equipment).

The full-wave high-vacuum diode (Fig. 1-8C) is designed especially for use in full-wave rectifier circuits. It consists of two individual plates, each surrounding a heated cathode. The two cathodes are electrically connected in parallel. Like half-wave diodes, full-wave diodes may use either a directly or an indirectly heated cathode, the former being more common.

Mercury-Vapor Diodes

High-vacuum diodes are limited to output currents of about 300 maximum. Higher current outputs than this from vacuum diodes re-

A full-wave high-vacuum rectifier tube designed for heavy duty in industrial and commercial equipment.

15
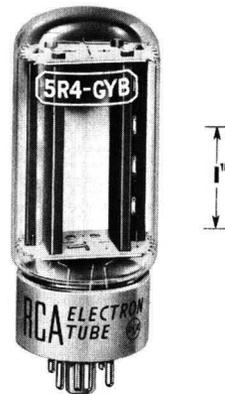
quire tubes of excessive size if satisfactory efficiency is to be maintained.

The mercury-vapor rectifier diode has a much higher current capacity because of the introduction of a small amount of mercury into its envelope. As the cathode is heated, a portion of the mercury vaporizes, filling the envelope with vapor. The mercury vapor greatly reduces the internal resistance of the diode, so that the tube can carry large values of current with only a small voltage drop.
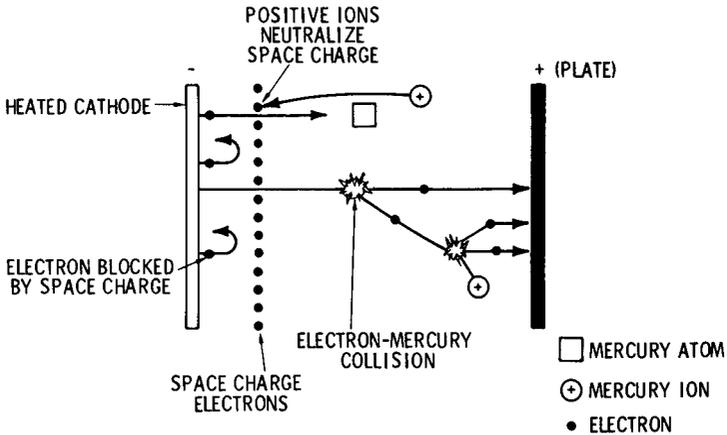

Fig. 1-9. Operation of mercury-vapor rectifier.

Fig. 1-9 shows how the introduction of mercury vapor reduces the cathode-to-plate voltage drop. When the plate is positive with respect to the cathode, it attracts some of the electrons emitted by the cathode. Other electrons remain near the cathode, forming what is known as a space charge; this tends to limit the electron flow to the plate. The electrons traveling toward the plate encounter the mercury-gas atoms. When they collide, electrons are knocked loose from the mercury atoms. The mercury atoms that have thus lost electrons become positive ions. The positive ions neutralize some of the space-charge electrons which surround the heated cathode, so more electrons are able to move toward the plate. As they do, they strike additional gas molecules, producing additional ions. This process "snowballs," producing a large flow of electrons between cathode and plate.

Cold-Cathode Gas Rectifiers

The cold-cathode gas rectifier is similar to the mercury-vapor rectifier just described in that a gas is placed in the envelope to reduce internal resistance. The major difference between the two, however, is that the cold-cathode rectifier does not contain a heated cathode. Its

16

operation is made possible by an internal construction which enables ionization to take place without the need for a heated cathode.

Cold-cathode gas diodes at one time were popular in portable and automotive electronic equipment where only a limited amount of power was available. The saving resulting from the elimination of heater current was an advantage. They have since been almost entirely replaced by semiconductor rectifiers.

Semiconductor Rectifiers

Semiconductor rectifiers, because of their small size, ruggedness, and low voltage drop, are rapidly replacing high-vacuum and gas-filled rectifier diodes in a large number of applications. There are four major types of semiconductor rectifiers—copper oxide, selenium, germanium, and silicon. The copper-oxide rectifier is the oldest type. However, it has been almost entirely replaced by selenium, germanium, and silicon rectifiers so it is of historic interest only.
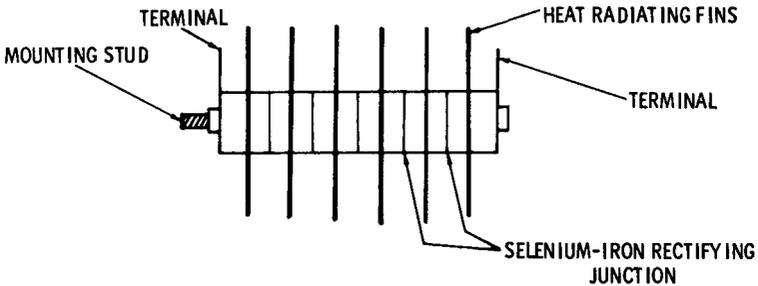

Fig. 1-10. Construction of selenium rectifier (half-wave).

Fig. 1-10 shows the physical construction of the selenium rectifier. The actual process of rectification takes place at the junction of a thin film of metallic selenium with an iron surface. Although selenium rectifiers offer advantages of size and ruggedness when compared to high-vacuum and gas-filled rectifiers, they have the disadvantage of allowing a small amount of current in the reverse direction (when the anode is negative with respect to the cathode). This lowers their operating efficiency.

The amount of current a rectifier passes in the reverse direction compared to the amount it passes in the normal (or forward) direction determines the forward-to-reverse current ratio of a rectifier. Vacuum and gas rectifiers have a very high forward-to-reverse current ratio because they conduct essentially zero current in the reverse direction. Semiconductor rectifiers do allow some reverse current, so they have a smaller forward-to-reverse current ratio. However, the small amount of reverse current in the selenium rectifier is of little importance in

most circuits, and the small size and ruggedness of selenium rectifiers make them useful in many applications.

Germanium-diode rectifiers have a much greater forward-to-reverse current ratio than selenium rectifiers. They can handle larger currents, because the ability to dissipate power in the form of heat is not wasted by reverse current in the rectifier. Also, germanium rectifiers have a very low forward-current impedance which further adds to their power-handling capability. The chief factor limiting the power which germanium-diode rectifiers can handle is their maximum operating temperature. When this is exceeded, the rectifier is destroyed.

A small silicon rectifier capable of handling 2 amperes, available with a PIV of 20 to 1000 volts, in an axial lead case.

Silicon-diode rectifiers are basically similar in characteristics to germanium rectifiers. However, silicon diodes can withstand a much higher operating temperature and thus can handle greater amounts of power.

Fig. 1-11 shows the basic construction of a silicon-diode rectifier. (The operation of the germanium rectifier is essentially the same.) A silicon diode consists of a piece of N-type and a piece of P-type semiconductor fused together.

The composition of the N-type material is such that there are a large number of molecules with loosely bonded electrons that are available for carrying current. The P-type material is just the opposite. The molecules of material there are capable of accepting additional electrons, so it is said that "holes" exist in their structure. The
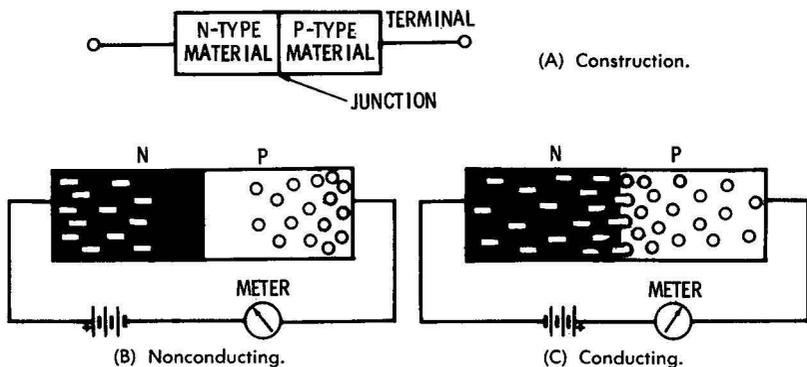
Fig. 1-11. Operation of silicon junction diode.

A 250-ampere silicon rectifier in a DO-9 case.

electrons in N-type material are called negative-charge carriers, and the holes in P-type material are called positive-charge carriers.

When the two materials are fused together a junction is formed that conducts current readily in one direction but not in the other. If a voltage is applied so the P-type is positive and the N-type is negative, there is current in the circuit. When the voltage reverses, there is no current.

Fig. 1-11B shows the silicon diode connected into a circuit containing a battery and an indicating meter. The negative terminal of the

(A) Conducting.

(B) Nonconducting.

(C) Positive output pulses.
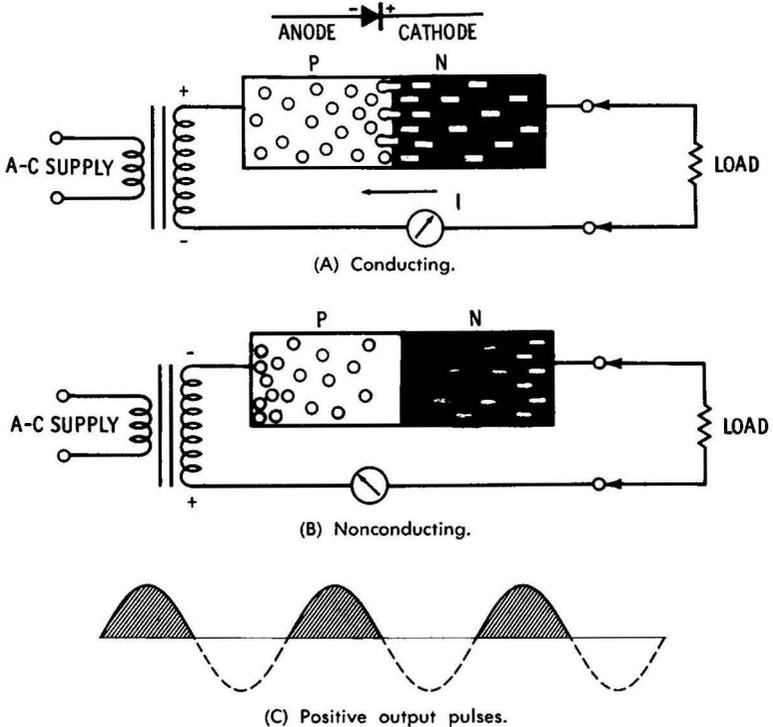
Fig. 1-12. Operation of a silicon junction diode as a rectifier.

19

battery is connected to the P-type material, and the positive battery terminal is connected to the N-type material (through the meter). Negative-charge carriers (electrons) are attracted to the positive battery terminal, thus moving away from the junction. The positive charge carriers (holes) are attracted to the negative battery terminal, and thus also move away from the junction. Since there are no charge carriers at the junction, there is no current in the circuit, as indicated by the meter. In a semiconductor diode, current is provided by the flow of charge carriers, either electrons or holes, across the junction.

In Fig. 1-11C, the battery connections are reversed so that the positive battery terminal is connected to the P-type semiconductor, and the negative battery terminal is connected to the N-type semiconduc-
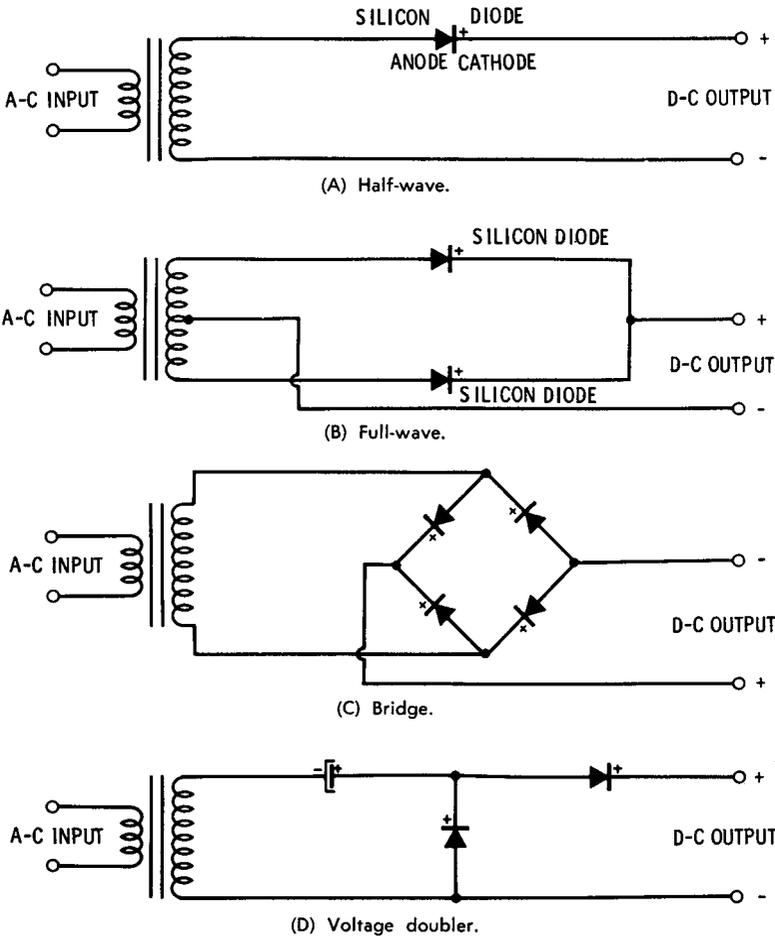

(A) Half-wave.

(B) Full-wave.

(C) Bridge.

(D) Voltage doubler.

Fig. 1-13. Silicon-diode rectifier configurations.

20

tor. The negative charge carriers are repelled away from the negative battery terminal, toward the junction of the N- and P-type semiconductors. Likewise, the positive charge carriers are repelled away from the positive battery terminal, toward the junction. The positive and negative charge carriers combine at the junction, resulting in current across the P-N junction. Current in the circuit is indicated by the meter.

Fig. 1-12 shows a silicon diode connected in a simple half-wave rectifier circuit. In Fig. 1-12A, the first half-cycle of the a-c input is applied so the P-type material is positive and the N-type material is negative. Under these conditions, the positive-charge carriers (holes) in the P-type semiconductor are repelled toward th P-N junction, and the negative-charge carriers (electrons) are likewise repelled toward the P-N junction. Electrons and holes combine at the P-N junction, and current in the circuit is indicated by the meter.

In Fig. 1-12B, the second half-cycle of the a-c input is applied so the P-type material is negative. Negative-charge carriers (electrons) are attracted away from the P-N junction, as are the positive-charge carriers. As a result, there is no charge-carrier combination at the junction, and no current is indicated by the meter. The resulting current pulses through the load are shown in Fig. 1-12C.

Fig. 1-13 shows how silicon-rectifier diodes may be used in half-wave, full-wave, bridge, and voltage-multiplier rectifier circuits.

CHAPTER 2

Power-Supply Filters

The function of the rectifier in a power supply is to change an a-c input to a d-c output. However, the output of the rectifier is not pure direct current, but rather a series of pulses. This can be considered as being made up of two parts, a d-c component and an a-c component. To make the output acceptable as a d-c power source, the a-c variations, known as ripple, must be removed, leaving only pure direct current. The job of removing this ripple is done by a filter.

Fig. 2-1 explains the operation of a simple power-supply filter. The unfiltered output from the rectifier is applied across capacitor C1. During the time the rectifier is conducting, C1 charges to the peak value of the a-c supply voltage, as indicated by line AB in Fig. 2-1B. During the period the rectifier is not conducting and provides no output, the capacitor starts to discharge through the load, as indicated by line BC. When the rectifier once again conducts, C1 is again charged, as shown by line CD. The resulting voltage across the capacitor (the output of the power supply) is shown in Fig. 2-1C. Note that the voltage is considerably smoother (less change in amplitude) than the unfiltered output of the rectifier.
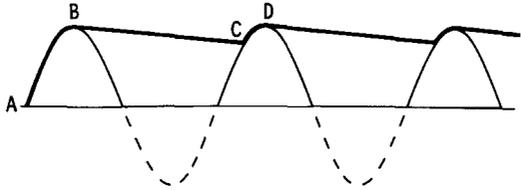
Fig. 2-2 shows capacitor C1 connected across the output of a full-wave rectifier. In this case, the power-supply output is much smoother because the capacitor discharges only half as far before being recharged by the next half-wave.

The amount the capacitor discharges between pulses is determined by the value of load connected across the capacitor. As the load resistance is decreased, more current is drawn from the capacitor while the rectifier is not conducting. As a result, the voltage across the capacitor drops more between successive "charges." This increases the variations in voltage (ripple) across the capacitor.

In Fig. 2-3A, no load is connected across the filter capacitor. Since no current is drawn from the filter between its successive charges from the rectifier, the voltage across it remains essentially constant.
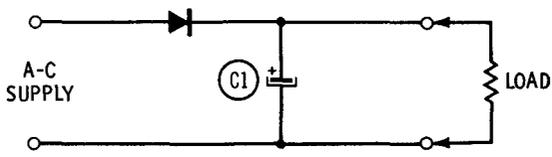
(A) Schematic.

(B) Combined waveforms.

VOLTAGE ACROSS C1

(C) Output waveform.

Fig. 2-1. Single-capacitor filter.

(A) Schematic.

VOLTAGE ACROSS C1

(B) Waveform.

Fig. 2-2. Single-capacitor filter across full-wave power supply.
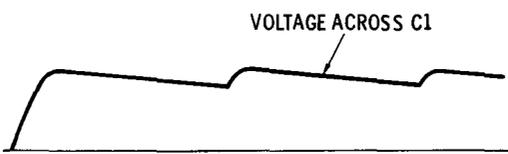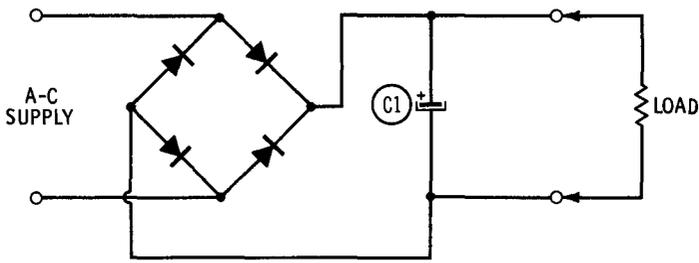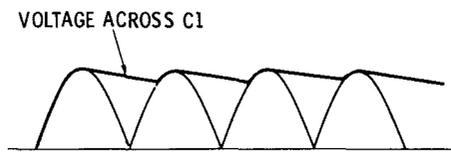
In Fig. 2-3B, a load is connected across the filter capacitor. Since current is drawn from the filter between charges, the output voltage varies to a much greater extent than in the case of Fig. 2-3A. This variation is ripple, and the greater the voltage variation, the greater the ripple.

This simple capacitor filter is not too efficient for removing ripple from the output of the rectifier, although it does serve to illustrate basic power-supply filter action. There are several methods of improving power-supply filtering.

OUTPUT VOLTAGE

(A) No load—low ripple.

OUTPUT VOLTAGE

(B) With load—more ripple.
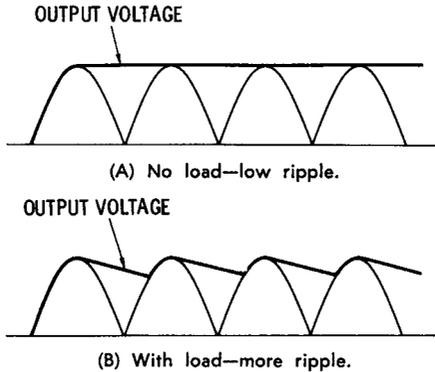
Fig. 2-3. Effect of loading on ripple voltage.

THE CHOKE-INPUT FILTER

Fig. 2-4 shows an arrangement known as a choke-input filter. Here advantage is taken of the fact that the inductance of a coil tends to oppose any change in the current through the coil. Thus, the inductance of the choke, placed between the output of the rectifier and the filter capacitor, tends to oppose the build-up of current in the load when the rectifier conducts, and maintains current in the load when the rectifier is not conducting. The effect is somewhat like a flywheel, which tends to smooth out mechanical variations.

CHOKE

RECTIFIER
OUTPUT

C1

POWER-SUPPLY
OUTPUT

Fig. 2-4. Choke-input filter.

The filtering action of a choke is normally used in conjunction with a filter capacitor. Fig. 2-5 shows the regulating characteristics of the choke-in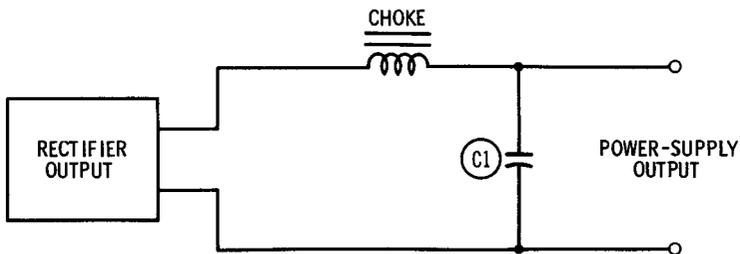put filter. Notice that above a certain minimum load current, the output voltage of the power supply remains fairly constant for wide variations in load. The main disadvantage of the choke-input filter is that the output voltage tends to be lower than that of other filter types.
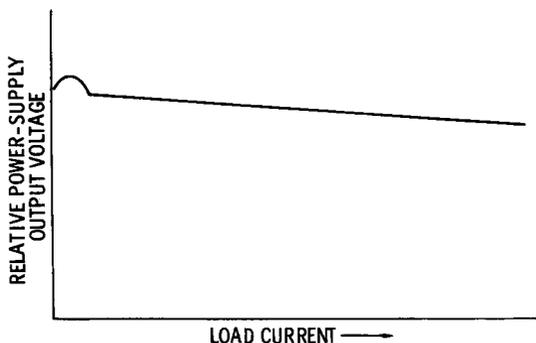

Fig. 2-5. Voltage regulation using a choke-input filter.

THE CAPACITOR-INPUT FILTER

Fig. 2-6A shows a configuration known as a capacitor-input filter. In this arrangement capacitor C1 is placed directly across the rectifier output. Choke L1 is connected in series between the output of the rectifier and the load. A second capacitor, C2, is placed across the load terminals.

Fig. 2-6B shows the characteristics of the capacitor-input filter. Note that its output voltage varies considerably with changes in load current. This type is often called a pi-section filter.

Another arrangement of capacitor-input filter is shown in Fig. 2-7. Here a resistor is substituted for the choke between input and output filter capacitors. The use of this resistor-capacitor filter provides acceptable filtering in low-current circuits where a physically larger, more expensive filter choke is not possible. This arrangement is found in most a-c–d-c radios, audio preamps, etc.

POWER-SUPPLY VOLTAGE REGULATION

In most cases the voltage at the output terminals of a power supply varies as the current in the load changes. This variation is referred to as the regulation of the power supply. The less the change in output voltage for changes in load current, the better the regulation is, and

A typical filter capacitor used in connection with tube circuits.
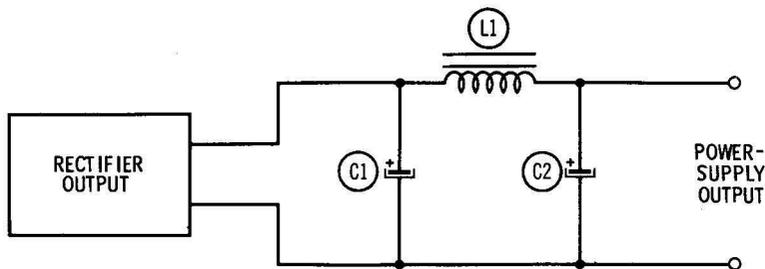
(A) Schematic.
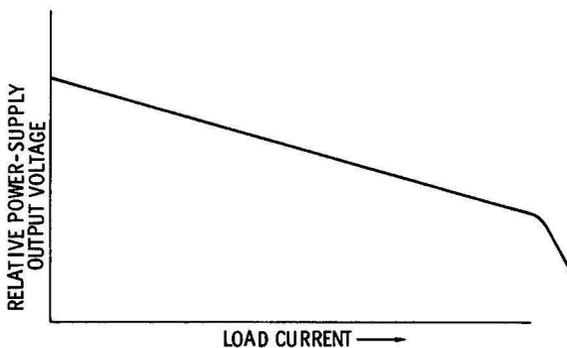
(B) Characteristic curve.

Fig. 2-6. Voltage regulation using a capacitor-input filter.
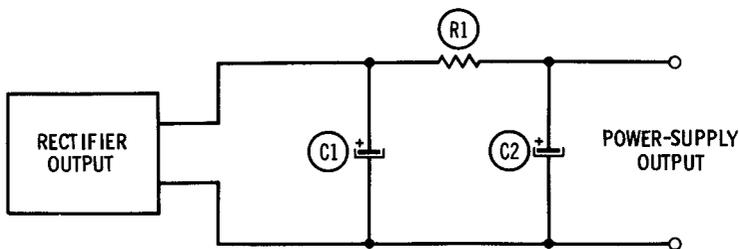
Fig. 2-7. Resistor-capacitor filter.

the better the power supply is. Regulation is generally expressed as a percentage and may be calculated from the following formula:

$$\% \text{ voltage regulation} = \frac{(\text{no load voltage}) - (\text{full load voltage})}{\text{full load voltage}} \times 100$$

OUTPUT VERSUS INPUT

For a given secondary voltage, the resulting d-c output voltage of a transformer power supply depends on several factors, including the type of rectifier circuit, type of filter, and load. There are several difference rectifier circuits. In the half-wave rectifier shown in Fig. 2-8, the peak d-c voltage output (before filtering) is the same as the peak
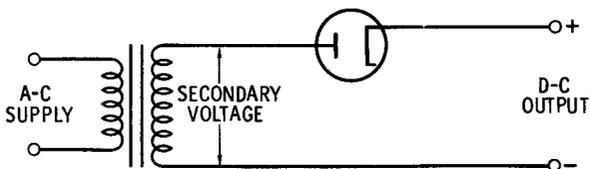
(A) Schematic.
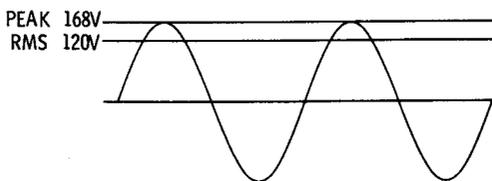
(B) Secondary voltage.
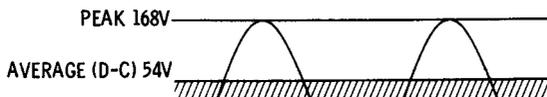
(C) Rectified voltage.

Fig. 2-8. Half-wave rectifier.

28

secondary voltage—1.4 times the rms value. If the secondary voltage is 120 volts rms, the peak output voltage is 120 × 1.4, or 168 volts.

The average d-c output voltage of this same half-wave rectifier is 0.318 times the peak voltage. Since this peak is 168 volts, the voltage appearing at the output terminals is 168 × .318, or approximately 54 volts.

(A) Schematic.

(B) Voltage applied to V1.

(C) Voltage applied to V2.

(D) Rectified voltage.
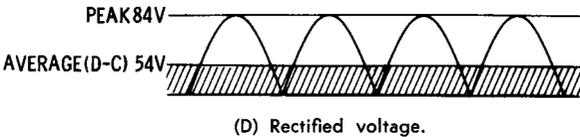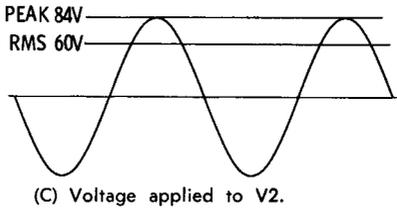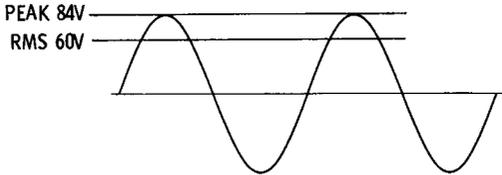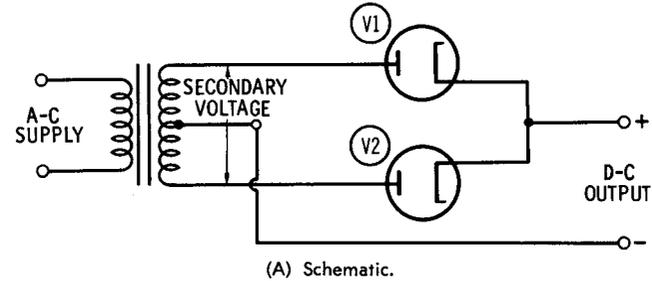
Fig. 2-9. Full-wave rectifier.

If, in the full-wave circuit of Fig. 2-9, the same voltage is developed across the secondary (120 volts rms), a different situation exists. Only half of this is applied to each rectifier. There is 60 volts rms (84 volts peak) across each tube (Fig. 2-9B and C). The average rectifier output in this case (Fig. 2-9D) is .637 × 84, or approximately 54 volts.

Thus, when the full-wave and half-wave circuits are compared, the d-c output is the same if the secondary voltage (but not the voltage across the rectifiers) is the same.

In the case of the bridge rectifier shown in Fig. 2-10, the average output voltage will be 0.9 times the applied secondary rms voltage, or .637 times the peak voltage. The peak output voltage of the bridge rectifier is 1.4 times the rms input voltage.
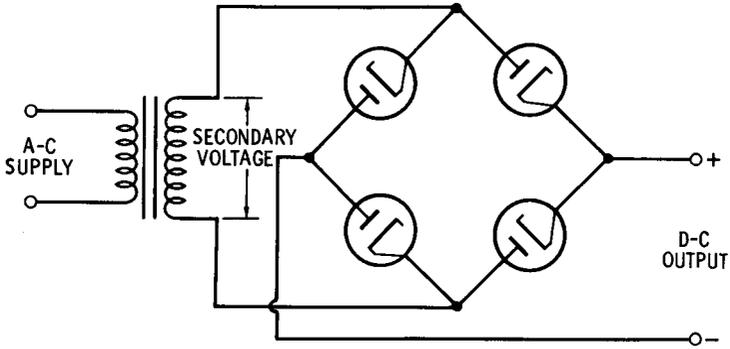

(A) Schematic.
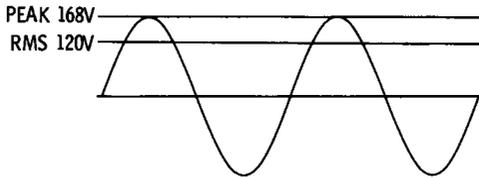
(B) Secondary voltage.
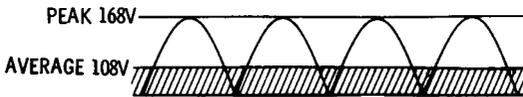
(C) Rectified voltage.

Fig. 2-10. Bridge rectifier.

For a given output voltage from the rectifier, the voltage developed at the output of the filter will depend on the particular filter configuration. Refer for a moment to the basic single-capacitor filter in Fig. 2-11A. When the rectifier conducts, capacitor C1 charges to the peak value of the rectifier output voltage. During the time the rectifier is not conducting, C1 retains essentially all of its charge if there is no load connected across it.

When a load is connected across its terminal, C1 partially discharges during the periods when the rectifier is not conducting. The amount

of this discharge, of course, depends on the amount of load—the discharge increasing as the load is increased. The same characteristic holds true in the case of a multisection capacitor-input filter such as the one shown in Fig. 2-11B. From all this, you can see that the d-c output voltage of a capacitor-input filter approaches the peak value of the rectifier output voltage with small values of load, the output voltage dropping as the load is increased.
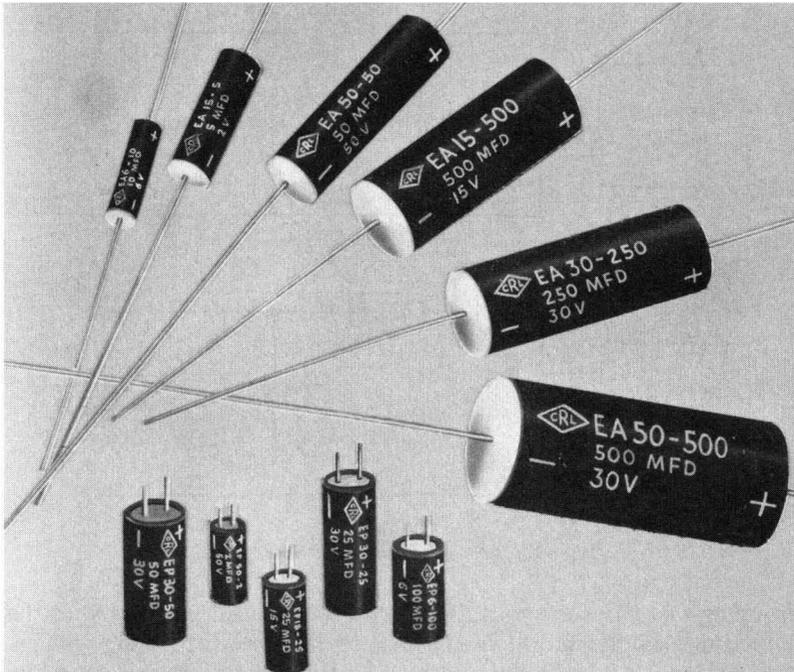
Small electrolytic capacitors used with transistor circuitry.

If a choke-input filter is used (Fig. 2-11C), the voltage across the output terminals is the average value of the voltage appearing at the rectifier output.

REDUCING OUTPUT VOLTAGE

Often, it is necessary to reduce the output voltage of a power supply to some other value. For example, the screen-grid voltage of a tube frequently must be lower than the plate voltage.

There are two principal methods of dropping voltage—series resistance and voltage division. Fig. 2-12 illustrates the idea of voltage
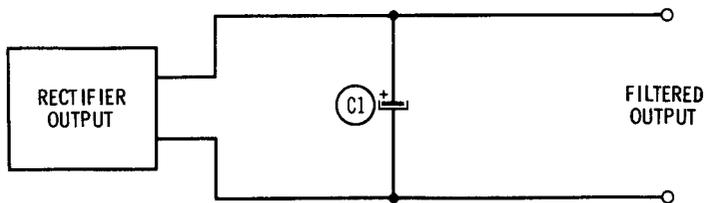
(A) Single section, capacitor input.
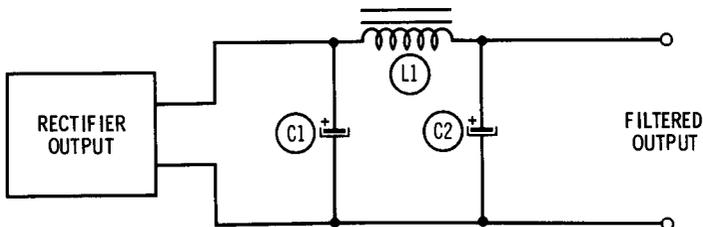
(B) Dual section, capacitor input.
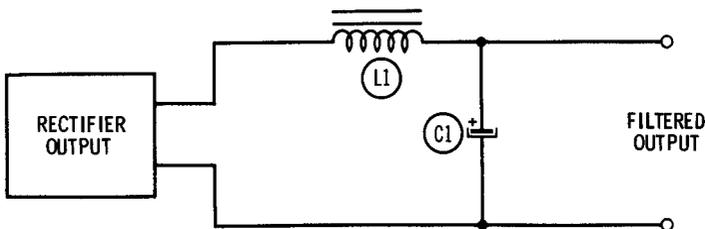
(C) Choke input.

Fig. 2-11. Filter configurations.

dropping by series resistance. Resistor R1 is placed in series with the filtered d-c supply and the load requiring the lower operating voltage. The value of R1 is determined by (1) the amount of voltage to be dropped across it, and (2) the amount of current drawn by the load. All this is summed up in Ohm's law:

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

where,
   R is the value of dropping resistor, in ohms,
   E is the desired voltage drop across the resistor, in volts,
   I is the current drawn by the load, in amperes.

   As a practical example of this, assume we have a tube that requires a plate voltage of 140 volts. At this plate voltage, the tube draws a plate current of 20 ma. The output from the power supply is 300 volts.

32
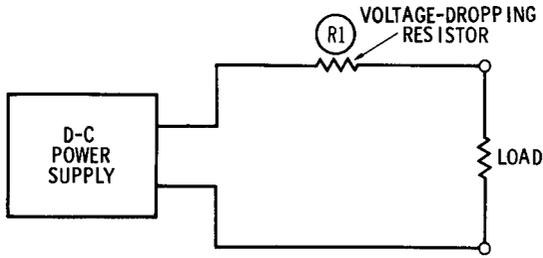
Fig. 2-12. Series voltage-dropping resistor.

To determine the correct value of the series-dropping resistor, Ohm's law is applied as follows:

$$R = \frac{E}{I} = \frac{(300 - 140)}{(.02)} = 8,000 \text{ ohms}$$

The power that must be dissipated by the series-dropping resistor is easily determined by the formula:

$$W = I^2R$$

where,
W is the power, in watts,
I is the value of current in the resistor, in amperes,
R is the value of series resistance, in ohms.

In the previous example, the power dissipated by the series-dropping resistor would be:

$$W = .02^2 \times 8000$$
$$= 3.2 \text{ watts}$$

A variation of the series-dropping resistor arrangement is shown in Fig. 2-13. This configuration, often called a decoupling network, uses filter capacitors C1, C2, and C3 at the junction of series-dropping resistors R1, R2, and R3. A number of different voltages can be ob-
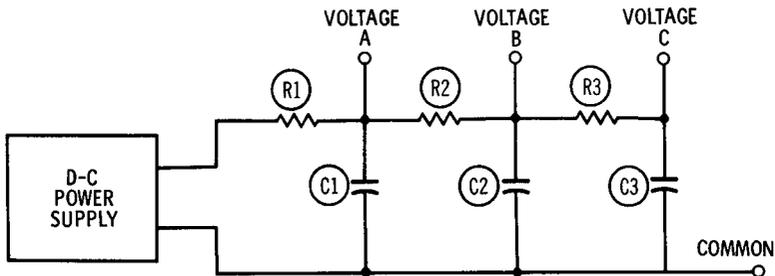
Fig. 2-13. Decoupling network.

tained by this arrangement, and the presence of the additional capacitors improves the overall filtering.

The voltage divider is another widely used method of voltage dropping. Several series resistors, R1, R2, and R3, are connected across the output of the power supply, as shown in Fig. 2-14. The values of
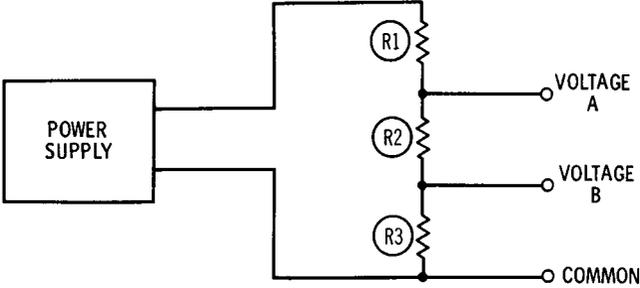
Fig. 2-14. Voltage divider.

R1, R2, and R3 are selected to provide the desired voltages between their junctions (A and B) and common. As many resistors as needed may be connected in series to obtain a wide selection of output voltages. When only a negligible amount of current is drawn from the taps of a voltage divider—as for example, the bias of a class-A amplifier—the voltage at the resistor taps is proportional to the ratio of the
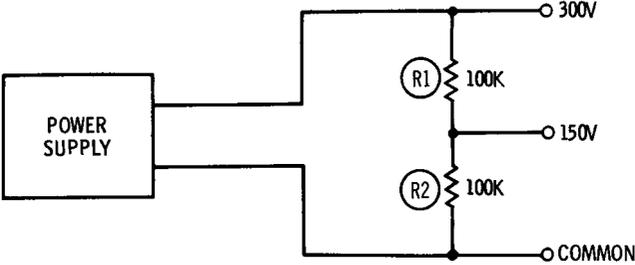
Fig. 2-15. Practical voltage divider.

resistance. In the voltage divider shown in Fig. 2-15 the voltage at the junction of R1 and R2 is 150 volts when equal-value resistors are used for R1 and R2.

When significant current is drawn from the taps of a voltage divider, the following formula may be used to determine the individual resistance values, using the configuration shown in Fig. 2-16:

34

$$R_3 = \frac{E_2}{I_3}$$

$$R_2 = \frac{E_1 - E_2}{I_2 + I_3}$$

$$R_1 = \frac{E - E_1}{I_1 + I_2 + I_3}$$

The number of series-connected resistors and taps may be extended to any desired number by expansion of the above formula. The value of I_3 can be assumed to be 10 percent of the total load current of all taps.
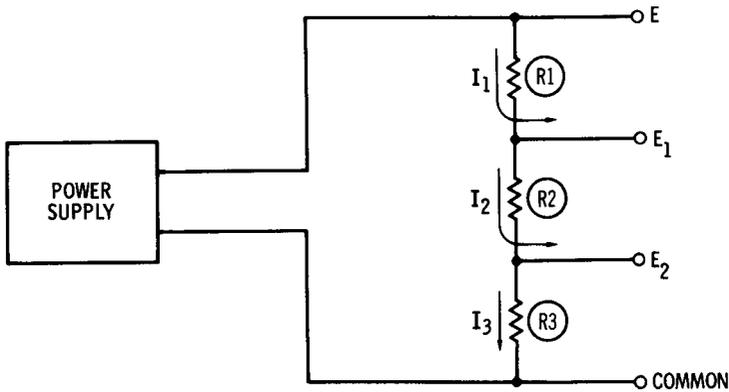
Fig. 2-16. Voltage divider.

PRACTICAL CIRCUITS

The following circuits, although simple, are handy as a source of operating power for radio receivers, small amplifiers, preamps, etc. All of them utilize a power transformer for maximum safety of operation. The primary and secondary windings are isolated, so neither side of the d-c output is connected directly to the power line. As a result, there is no "hot-chassis" problem to cause a possible shock.

A Simple Half-Wave, Low-Current Power Supply

The half-wave power supply in Fig. 2-17 is capable of furnishing a d-c output of 120 volts at an output current of 50 ma. Actually, with light loading the output voltage will rise to nearly the peak value of the input volts (168 volts) because of the use of a capacitor-input filter. In addition to the d-c output, this supply also furnishes a 6.3-volt a-c supply at a current rating of 2 amps.
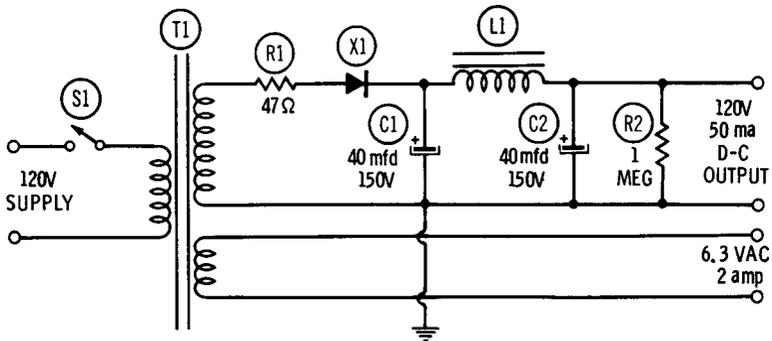
Fig. 2-17. Half-wave power supply.

Parts List for Fig. 2-17

Item No.	Description
C1	Capacitor, 40 mfd, 150 volts, electrolytic
C2	Capacitor, 40 mfd, 150 volts, electrolytic
L1	Choke, 16 hy, 50 ma (Stancor C1003, or equivalent)
R1	Resistor, 47 ohms, 1 watt
R2	Resistor, 1 megohm, ½ watt
S1	Switch, spst
T1	Transformer, power. Secondaries: 125 volts, 50 ma; 6.3 volts, 2 amps (Stancor PA8421, or equivalent)
X1	Rectifier, silicon, 1N2483

Fig. 2-17 is the power-supply schematic. An a-c input of 120 volts rms from the power line is applied to the primary of power transformer T1. The a-c voltage developed across the secondary of T1 is applied to silicon rectifier X1. Resistor R1, connected between the top of the secondary and X1, serves to limit the surge current through X1 when filter capacitor C1 charges during initial application of power to the unit.

The output of the silicon rectifier is applied to the two-section capacitor-input filter consisting of C1, L1, and C2. Resistor R2, connected across the output terminals of the filter, serves to discharge the capacitors when power is removed from the supply. Without R2, the charge retained by C1 and C2 can provide an unpleasant "surprise" if the power-supply output terminals are accidentally touched.

A Full-Wave, Medium-Current Power Supply

The supply in Fig. 2-18 is designed to provide a higher current than the unit just described. It has a d-c output voltage of 350 volts at a current of 90 ma. This voltage will rise to more than 450 volts under

36

light loading conditions because a capacitor-input filter is used. In addition to the d-c output, this supply also furnishes 6.3 volts of alternating current at a rating of 3 amps.

In operation, a-c line current is applied to the primary of power transformer T1. The high-voltage developed across the secondary of T1 is rectified by the full-wave rectifier tube, V1. The output of V1 is applied to the double-section capacitor-input filter consisting of C1, L1, and C2. Resistor R1, placed across the output of the filter, serves to discharge C1 and C2 after power has been removed from the supply.

A Voltage-Doubler Power Supply

Fig. 2-19 is the schematic of a half-wave doubler power supply. Depending on the load, this supply will put out between 200 and 300 volts. Maximum rated load current is 25 ma. A separate 6.3-volt a-c output at 5.5 amperes is also provided.
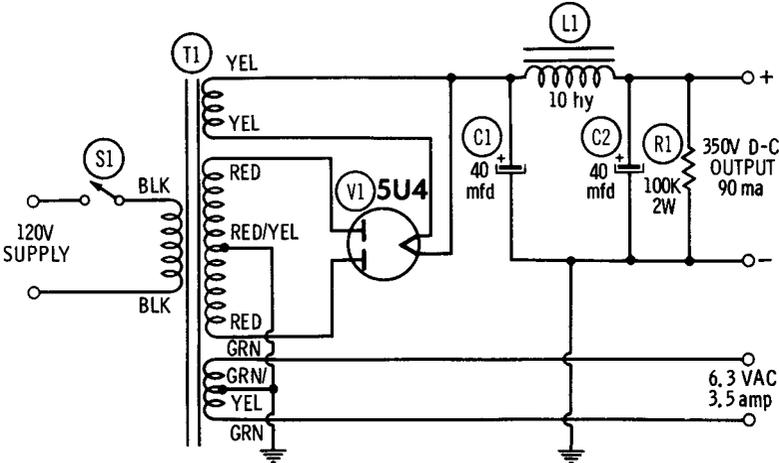
Fig. 2-18. Full-wave power supply.

Parts List for Fig. 2-18

Item No.	Description
C1	Capacitor, 40 mfd, 450 volts, electrolytic
C2	Capacitor, 40 mfd, 450 volts, electrolytic
L1	Choke, 10 hy, 90 ma (Knight 54D4707, or equivalent)
R1	Resistor, 100K ohms, 2 watts
S1	Switch, spst
T1	Transformer, power. Secondaries: 700 volts center-tapped, 90 ma; 5 volts, 3 amps; 6.3 volts, 3.5 amps (Knight 54D2043, or equivalent)
V1	Tube, 5U4

37

Referring to the schematic, the a-c line current is applied to the primary of power transformer T1. The resulting voltage developed across the high-voltage secondary is applied to the voltage doubler, which consists of X1, X2, C1, and C2. The output of the voltage doubler is filtered by C2, L1, and C3. Resistor R2 discharges the filter capacitors when power is removed from the unit.
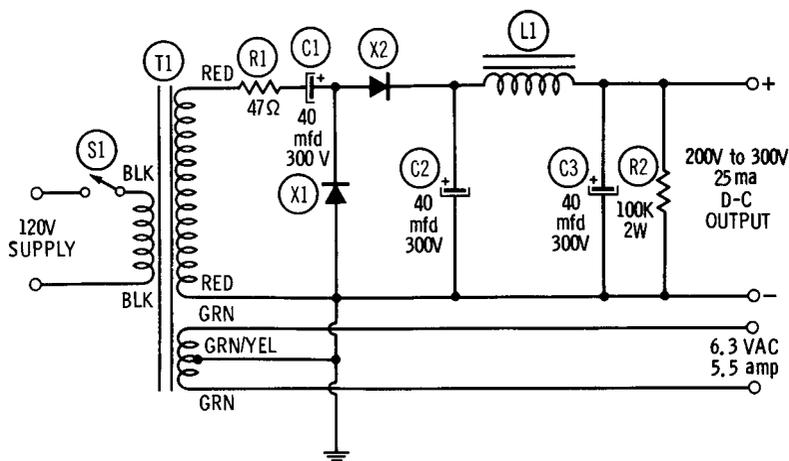
Fig. 2-19. Voltage-doubler power supply.

Parts List for Fig. 2-19

Item No.	Description
C1	Capacitor, 40 mfd, 300 volts, electrolytic
C2	Capacitor, 40 mfd, 300 volts, electrolytic
C3	Capacitor, 40 mfd, 300 volts, electrolytic
L1	Choke, 10 hy, 90 ma (Knight 54D2139, or equivalent)
R1	Resistor, 47 ohms, 1 watt
R2	Resistor, 100K ohms, 2 watts
S1	Switch, spst
T1	Transformer, power. Secondaries: 135 volts, 200 ma; 6.3 volts, 5.5 ma (Knight, 54D3708, or equivalent)
X1	Rectifier, silicon, 1N2613
X2	Rectifier, silicon, 1N2613

Low-Voltage Power Supply

In Fig. 2-20 is a power supply that is ideal for furnishing operating voltages for transistor circuitry. Supplying 12 volts at 1 ampere, the unit will furnish sufficient current for most conventional transistor cir-

38
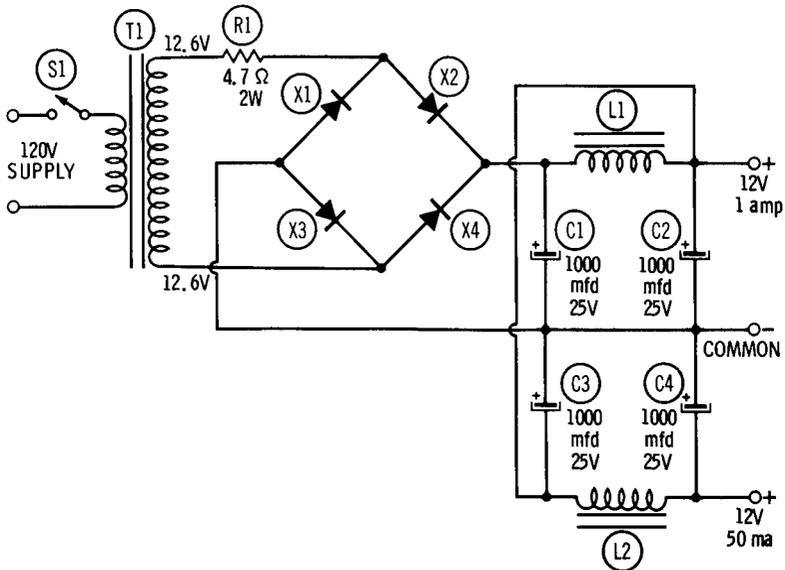
Fig. 2-20. Transistor power supply.

Parts List for Fig. 2-20

Item No.	Description
C1	Capacitor, 1000 mfd, 25 volts, electrolytic
C2	Capacitor, 1000 mfd, 25 volts, electrolytic
C3	Capacitor, 1000 mfd, 25 volts, electrolytic
C4	Capacitor, 1000 mfd, 25 volts, electrolytic
L1	Choke, .035 hy, 2 amps (Knight 54D2343, or equivalent)
L2	Choke, 16 hy, 50 ma (Knight 54A2137, or equivalent
R1	Resistor, 4.7 ohms, 2 watts
S1	Switch, spst
T1	Transformer, filament, 12.6 volts, 1.5 amps (Knight 54D4136, or equiv.)
X1	Rectifier, silicon, 1N1081
X2	Rectifier, silicon, 1N1081
X3	Rectifier, silicon, 1N1081
X4	Rectifier, silicon, 1N1081

cuitry. An additional output, also 12 volts, with a maximum current of 50 ma is available. This latter output has much better filtering because of the additional filter element. It is useful where an output of extremely low ripple is required.

As shown in Fig. 2-20, operating power is applied to the primary of power transformer T1—actually a 12-volt filament transformer.

The voltage developed across the secondary is applied to the full-wave bridge rectifier consisting of X1, X2, X3, and X4. The d-c output of the bridge rectifier is fed to the two-section capacitor-input filter C1, L1, and C2. The output from this filter is fed to the 12-volt, 1-ampere output terminal. An additional filter, consisting of L2, C3, and C4, provides further filtering. The output of this filter is available at the 12-volt, 50-ma output terminals.

CHAPTER 3

Voltage-Regulation Basics

One of the most important characteristics of a power supply is its voltage regulation. As was pointed out in the last chapter, voltage regulation relates to how the output voltage of a power supply changes with variations in the load current. A power supply that has good voltage regulation maintains an essentially constant output voltage with reasonable changes in its load current.

Voltage regulation of a power supply is generally expressed as a percentage which can be calculated as follows:

$$\% \text{ voltage regulation} = \frac{(\text{no-load voltage}) - (\text{full-load voltage})}{\text{full-load voltage}} \times 100$$

Thus, if a power supply has a no-load output voltage of 275 volts and a full-load output voltage of 250 volts, its percentage of regulation is:

$$\frac{275 - 250}{250} \times 100 = \frac{25}{250} \times 100 = 10\%$$

Ideally, a power supply should have perfect voltage regulation, the output voltage remaining constant for changes in the output (load) current. Practical power supplies never reach perfection, although laboratory-type power supplies have been produced with voltage regulation of .001% or better.

The voltage regulation of a conventional power supply, such as the one shown in Fig. 3-1, will be relatively poor for several reasons. First, any variations in the a-c line input voltage will be reflected in changes of the output voltage. If the line voltage should increase, the output voltage will increase proportionally, and vice versa.

Secondly, as the load increases, the output of the power supply will drop. One cause of this is the filter (mentioned in the last chapter). In the case of the capacitor-input filter, such as the one shown in Fig.

3-1, light loading will result in the output voltage of the supply nearly equaling the peak value of the output voltage from the rectifier. The output voltage drops as the loading is increased. The regulation can be improved by the use of a choke-input filter which will cause the supply output to remain near the average output voltage of the rectifier under varying load conditions. However, the output voltage will still change as the load current is varied.
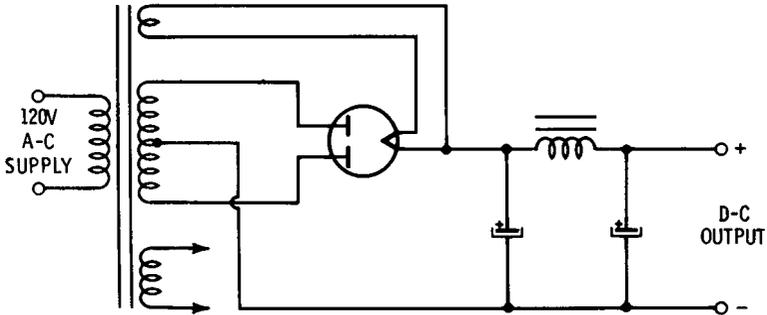
Fig. 3-1. Typical full-wave power supply.

Third, a drop in power-supply output voltage is caused by the internal impedance of the rectifier and the power transformer. Any rectifier, whether it be a high-vacuum diode, gas-filled diode, or semiconductor diode, has an internal resistance (or impedance); this internal impedance causes a voltage drop in the rectifier. The effect is the same as though there were a resistor in series with the rectifier, as shown in Fig. 3-2. As with any resistor, when the current through it is increased, the voltage drop across it increases. Thus, as the current drawn from the power supply is increased, the voltage drop due to the internal impedance of the rectifier reduces the output voltage. In addition, the power-transformer windings have resistances which
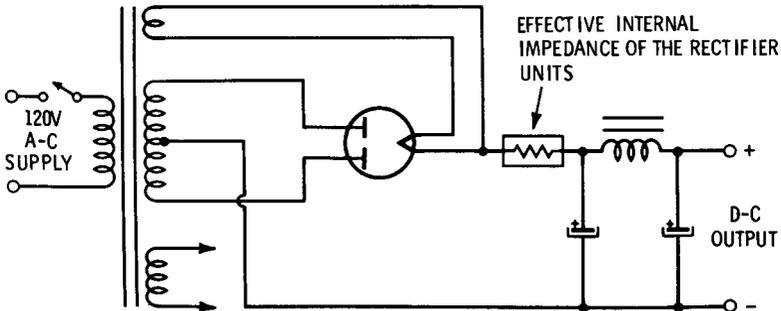
Fig. 3-2. Effect of power-supply internal impedance.

are effectively in series with the power-supply output, thus further reducing the power-supply voltage output as the load current increases.

SHUNT VOLTAGE REGULATION

While the voltage regulation of the standard power-supply configuration of rectifier and filter is generally more than adequate for most applications, there are instances when better regulation is required. There are a number of methods of improving the power-supply voltage regulation. Perhaps the simplest involves the use of a gas-filled shunt voltage-regulator tube.
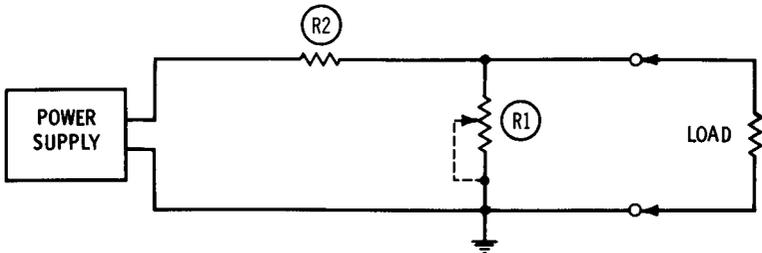
Fig. 3-3. Principle of shunt voltage regulation.

Fig. 3-3 shows the basic concept of the shunt voltage regulator. Shunt voltage-regulation element R1 and series resistor R2 form a voltage divider, with the external load of the power supply connected to the junction of R1 and R2. When the load current increases, the voltage across the load drops because of the increased voltage drop across R2. Assuming for a moment that the value of R1 can be manually changed, then the voltage across the load can be returned to normal by increasing the value of R1 since this will decrease the current through R2 and, hence, the voltage drop across it. Conversely, a decrease in load current will increase the voltage across the load. This can be compensated for by decreasing the value of R1. There will be more current through R2, resulting in a greater voltage drop across it and less voltage applied to the load.

All that is needed is to replace the variable shunt resistor, R1, with a device that will automatically adjust its resistance in accordance with load changes so as to maintain a constant voltage across the load. Such a device is the gas-filled voltage-regulator tube. It has the property of acting like a self-adjusting resistor that automatically changes value in order to maintain a constant voltage across itself.

Fig. 3-4 shows the physical construction of the gas-filled voltage-regulator tube. It consists of only two electrodes—a cathode and an anode. The cylindrical cathode surrounds the anode, which consists

ANODE   CATHODE

GLASS OR METAL
ENVELOPE

CATHODE

ANODE

ANODE

CATHODE

(A) Construction.   (B) Symbol.
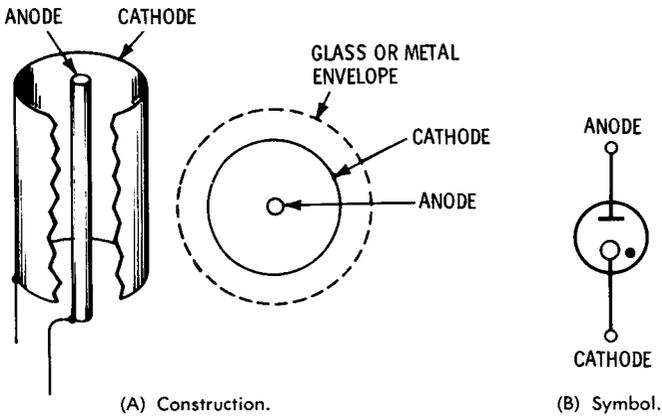
Fig. 3-4. Gas-filled voltage-regulator tube.

simply of a single wire. The envelope is filled with either argon or neon.

Fig. 3-5 shows the electrical characteristics of the gas-filled voltage-regulator tube. As the voltage applied to the tube, through a current-limiting resistor, is increased from zero toward point A, the full applied voltage appears across the tube. The reason is that, because the

ARC

A   B   C

ANODE VOLTAGE

0

ANODE CURRENT
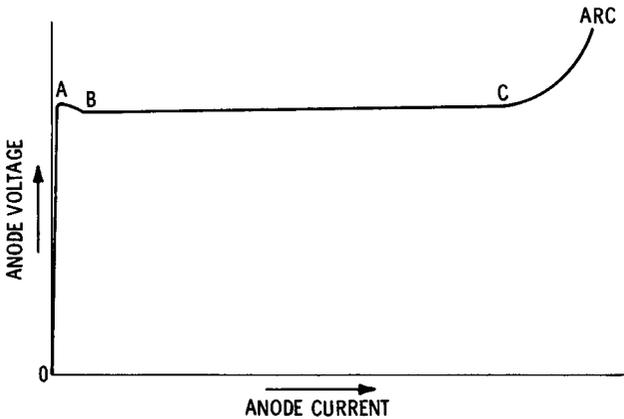
Fig. 3-5. Gas-filled voltage-regulator characteristics.

tube is not conducting, there is no current to cause a voltage drop across it.

When the voltage reaches the value indicated by point A, the tube suddenly ionizes, or "fires." At this time, the voltage across the tube drops to point B. The current through the tube can continue to increase, but the voltage across the tube remains essentially constant,

44

as indicated by the line from B to C. If the applied voltage is increased greatly, the current through the tube will continue to increase until the point is reached where an arc will develop between cathode and plate. At this point, the tube will be severely damaged, with permanent loss of its original regulating characteristics.

Fig. 3-6 shows how the gas-filled voltage regulator is used in a practical circuit. The output from the power supply is applied to the regulator tube (v-r tube) through current-limiting resistor R1. The value of this resistor is selected to limit the current through the v-r tube to its recommended value. The regulated voltage is taken from the anode of the v-r tube and ground.
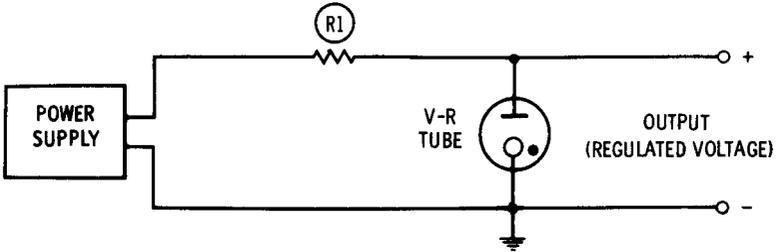
Fig. 3-6. Practical voltage-regulator circuit.

Most commercial voltage-regulator tubes are designed to provide a regulated voltage of between 75 and 150 volts, depending on the particular tube type. For example, the VR-75 will provide a regulated voltage of 75 volts, the VR-105 will supply 105 volts, etc. Common v-r tubes are designed to operate in the current range from 5 to 40 ma.

It was noted earlier that a current-limiting resistor is required between the power-supply output and the v-r tube in order to limit the current through the tube to its rated value. The value of this resistor will depend on the output voltage of the power supply, the voltage rating of the v-r tube, and its current rating. It can be easily determined from the following formula:

$$R = \frac{E_s - E_T}{I}$$

where,

R is the value of the series-dropping resistor,
E_s is the output voltage of the power supply,
E_T is the voltage drop across the v-r tube,
I is the no-load current through the tube. This value is generally 40 ma for tubes such as the VR-75, VR-90, VR-105, VR-150, OA2, OB2, OC2, etc.

SERIES OPERATION OF GAS-FILLED V-R TUBES

It is possible to connect two or more v-r tubes in series in order to obtain a higher value of regulated voltage. Fig. 3-7 shows v-r tubes arranged in this manner. The regulated output voltage is now the sum of the individual ratings. Thus, the value of regulated voltage in Fig. 3-7A is 75 + 150, or 225 volts. In Fig. 3-7B, the regulated voltage is 105 + 75 + 150, or 330 volts.

In determining the value of the series-dropping resistor for series-connected v-r tubes, the same formula applies as in the case of a single tube, except that the *sum* of the individual v-r tube ratings is used for E_T in the formula.

Fig. 3-7 also shows how individual output voltages can be obtained from series-connected v-r tubes. In this arrangement, the desired voltage is taken from the junction of the v-r tubes.
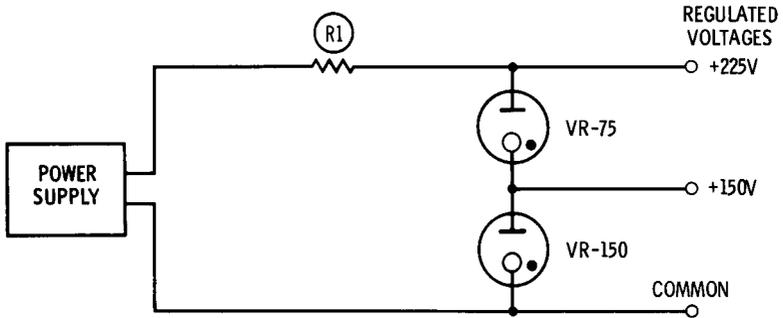
(A) Two in series.
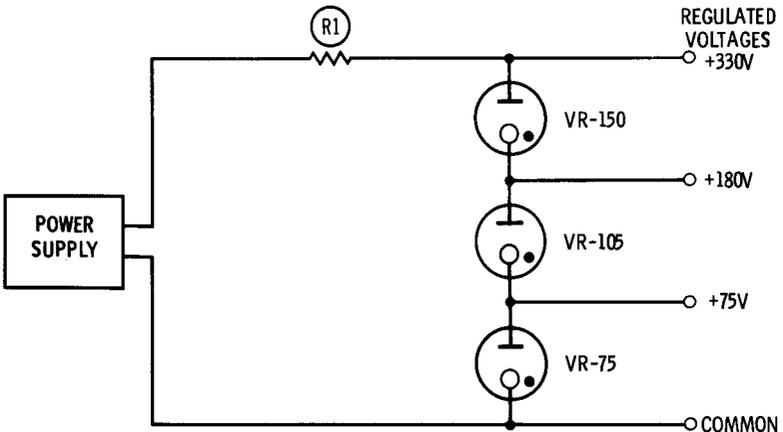
(B) Three in series.

Fig. 3-7. Series-connected voltage-regulator tubes.

PRACTICAL VOLTAGE-REGULATOR CIRCUITS

The following circuits illustrate practical applications of gas-filled regulator elements. When these circuits are connected to the output of an unregulated supply, they will provide a voltage regulation of approximately two percent.
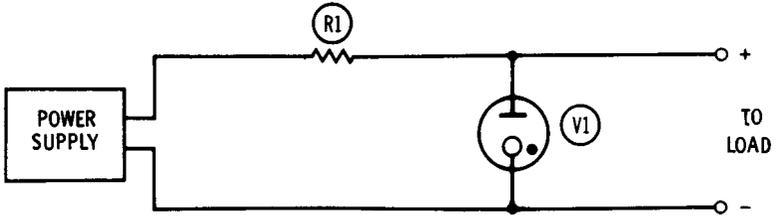
Fig. 3-8. Simple voltage-regulator circuit.

Fig. 3-8 shows a simple gas-filled voltage regulator useful in such applications as providing stable voltage for the local oscillator in a communications receiver or for the screen grids of the output tubes in a hi-fi audio amplifier.

As shown in Fig. 3-8, the circuit consists simply of gas-filled voltage-regulator tube V1 and series-dropping resistor R1. The value of regulated output voltage will depend on the choice of regulator tube. For a regulated output voltage of 75 volts, use an OA3/VR-75, or an OC2 if you would rather use a miniature tube. For a regulated
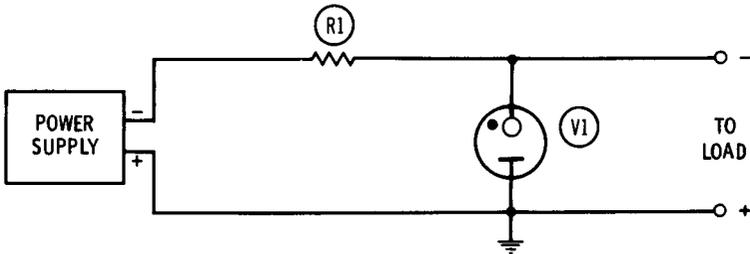
Fig. 3-9. Inverted voltage regulator.

output of 90 volts, use an OB3/VR-90. For 105 volts, an OC3/VR-105 may be used. For an output of 150 volts, use either an OD3/VR150 or its miniature equivalent, the OA2.

No value of series-dropping resistor is given since it depends on the output voltage of the power supply with which this regulator is to be used. The proper value of series-dropping resistor can be easily calculated from the formula:

$$R = \frac{E_S - E_T}{I}$$

where,

R is the value of the series-dropping resistor,
E_S is the unregulated power-supply output voltage,
E_T is the rated v-r tube operating voltage,
I is the v-r tube no-load current.

If a negative regulated output voltage is desired—as, for example, a negative bias source—the circuit of Fig. 3-8 can be "inverted," as shown in Fig. 3-9.

Because of its simplicity, this circuit can be easily tucked away inside an existing piece of equipment.

CHAPTER 4

Closed-Loop Voltage Regulation

The circuits that were examined in the previous chapter are termed "open-loop" voltage regulators. This chapter deals with so-called "closed-loop" voltage regulators. The difference between the two is that the closed-loop regulator makes use of a feedback system for voltage regulation. The change in output voltage of the power supply, due to either input-voltage variations or load-current change, is used to control a variable-resistance element in such a way as to bring the load voltage back to normal. This element may be either in series with or shunted across the load. The closed-loop system is capable of regulating output voltage much more closely with larger load-current variations than is an open-loop system.

Fig. 4-1 illustrates the basic concept of closed-loop voltage regulation. This configuration is known as a series-type closed-loop regulator. The component that provides the regulating action in this circuit is known as a losser element. It may be a transistor or a vacuum tube. The losser element is placed in series with the output of the unregulated power supply and the load. The voltage applied to the load stays constant because the voltage drop across the losser is maintained at the difference between the power-supply output and the desired load voltage.

Voltage divider R1 and R2 is connected across the output of the power supply in parallel with the load. The voltage appearing at the junction of R1 and R2 is applied as a signal to the losser element. When there is an increase in load current the voltage across the load drops, causing a corresponding drop in voltage at the junction of R1 and R2. This decrease in voltage at the input of the losser element lowers its internal resistance. Less voltage is dropped across the losser so a greater voltage is applied to the load, bringing the load voltage back up to normal.
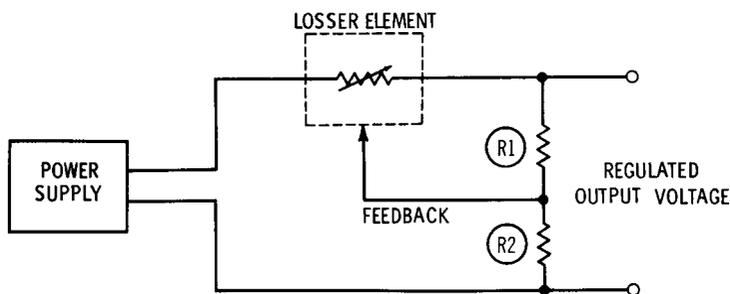
Fig. 4-1. Closed-loop series voltage regulator.

On the other hand, if the load current should decrease, the voltage across the load, and hence at the junction of R1 and R2, will increase. This causes the voltage dropped across the losser element to increase because the internal resistance of the losser increases. A greater voltage loss across the losser element reduces the voltage across the load to its normal value. Now take a closer look at the various elements that make up the closed-loop series regulator.

THE LOSSER ELEMENT

The operation of a vacuum-tube losser element (pass tube, as it is sometimes called) can be easily understood by referring to the circuit in Fig. 4-2. Tube V1 is connected in series with the load so all the load current from the power supply must pass through it. Because the control grid of V1 is connected to the arm of a potentiometer, the grid voltage can be varied from 0 to 100 volts negative with respect to its cathode.

A vacuum tube possesses an internal resistance between its cathode and plate (plate resistance), the amount depending on the construction of the tube. It ranges from a few thousand ohms for low-μ triodes to well over a megohm for pentodes. This resistance in a given tube
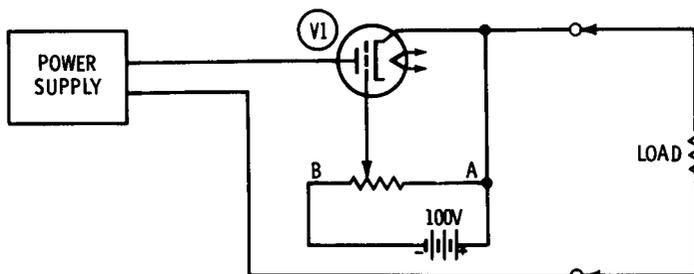
Fig. 4-2. Operation of series voltage-regulator element.

varies with grid bias. It is a minimum when the control grid is at the same potential as its cathode, and it increases as the control grid is made more negative with respect to the cathode.

Referring to Fig. 4-2, when the control grid of the tube is at the same potential as its cathode (potentiometer set at A), the internal resistance of the tube is at a minimum. As a result, there will be minimum voltage drop across V1, and maximum voltage will be applied to the load.

As the slider is moved toward point B, the negative voltage applied to the grid (grid bias) increases, thereby increasing the effective internal resistance of V1. This increases the voltage drop across V1 so less voltage is applied to the load.

A SERIES VOLTAGE-REGULATOR OUTPUT

In order to use the capabilities of the pass tube, its internal resistance must be controlled in such a manner as to automatically correct for variations in load voltage. This is done as shown in Fig. 4-3, the circuit of a basic closed-loop series voltage regulator. V1, the pass tube, is connected between the output of the unregulated power supply and the load. A voltage divider consisting of R1, R2, and R3 is connected across the load terminals. A slider on R2 provides a feedback voltage that is used to control the pass tube.

When the voltage across the load drops because of an increase in load current, there is a corresponding voltage decrease between the tap on the voltage divider and ground. This voltage is applied to the control grid of V2, which operates as a direct current (d-c) amplifier. Its purpose is to amplify the feedback voltage to a level sufficient to control the series pass tube (V1).
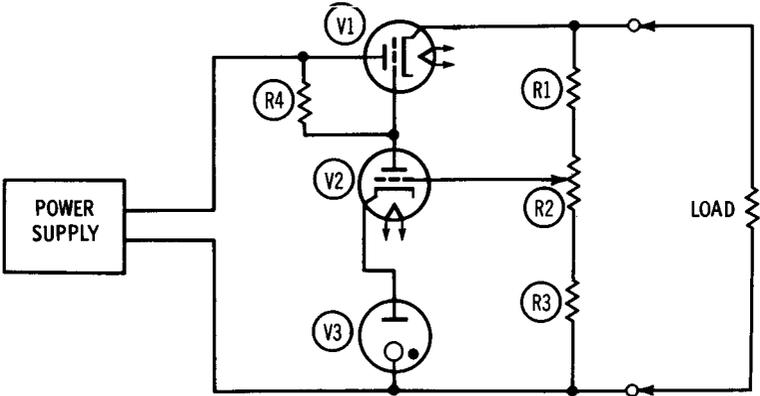
Fig. 4-3. Basic closed-loop voltage regulator.

Since the V2 cathode is held at a constant voltage by gas-filled voltage regulator V3, a decrease in the grid voltage causes V2 to conduct less plate current. As a result, there will be a smaller voltage drop across plate-load resistor R4, and the plate will become more positive (less negative). Since the V1 control grid is directly connected to the V2 plate, the grid bias on V1 decreases, increasing the current through V1. There will be a lower voltage drop across V1, and more voltage will be applied to the load, bringing it back up to its original value.

When the voltage across the load increases, the voltage at the voltage-divider tap increases proportionally, causing the V2 control grid to become more positive with respect to its cathode. V2 conducts more plate current, and the plate voltage becomes less positive, as does the V1 control grid. With the increase in grid bias the internal resistance of V1 increases. This results in a greater voltage drop across V1, and the voltage across the load is reduced to its original value.

When the circuit in Fig. 4-3 is operating normally, there is a certain voltage on the slider of R2 that is applied to the grid of V2, amplified, and fed to V1 where it regulates the effective resistance of the pass tube. Any change from the normal voltage—caused by a change in
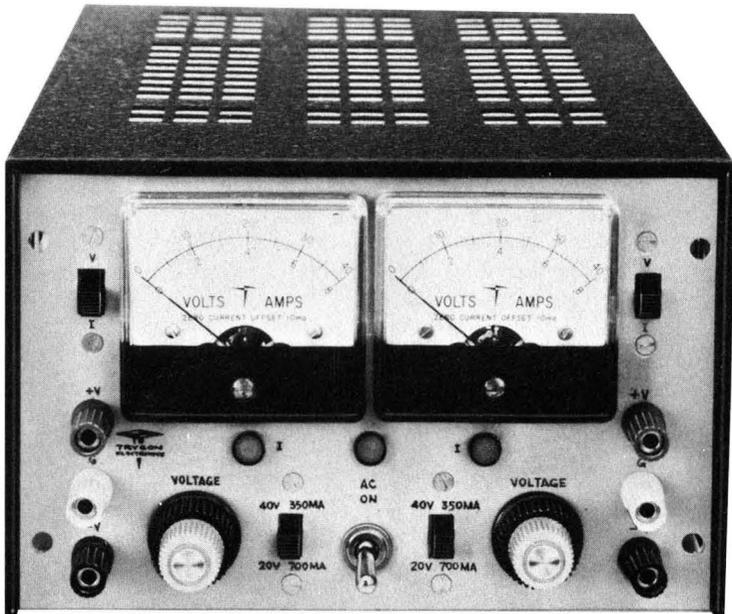
A dual, voltage-regulated power supply. Output voltage is continuously variable and is regulated within .01 percent.

load voltage—is called an error signal. In other words, the actual voltage on the slider of R2 minus the voltage present during normal operation equals the error signal. This can be positive or negative. Tube V2 is sometimes referred to as an error amplifier.

While the simple circuit of Fig. 4-3 serves to illustrate the basic closed-loop series-regulator action, there are a number of changes that can be made to improve its performance. Fig. 4-4 shows a practical circuit. A triode-connected beam-power tube, V1, is used as the series pass tube. D-c amplifier V2 is a pentode rather than a triode in order to obtain greater amplification of the error signal.
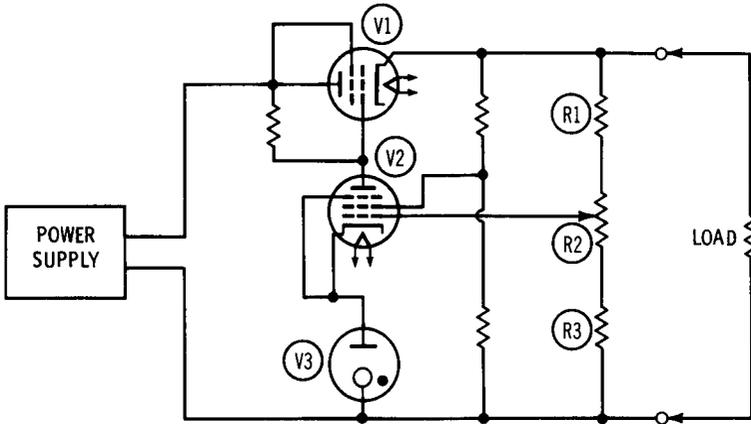
Fig. 4-4. Improved closed-loop voltage regulator.

The tap on the voltage divider connected across the load is made variable by means of potentiometer R2. This permits a range of output voltages to be selected.

Fig. 4-5 illustrates another arrangement. While the circuit operation is unchanged, two stages of d-c amplification, provided by V2 and V3, are used instead of the single pentode in the circuit of Fig. 4-4.

The voltage-regulating ability of the closed-loop circuit is improved as the gain of the d-c error-signal amplifier is increased. The increased gain means that a progressively smaller change in load current will be sufficient to control the series pass tube for voltage correction. However, as the gain of the d-c error amplifier is increased beyond a certain point, problems arise. The most important is variation in tube amplification. The series pass tube "sees" all changes in the d-c amplifier plate voltage as a change in load voltage, and compensates for it. As a result, the voltage across the load is varied by the d-c amplifier drift. This problem can be minimized by proper design of the multistage d-c amplifiers.

Another problem encountered in high-gain d-c error amplifiers is oscillation. These circuits are capable of amplifying a-c as well as d-c signals. As a result, unless the d-c amplifier is properly designed, phase shift at some high frequency can be great enough to cause oscillation.

The current-handling capability of the series regulator can be increased by paralleling series pass tubes, as shown in Fig. 4-6. When this is done, it is advisable to place isolating resistors in series with the plate and screen-grid leads.
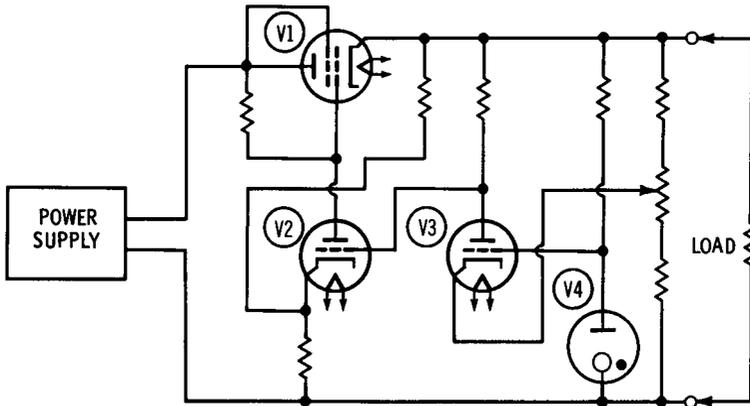
Fig. 4-5. Closed-loop voltage regulator using two-stage error-signal amplifier.

Ripple Reduction

A bonus obtained from the closed-loop series voltage regulator is less output-voltage ripple. Refer to Fig. 4-6. Notice that resistor R4 has been placed between the tap on the voltage divider and the control grid of the d-c error-signal amplifier. Capacitor C1 is connected from the regulated voltage output to the control grid of V3. This capacitor has a low reactance at the ripple frequency (120 Hz for a full-wave rectifier), and so passes the ripple signal to the grid of V3. R3 has sufficient resistance to prevent the ripple signal from being bypassed to ground via the voltage divider R1-R2-R3. The error-signal amplifier (V3) "sees" the ripple voltage as a rapid change in voltage across the load and, as a result, tends to correct for this as well as for other changes in load voltage. For this reason less conventional filtering is required when a closed-loop regulator is added to a power supply.

Input-Voltage Variations

So far, the action of the closed-loop series voltage regulator has been described in correcting variations in load voltage caused by

54

changing load current. It also compensates for changes in input voltage caused by line-voltage variations.

To see why this is so, refer to the basic closed-loop series voltage regulator in Fig. 4-6. When the line voltage increases, the power supply delivers a higher output voltage to the voltage regulator and load. This increase in output voltage is then handled by the regulator in
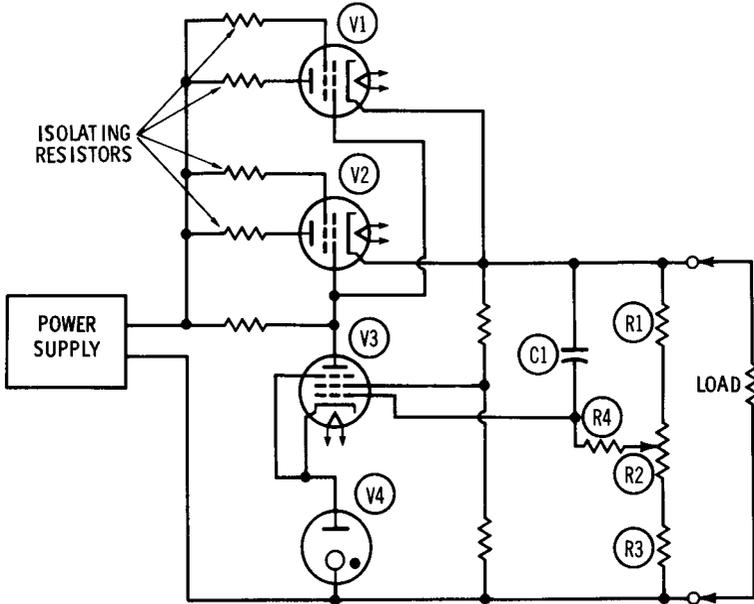
Fig. 4-6. Regulated power supply with multiple series control elements.

exactly the same manner as an increase in output voltage caused by a decrease in load current. A decrease in line voltage will cause the regulator to operate in exactly the same manner as if the load current had increased.

PRACTICAL CIRCUITS

Here are two practical voltage-regulator circuits that can be useful around your test bench, ham shack, or lab. The circuits are simple and straightforward, with no critical kinks to "debug."

Regulated Power Supply

Fig. 4-7 is a very versatile circuit, capable of supplying an unregulated output voltage of 400 volts at 150 ma. The regulated voltage is continuously variable from 130 to 350 volts at load currents up to 75 ma. In addition, a 6.3-volt filament supply is furnished at a current

Fig. 4-7. Versatile voltage-regulated power supply.

Parts List for Fig. 4-7

Item No.	Description
C1	Capacitor, 40 mfd, 450 volts, electrolytic
C2	Capacitor, 40 mfd, 450 volts, electrolytic
C3	Capacitor, 0.1 mfd, mylar
C4	Capacitor, 20 mfd, 450 volts, electrolytic
C5	Capacitor, 40 mfd, 450 volts, electrolytic
C6	Capacitor, .01 mfd, mylar
C7	Capacitor, .01 mfd, mylar
L1	Choke, 6 hy, 200 ma (Knight 54D4704, or equivalent)
R1	Resistor, 100 ohms, 1 watt
R2	Resistor, 100 ohms, 1 watt
R3	Resistor, 47K ohms, 2 watts
R4	Resistor, variable, 50K ohms
R5	Resistor, 68K ohms, 2 watts
R6	Resistor, 100K ohms, ½ watt
R7	Resistor, 100K ohms, ½ watt
R8	Resistor, 100K ohms, ½ watt
R9	Resistor, 470K ohms, ½ Watt
R10	Resistor, 680 ohms, 5 watts
R11	Resistor, 75 ohms, 5 watts
R12	Resistor, variable, 50K ohms, 5 watts
S1	Switch, spst
S2	Switch, spst
T1	Transformer, power. Secondaries: 400 volts center-tapped, 200 ma; 6.3 volts, 5 amps; 5 volts, 2 amps (Knight 54D2033, or equivalent)
V1	Tube, 5U4
V2	Tube, 6L6
V3	Tube, 6L6
V4	Tube, 6AU6
V5	Tube, VR-75
V6	Tube, 6DE4
V7	Tube, VR-150

rating of 3 amperes. Finally, a regulated negative output voltage of zero to 150 volts is provided. This power supply is ideal for the experimenter, ham, or service technician working with vacuum tubes, because it provides such a wide range of output voltages.

Fig. 4-7 is the schematic of the supply. The line voltage, controlled by on-off switch S1, is applied to the primary of power transformer T1. The center-tapped 400-volt secondary of T1, in conjunction with V1, forms a full-wave rectifier, the output of which is applied to the capacitor-input filter, C1-L1-C2. A standby switch, S2, is placed in the center-tap lead of the high-voltage winding. When this is turned to the OFF position, the heater voltage can be applied to the unit

being operated from the supply without the B+. Thus, it is not necessary to turn off the entire supply when you want to remove the d-c output voltage from the unit it is powering.

The positive voltage appearing at the junction of L1 and C2 is applied to the plates of the two series pass tubes, V2 and V3. The voltage is also applied to the screen grids through isolating resistors R1 and R2. The cathodes of V2 and V3 are both connected to the regulated positive output terminal of the power supply.

The voltage-divider network, R3, R4, and R5, is connected from the cathode of V2 and V3 to common (ground). R4 is the output adjust potentiometer; it connects to the control grid of d-c error amplifier V4 via isolating resistor R6. The cathode of V4 is held at a constant potential by gas-filled voltage-regulator tube V5. The V4 screen grid receives its operating voltage from voltage divider R7 and R8.

The plate of V4 is direct-connected to the control grids of series pass tubes V2 and V3. R9 is the V4 plate-load resistor. C3 reduces output ripple by feeding a small portion of the ripple voltage appearing in the regulated output to the V4 control grid.

The negative voltage output is obtained from half-wave rectifier V6. The cathode of V6 is connected to one side of the high-voltage secondary winding. The negative voltage appearing at the plate of V6 is filtered by an r-c network consisting of R10, C4, and C5. A simple r-c filter is used here, rather than an 1-c filter, because of the low current that is anticipated. This is designed as a grid-biasing voltage, and there is normally no current in the grid circuit.

The output of the filter is kept steady by voltage regulator V7; R11 is the current-limiting resistor. A potentiometer, R12, is connected across V7; the slider of this potentiometer is connected to the negative output terminal.

A "Plug-In" Voltage Regulator

Here is a handy little voltage regulator (Fig. 4-8) which offers the plug-in simplicity of a gas-filled voltage-regulator tube, yet it will provide considerably better regulation. Unlike a v-r tube, this has an adjustable output voltage and a higher current capacity (up to 50 ma.) In short, this small compact variable regulator may be just what you need.

As shown in Fig. 4-8, the circuit is that of a simple closed-loop series voltage regulator. It is a bit unusual in that the series pass tube and the d-c amplifier tube are contained in a single envelope. Also, a neon tube is used in place of the more conventional gas-filled voltage-regulator tube.

In operation, the unregulated voltage is applied through pin 3 of the plug to the plate of series pass tube V1A. The error signal appearing
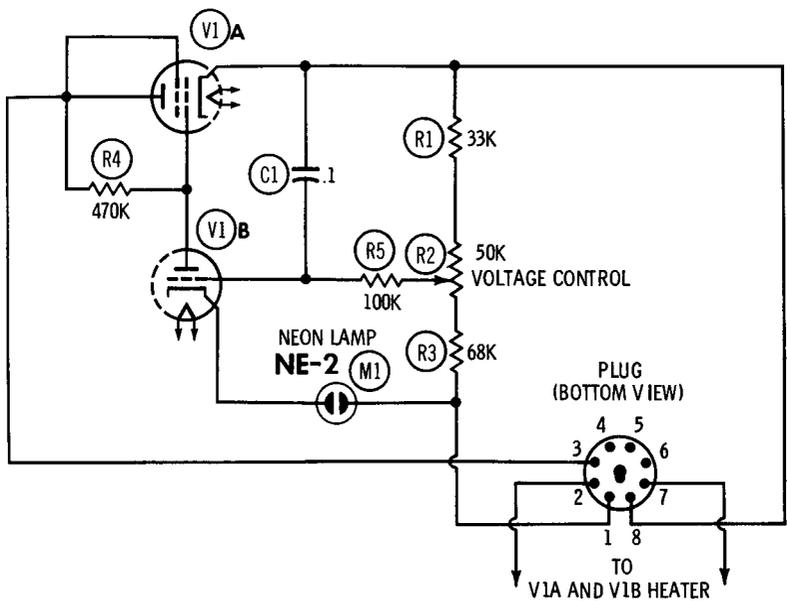
58

Fig. 4-8. Plug-in voltage regulator.

Parts List for Fig. 4-8

Item No.	Description
C1	Capacitor, 0.1 mfd, mylar
M1	Lamp, neon, NE-2
R1	Resistor, 33K ohms, 1 watt
R2	Resistor, variable, 50K ohms
R3	Resistor, 68K ohms, 1 watt
R4	Resistor, 470K, ½ watt
R5	Resistor, 100K ohms, ½ watt
V1	Tube, ECL-80 or 6AB8

at the slider of voltage control potentiometer R2 is applied to the control grid of d-c error amplifier V1B.

The plate of V1B is connected to the control grid of V1A; R4 is the plate-load resistor. The cathode of V1B is held at a constant voltage by an NE-2 neon lamp. It has electrical characteristics similar to those of a gas-filled voltage-regulator tube, although it is not capable of handling as high a current.

The regulated output is available at pin 8 of the plug. Pin 1 is common to both input and output circuits.

Fig. 4-9 shows how the completed plug-in voltage regulator is connected into a power supply which was formerly equipped with a

59
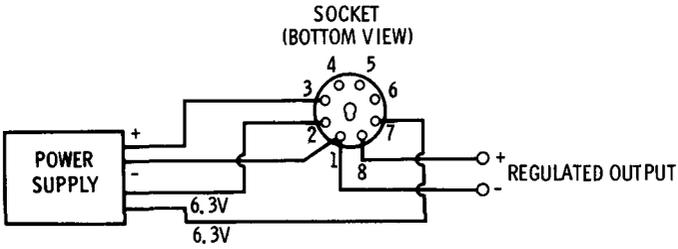
Fig. 4-9. Plug wiring for plug-in supply.

voltage-regulator tube. The original wiring is removed from the v-r tube socket, and the socket is rewired as shown in Fig. 4-9. When the wiring is completed, remove the v-r tube and plug in the voltage-regulator "package." With power applied to the supply, set the "voltage-adjust" potentiometer for the desired output voltage.

60

CHAPTER 5

Semiconductor Power Supplies

Semiconductor rectifiers offer a number of advantages over vacuum-tube and gas-filled rectifiers. Chief among these are smaller size, greater reliability, absence of a heated cathode, lower forward-voltage drop, and greater mechanical ruggedness.

Fig. 5-1 illustrates how the semiconductor rectifier may be used in the four basic rectifier circuits: half-wave, full-wave, bridge, and voltage-multiplier. Although there are various types of rectifiers which are broadly classified as "semiconductor rectifiers," in this chapter we will deal primarily with silicon rectifiers, as they are the type most commonly used in power supplies.

SEMICONDUCTOR-RECTIFIER RATINGS

As in the case of high-vacuum and gaseous rectifiers, semiconductor rectifiers have specific operating limitations. In circuits where they are employed it is very important that these ratings not be exceeded.

Peak Inverse Voltage (piv)

The peak inverse voltage, sometimes referred to as the peak reverse voltage (prv), is a rating of a semiconductor diode that denotes the maximum reverse voltage which may be applied to the diode. It is dependent in part upon the temperature of the diode, decreasing as the diode temperature increases.

Peak Surge Current

This rating refers to the peak instantaneous value of forward current which a semiconductor diode can safely conduct for a limited time (usually one cycle of the applied alternating current). It is especially significant in circuits where the output of the semiconductor

SILICON DIODE
+
ANODE CATHODE
A-C INPUT
D-C OUTPUT
+
-

(A) Half-wave.

SILICON DIODE
+
A-C INPUT
D-C OUTPUT
+
+
SILICON DIODE
-

(B) Full-wave.

A-C INPUT
D-C OUTPUT
-
+

(C) Bridge.

A-C INPUT
D-C OUTPUT
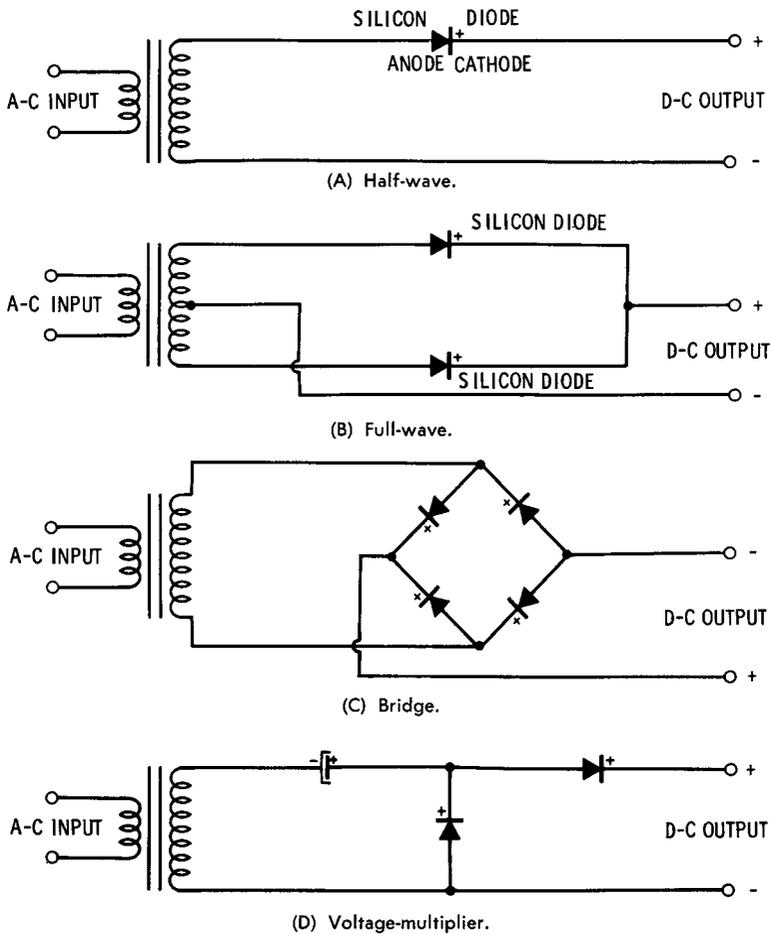+
+
+
-

(D) Voltage-multiplier.

Fig. 5-1. Semiconductor-rectifier circuits.

diode is applied to a capacitor-input filter. Under this condition, care must be taken to assure that the initial current charging the input filter capacitor does not exceed the peak surge-current rating. When a large value of input filter capacitor is required, a current-limiting resistor should be placed in series with the input capacitor.

Average Forward Current

The average forward-current rating of a semiconductor diode refers to the maximum value of forward current which the diode can safely handle on a continuous basis. Average forward-current ratings of silicon diodes range from a fraction of an ampere to many hundred amperes.

SERIES CONNECTION OF SEMICONDUCTOR DIODES

Often it may be necessary to connect several semiconductor diodes in series in order to obtain a higher piv (peak inverse voltage) than is obtainable from a single unit. In order to do this safely, several precautions must be observed.
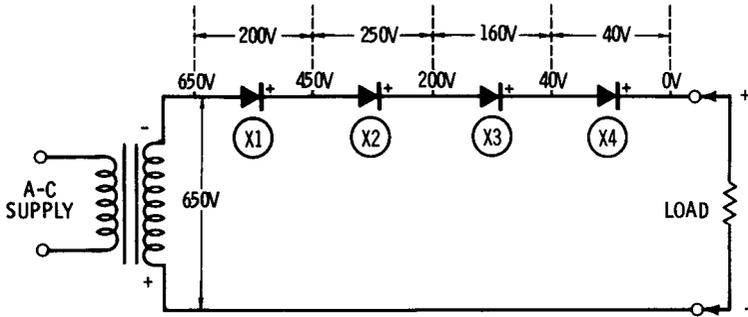

Fig. 5-2. Voltage distribution across series-connected diodes.

Fig. 5-2 shows four typical series-connected silicon diodes in a simple half-wave power-supply configuration. Notice that the reverse-voltage distribution across the diodes is unequal, the voltage across X1 and X2 being higher than that across X3 and X4. The cause of this voltage variation is the difference in reverse leakage currents of the individual diodes. In this situation, the voltage across one or more of the series-connected diodes may exceed their piv rating, causing their failure.

Fig. 5-3 illustrates a method for equalizing this variation in voltage division across the diodes. A resistor is connected across each diode, the value of each resistor being low in comparison to the normal re-
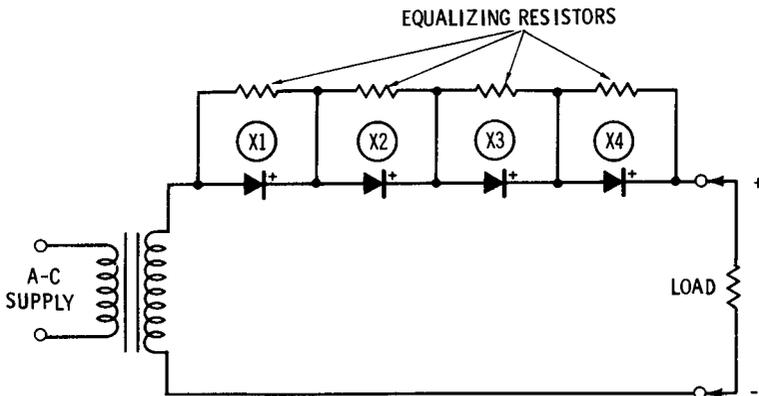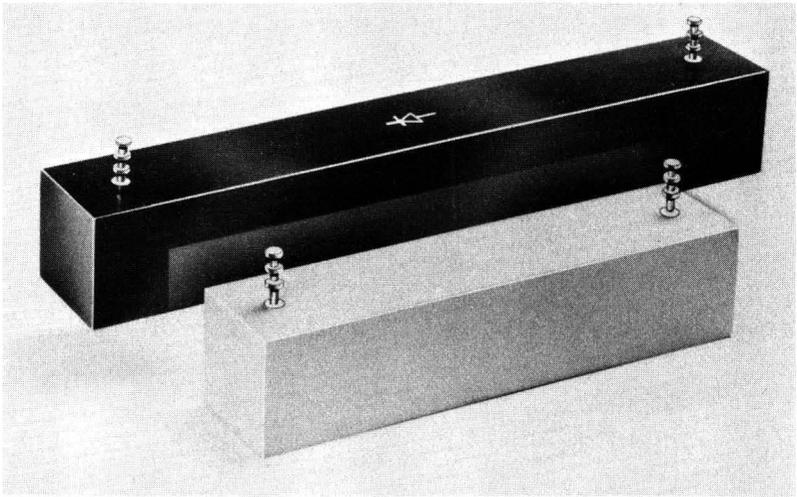

Fig. 5-3. Use of equalizing resistors.

A commercial silicon-rectifier unit to be used in high-voltage (3000 to 50,000 volts) applications.

verse resistance of the diodes. The effect of these resistors is to provide a constant voltage division across the diode string. Typical values of these resistors are 250,000 to 500,000 ohms. Their value is not critical.

In addition to equalizing resistors, it is wise to place bypassing capacitors across each series-connected diode, as shown in Fig. 5-4. These capacitors bypass any transient-voltage pulses in the power line feeding the diodes. Transients occasionally reach a high enough amplitude to exceed the piv of the diodes. The value of these bypass
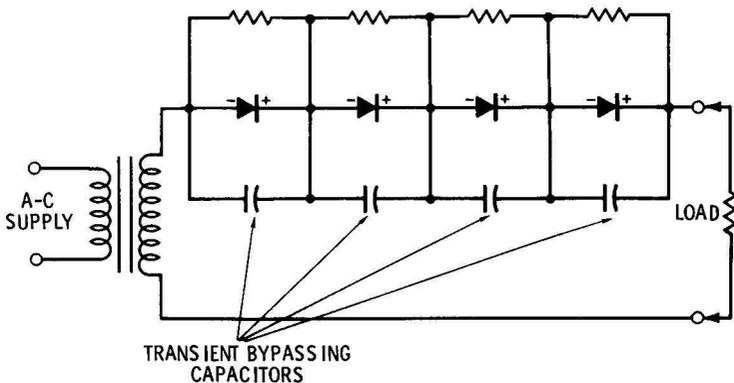
Fig. 5-4. Use of bypass capacitors.

64

capacitors should be between .01 and 0.1 mfd, and their voltage rating should be equal to or greater than the piv rating of the diode across which they are connected.

Another method of reducing the chance of diode damage by line-voltage transients is shown in Fig. 5-5. A thyrector diode is connected directly across the primary of the transformer feeding the diodes. The thyrector is a special type of semiconductor which will abruptly conduct in either direction when the voltage across it exceeds a certain predetermined value, thereby absorbing any voltage transients above its design value. Below this value, the thyrector appears as an open circuit. In effect, the thyrector is like two back-to-back zener diodes.
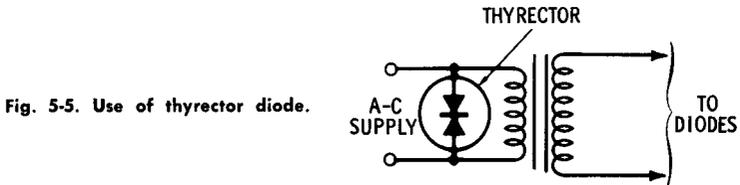

Fig. 5-5. Use of thyrector diode.

SUBSTITUTING FOR TUBE RECTIFIERS

Because of the much smaller physical size and lower voltage drop of silicon rectifiers, it is often advantageous to use them as replacements for their vacuum-tube or gas-filled rectifier counterparts in existing power supplies. When this is done, certain precautions must be observed if satisfactory performance is to be achieved. To see what these are, examine the following circuits.

Fig. 5-6 shows a typical full-wave rectifier circuit using silicon diodes. The piv rating of X1 and X2 should be equal to at least the peak value of the voltage appearing across the *entire* secondary of T1—not just one-half of the winding as you might expect. The reason
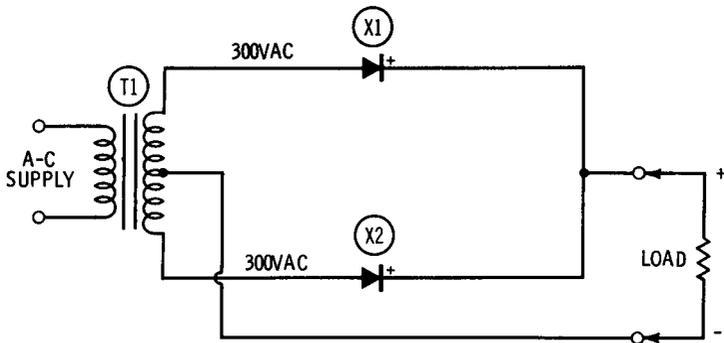

Fig. 5-6. Full-wave semiconductor-rectifier circuit.

for this becomes clear when you examine the circuit of X1 and X2 during a half-cycle of operation. Notice that while X2 is conducting, the full secondary voltage appears across the reverse-biased X1. In effect, X2 is a short circuit. On the following half-cycle of operation X1 is conducting, thereby placing the full secondary voltage of T1 across X2. From this, it is apparent that the piv rating of X1 and X2 should equal at least the peak voltage across the secondary of T1— 1.4 × 600 volts, or 840 volts. Actually, an additional 20 percent
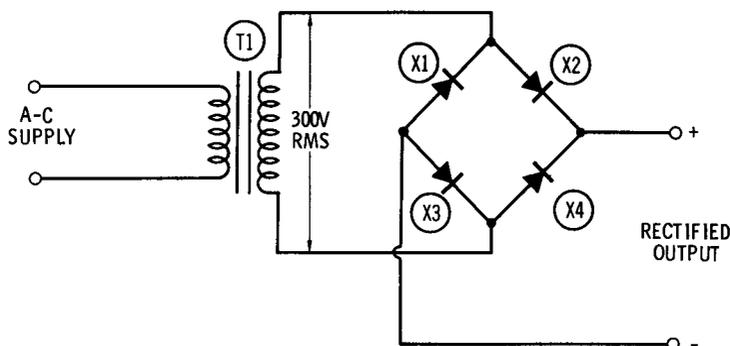

Fig. 5-7. Bridge rectifier.

should be added to this value to allow for power-line voltage variations. X1 and X2 should therefore have a piv rating of 1080 volts. Either 1000-volt diodes may be used, or X1 and X2 may be made up of strings of series-connected diodes of lower piv ratings. If the latter is done, the precautions outlined earlier in this chapter should be observed.

Fig. 5-7 shows a bridge-rectifier configuration using silicon diodes. The bridge arrangement is an advantage under some circumstances since a center-tapped transformer winding is not required.

The piv ratings of X1, X2, and X3, and X4 should be at least equal to the peak value of the voltage developed across the secondary of T1. In the case of Fig. 5-7, this would be 300 × 1.4, or 420 volts. Add to this a 20-percent safety factor, and we get a piv rating per diode of 504 volts. This can be rounded off to 500 volts. If desired, series-connected diodes may be used for any or all of the four rectifiers.

When silicon diodes are substituted for vacuum tubes, the rectified d-c voltage from the diodes will increase. The reason is that the diodes have a lower forward-voltage drop than tubes. For example, the forward-voltage drop across a typical silicon diode will be approximately one volt, while the voltage drop across a typical vacuum-tube rectifier may be as high as 30 volts. This higher output voltage can, under
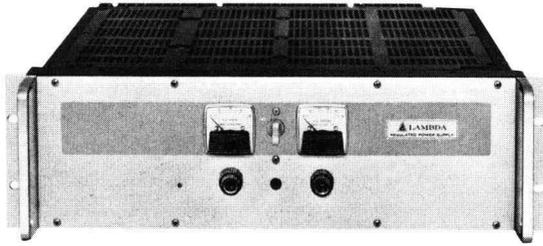
An all-silicon regulated power supply with continuously variable voltage output.

some circumstances, cause difficulties in the circuit being supplied with power by the diodes.

Fig. 5-8 shows how the voltage output of a full-wave rectifier circuit can be decreased. Resistor R1 has been placed in series between the output of the diodes and the input of the filter. The correct value of this series resistor can be obtained by the use of Ohm's law:

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

where,
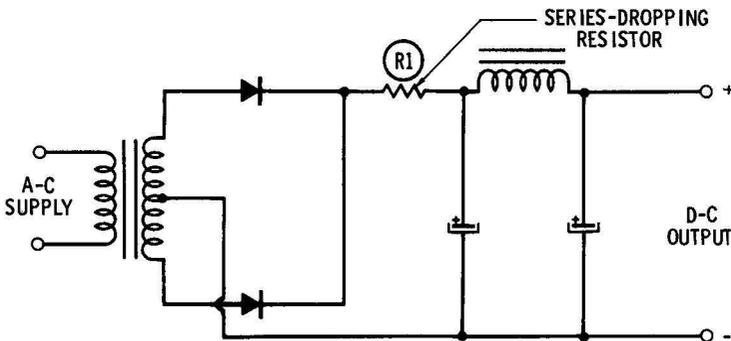
R is the value of the resistor, in ohms,
E is the desired drop in voltage, in volts,
I is the d-c output current, in amperes.

The required wattage rating of the resistor can be calculated from

$$W = \frac{E^2}{R}$$

where,

E is the voltage drop across the resistor, in volts,
R is the value of the resistor, in ohms.

Fig. 5-8. Use of series-dropping resistor.

Another method of voltage dropping is considerably more efficient than the resistor method just described. A choke can replace the series-dropping resistor (Fig. 5-8) since it reduces the output of the filter to nearly the rms value of the input to the rectifier. Without choke or resistor the output would be nearly equal to the peak value. This choke also makes life easier for the rectifier diodes by greatly reducing the high initial charging current of the input-filter capacitor.

A DUAL LOW-VOLTAGE POWER SUPPLY

The low-voltage power supply shown in Fig. 5-9 can furnish two switch-selected d-c output voltages at a current rating of up to 1 amp.
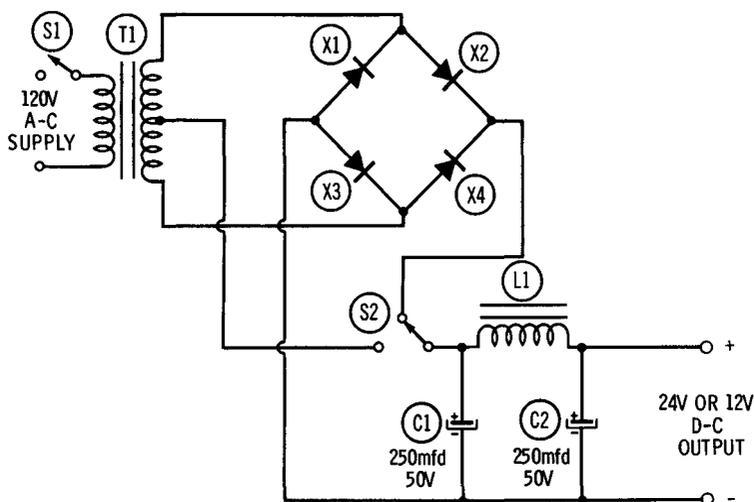
Fig. 5-9. Dual-voltage power supply.

Parts List for Fig. 5-9

Item No.	Description
C1	Capacitor, 250 mfd, 50 volts, electrolytic
C2	Capacitor, 250 mfd, 50 volts, electrolytic
L1	Choke, .035 hy, 2 amps (Knight 54D2343, or equivalent)
S1	Switch, spst
S2	Switch, spst
T1	Transformer, power, 25 volts center-tapped, 1 amp (Knight 54D1421, or equivalent)
X1	Rectifier, silicon, 1N2482
X2	Rectifier, silicon, 1N2482
X3	Rectifier, silicon, 1N2482
X4	Rectifier, silicon, 1N2482

The supply uses step-down transformer T1 in conjunction with a bridge rectifier composed of X1, X2, X3, and X4. The output from the rectifier is filtered by C1, C2, and L1. The dual voltage is obtained by making use of either the entire bridge rectifier (full output voltage) or half of the bridge and the secondary center tap (half voltage). The full-voltage output of the supply is 24 volts at the rated load of 1 amp, and the half-voltage output is 12 volts, also at 1 amp. Since a capacitor-input filter is used, the output voltages from the supply are higher under light loads.

A 600-VOLT "HAM-TRANSMITTER" POWER SUPPLY

This high-voltage power supply is ideal for a medium-power transmitter. The supply provides 600 volts at 200 ma, with more than adequate filtering. The unit is physically small because no bulky mercury-vapor rectifier tubes are required. As an added bonus, the supply provides "instant-on" operation. There are no tubes that need to warm up before they can function, so the voltage is available at the output the instant the switch is closed.

As shown in Fig. 5-10, the voltage across the secondary of power transformer T1 is rectified by a full-wave circuit consisting of X1, X2, X3, and X4. Each half of the full-wave rectifier consists of two series-connected 800-piv silicon diodes. Equalizing resistors and transient bypassing capacitors are connected across the diodes. As mentioned earlier in this chapter, the high piv rating of the diodes in a full-wave rectifier is necessary because the full peak voltage of the transformer secondary appears across the nonconducting diodes.

The output from the rectifier is applied to the filter consisting of L1, L2, C5, C6, C7, C8, R1, R2, R3, and R4. A choke-input filter is used both to limit the initial charging current drawn from the rectifier and to improve voltage regulation. Because of the choke-input filter, the output voltage of this supply will vary only slightly from no-load to full-load operation.

In order to obtain the required voltage rating, the filter capacitors are stacked—C5 with C6, and C7 with C8. The actual capacitance is half the value of each of the stacked capacitors—20 mfd. Equalizing resistors are placed across the capacitors to assure equal voltage distribution across them.

VOLTAGE-MULTIPLIER CIRCUITS

Because of their small physical size and their freedom from filament power requirements, silicon diodes are ideally suited to voltage-multiplier circuits. The following are a few practical examples of such circuits.
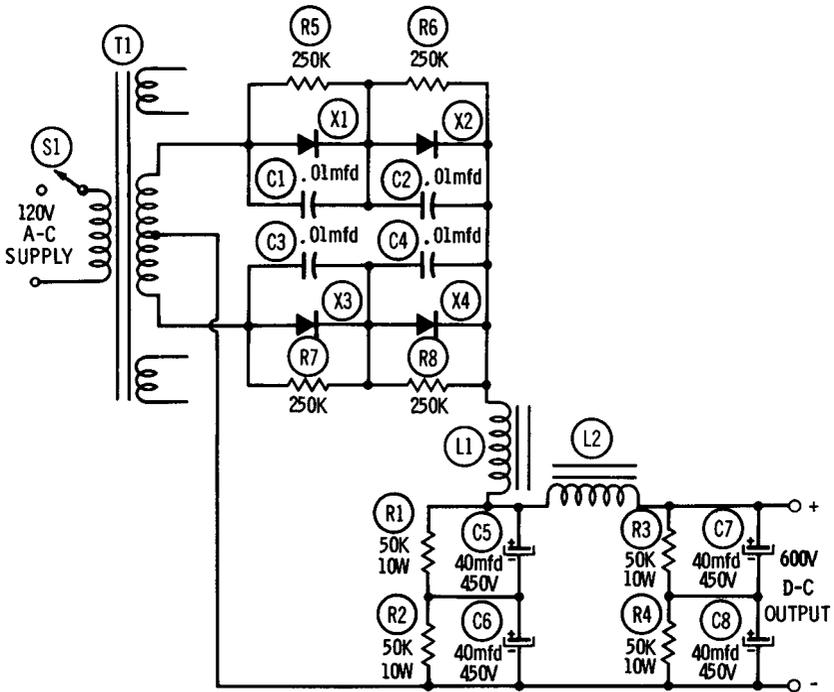
Fig. 5-10. Transmitter power supply.

Parts List for Fig. 5-10

Item No.	Description
C1	Capacitor, .01 mfd, 1000 volts, mylar
C2	Capacitor, .01 mfd, 1000 volts, mylar
C3	Capacitor, .01 mfd, 1000 volts, mylar
C4	Capacitor, .01 mfd, 1000 volts, mylar
C5	Capacitor, 40 mfd, 450 volts, electrolytic
C6	Capacitor, 40 mfd, 450 volts, electrolytic
C7	Capacitor, 40 mfd, 450 volts, electrolytic
C8	Capacitor, 40 mfd, 450 volts, electrolytic
L1	Choke, 6 hy, 200 ma (Knight 54D4704, or equivalent)
L2	Choke, 6 hy, 200 ma (Knight 54D4704, or equivalent)
S1	Switch, spst
T1	Transformer, power, 600 volts, 200 ma (Knight 54D2549, or equivalent)
X1	Rectifier, silicon (Sarkes Tarzian F8, or equivalent)
X2	Rectifier, silicon (Sarkes Tarzian F8, or equivalent)
X3	Rectifier, silicon (Sarkes Tarzian F8, or equivalent)
X4	Rectifier, silicon (Sarkes Tarzian F8, or equivalent)

Voltage-Doubler Power Supply

The power supply in Fig. 5-11 is ideal for the experimeter who needs a well-filtered voltage source for experimental vacuum-tube circuits. It may also be integrated into a new design such as a ham transmitter or exciter.
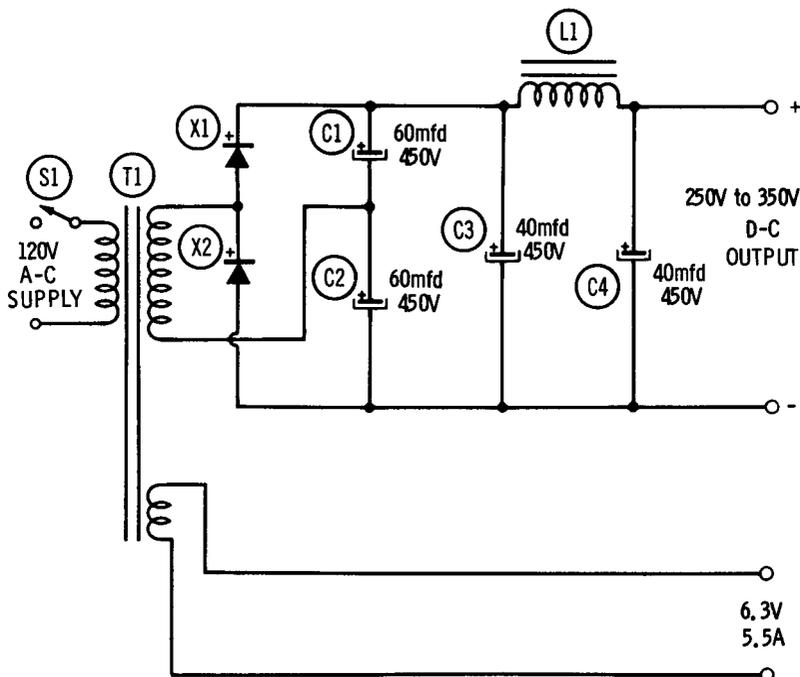

Fig. 5-11. Dual low-voltage power supply.

Parts List for Fig. 5-11

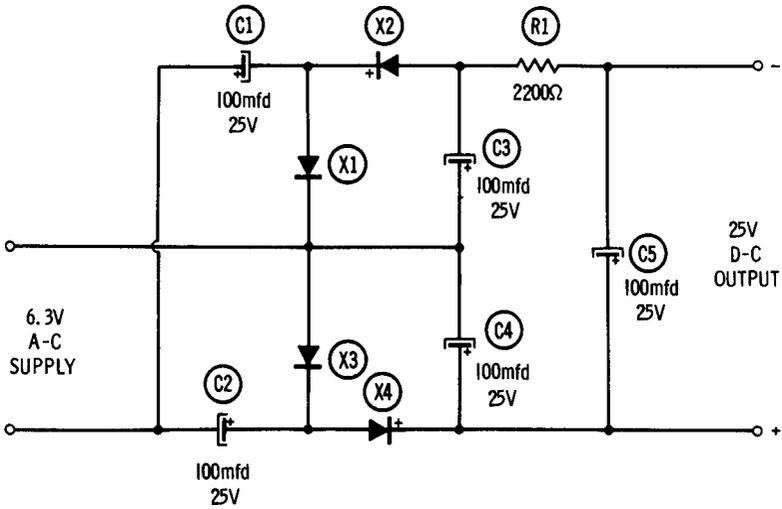| Item No.	Description
C1	Capacitor, 60 mfd, 450 volts, electrolytic
C2	Capacitor, 60 mfd, 450 volts, electrolytic
C3	Capacitor, 40 mfd, 450 volts, electrolytic
C4	Capacitor, 40 mfd, 450 volts, electrolytic
L1	Choke, 5 hy, 100 ma (Knight 54D2348, or equivalent)
S1	Switch, spst
T1	Transformer, power. Secondaries: 135 volts, 200 ma; 6.3 volts, 5.5 amps (Knight 54D3708, or equivalent)
X1	Rectifier, silicon, 1N2483
X2	Rectifier, silicon, 1N2483

Fig. 5-12. Voltage-quadrupler bias supply.

Parts List for Fig. 5-12

Item No.	Description
C1	Capacitor, 100 mfd, 25 volts, electrolytic
C2	Capacitor, 100 mfd, 25 volts, electrolytic
C3	Capacitor, 100 mfd, 25 volts, electrolytic
C4	Capacitor, 100 mfd, 25 volts, electrolytic
C5	Capacitor, 100 mfd, 25 volts, electrolytic
R1	Resistor, 2200 ohms, ½ watt
X1	Rectifier, silicon, 1N2482
X2	Rectifier, silicon, 1N2482
X3	Rectifier, silicon, 1N2482
X4	Rectifier, silicon, 1N2482

As shown in Fig. 5-11, the power supply consists of power transformer T1; diodes X1 and X2; capacitors C1, C2, C3, and C4; and choke L1. In operation, the voltage across the secondary of T1 is fed to a full-wave voltage doubler. The voltage at the output of the rectifier is filtered by L1, C3, and C4.

The output voltage from the power supply will be approximately 250 volts at a load current of 100 ma. It will rise to a maximum of about 350 volts at no-load.

Voltage-Quadrupler Bias Supply

This is a relatively simple way of obtaining a bias supply up to 25 volts without the use of an extra transformer or special tapped sec-

72

ondary winding. As shown in Fig. 5-12, a voltage quadrupler consisting of X1, X2, X3, X4, C1, C2, C3, C4, C5, and R1 is connected across a 6.3-volt filament winding of the equipment in which the bias supply is to be incorporated. The output of the quadrupler is applied to a simple filter consisting of R1 and C5. A resistor is used in place of the more conventional filter choke since the current drawn from the bias supply is almost negligible.

Solid-State Voltage Regulation

Vacuum-tube voltage regulators have equivalents in solid-state circuitry. Both open-loop and closed-loop regulation is used, depending on the amount of variation that can be tolerated in the power-supply output. Shunt and series circuits have been developed.

OPEN-LOOP OPERATION

Earlier in this book it was pointed out that, by the use of a gas-filled shunt-regulator tube, the d-c output of a power supply can be held to within quite close limits in spite of variations in load current and supply voltage. There exists a solid-state equivalent of the gas-filled voltage-regulator tube—the zener diode. Before examining the basic zener regulator circuit, it is necessary to understand the operation of the zener diode itself.

Fig. 6-1 is the characteristic curve of a typical zener diode. Notice that as the reverse voltage applied to the diode is increased from zero to point X, there is negligible reverse current through the diode. When the voltage is increased beyond point X, the reverse current suddenly increases. At this point, electrical activity in the diode "avalanches," and the reverse current increases rapidly, although there is only a small increase in reverse voltage. In other words, the voltage drop across the zener diode remains practically constant for wide variations in current. As you can see, this characteristic of the zener diode is very similar to that of the gas-filled voltage-regulator tube when the latter ionizes.

Fig. 6-2 shows a zener diode connected to a source of variable voltage. Note that the polarity is such that the diode blocks the flow of electrons. A resistor is placed in series with the zener diode to limit the current through the diode to a safe value when it avalanches. As the voltage from the potentiometer (through the current-limiting re-
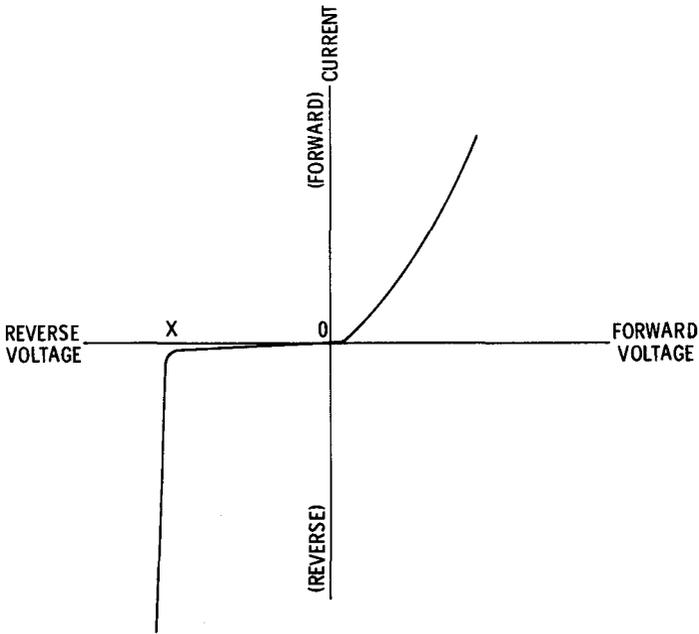
Fig. 6-1. Zener-diode electrical characteristics.

sistor) is increased, the voltage across the diode also increases. When the applied voltage reaches the avalanche voltage, the diode will conduct (in the reverse direction from normal conduction). As the applied voltage is raised still further, the voltage across the diode remains constant. The series resistor limits the current through the diode to a value that does not exceed the power-dissipation rating of the diode.

From this explanation you can see that the zener diode acts like a variable resistor, the resistance increasing or decreasing, as required, to maintain a constant voltage drop in spite of varying current. It functions in a manner similar to the gas-filled voltage regulator.

Fig. 6-3 shows the zener diode used as a shunt regulator in a power-supply circuit. To examine briefly its operation, assume that the load
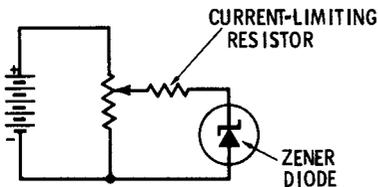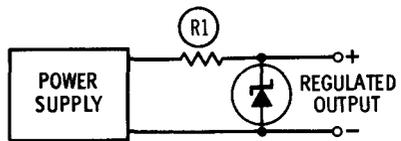

Fig. 6-2. Operation of a zener diode.

Fig. 6-3. Basic zener-diode voltage regulator.

76

connected to the output of the regulator draws an increasing amount of current. This results in a greater voltage drop across current-limiting resistor R1 and a smaller voltage drop across the diode. The diode will then pass less current, the voltage drop across the current-limiting resistor will be reduced, and the voltage applied to the load will come back up to its original value.
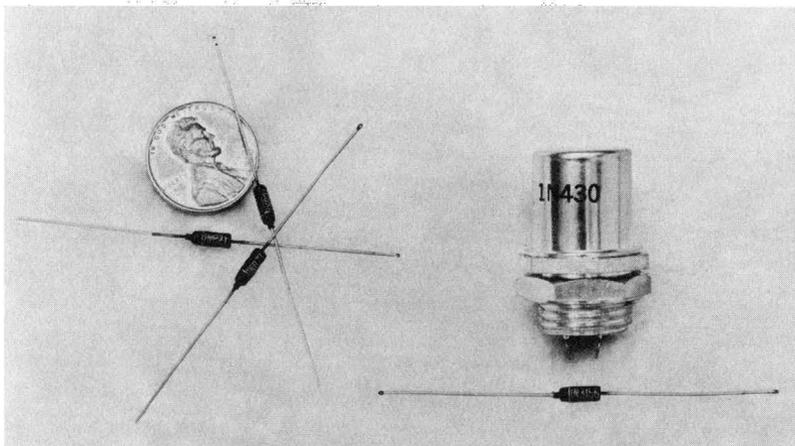
Typical zener diodes of varying capabilities for use as reference-voltage sources.

Should the load current decrease, there will be a smaller voltage drop across the current-limiting resistor, tending to raise the voltage across the zener diode. This will increase the current through the diode, thereby increasing the voltage drop across R1. As a result, the voltage across the load will drop back to its original value.

Zener diodes are available in a much wider range of operating voltages than are gas-filled voltage regulators. The latter can be purchased in ranges from 75 to 150 volts. The low voltage limit on these tubes is due to the fact that the gas used in them will not ionize below approximately 75 volts. Zener diodes, which do not depend on the ionization of gas for their operation, may be obtained with operating voltages as low as several volts and as high as several hundred volts.

Zener diodes are also available in a much wider range of operating currents than are tube-type voltage regulators. The typical gas-filled unit has a recommended operating current of 40 ma. In contrast, zener diodes are available in operating currents ranging from several milliamperes for reference-voltage units to several hundred milliamperes for the high-power units.

In all voltage-regulator circuits, a supply voltage is required that is somewhat higher than the actual value of the regulated voltage. The

reason for this is that there is a voltage drop across the current-limiting resistor.

The approximate value of the current-limiting resistor needed for use in a zener-diode shunt voltage-regulator circuit can be found by the following formula:

$$R = \frac{E_S - E_T}{I}$$

where,

R is the value of the current-limiting resistor, in ohms,
E_S is the unregulated supply voltage, in volts,
E_T is the value of the regulated (zener) voltage, in volts,
I is the maximum zener-diode current (no-load), in amperes.

This formula does not take into account the effects of elevated temperature and other variables on the zener diode. Nevertheless it is sufficient to place the resistance value "in the ball park" and is adequate for most experimental projects.
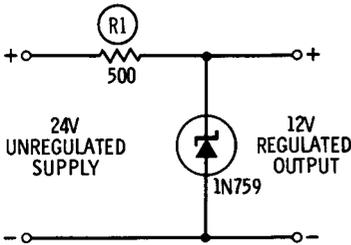

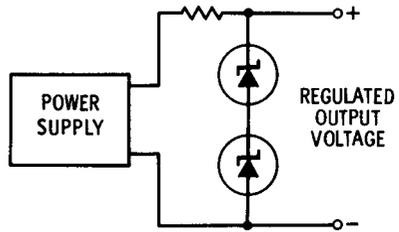Fig. 6-4. "Add-on" zener
voltage regulator.

Fig. 6-5. Two zener diodes connected
in series.

Fig. 6-4 is the schematic of a simple "add-on" zener-diode voltage regulator that can be connected to the unregulated output of a 24-volt power supply to yield a regulated output of 12 volts. The unregulated voltage is applied to the zener diode via current-limiting resistor R1. The value of this resistor is selected to provide the rated no-load current through the zener diode (30 ma).

The values given in Fig. 6-4 are for a specific zener-diode type and supply voltage; however, a zener diode with a different rating may be substituted for the one shown to obtain a different value of regulated voltage. The value of series-dropping resistor will have to be changed if a different diode is used.

Like their regulator-tube counterparts, zener diodes may be connected in series to raise the total regulated voltage, as shown in Fig. 6-5. When zener diodes are used in this manner, care should be taken to select units of identical power ratings.

78

Fig. 6-6. Basic closed-loop
voltage regulator.

POWER
SUPPLY

Q1
PNP

REGULATED
OUTPUT
VOLTAGE
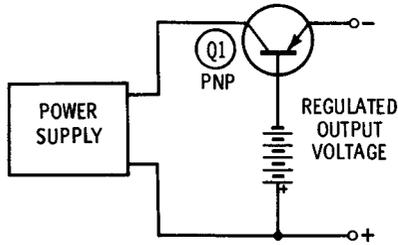
CLOSED-LOOP OPERATION

The basic circuitry of solid-state closed-loop voltage regulators is essentially the same as that of their vacuum-tube counterparts. Regulation is achieved by comparing the change in output voltage of the power supply with a fixed reference voltage. The resulting error signal is then used to actuate a control device in such a way as to either increase or decrease the current through it; this change brings the load voltage back to its original value.

Fig. 6-6 shows perhaps the simplest of all closed-loop semiconductor voltage regulators. In operation, the collector and emitter of transistor Q1 are connected in series between one side of the unregulated voltage and the load. The base-to-emitter bias consists of battery M1 plus the voltage drop across the load. The size of the battery is selected in such a manner that the algebraic sum of the battery voltage and the desired load voltage will give a suitable base-to-emitter (base-bias) voltage.

When the load voltage changes, the base bias of the transistor also changes. The difference between this resultant base bias and the normal bias is called the error signal. If the load voltage decreases, the error signal changes the bias so the transistor conducts less current. A smaller voltage drop across the transistor results in a higher voltage across the load, so normal operation is restored.

Fig. 6-7 shows the same basic circuit, except that the reference battery has been replaced with a zener diode which furnishes the required reference voltage.

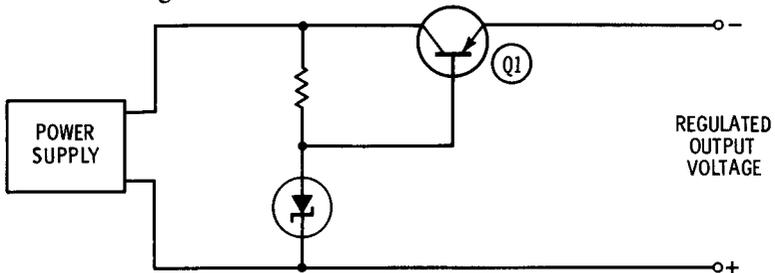

POWER
SUPPLY

Q1

REGULATED
OUTPUT
VOLTAGE

Fig. 6-7. Use of zener diode to provide reference voltage.

The circuits shown in Figs. 6-6 and 6-7 employ a series-regulator transistor (Q1) as the current-controlling element. The circuit of Fig. 6-8 makes use of a shunt regulator (Q1). This configuration differs from the series regulator in that the regulating element is in parallel with the load. In operation, Q1 shunts more or less of the current through resistor R1, the amount depending on the load-current variations. In this circuit zener diode X1 provides the required reference voltage for the base of Q1.
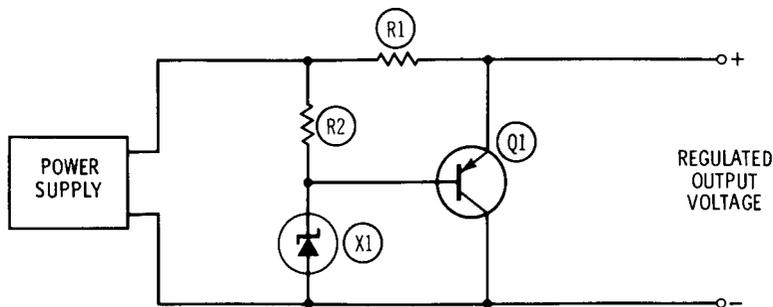

Fig. 6-8. Basic shunt voltage regulator.

The choice between the series and shunt voltage regulator is largely determined by the value of load current. Operation of the shunt regulator is such that under conditions of little or no load, the control element, Q1, must conduct the entire load current. As the external load current is increased, Q1 conducts less current, drawing the least current at full external load.

On the other hand, the series-regulator element dissipates the least amount of power at zero load conditions. As the external load is increased, current through the regulator and its dissipation increase. Thus, the shunt regulator is best suited for conditions where nearly maximum load current will be drawn most of the time, and the series regulator is best for light-load conditions.

One advantage of the shunt regulator is that it is protection against short circuits in the load. As you can see from Fig. 6-8, Q1 is connected directly across the external load. Should the load become short-circuited, all that will happen is that operating voltage will be removed from Q1. In the case of the series regulator, however (Fig. 6-6), a shorted external load will cause an excessive current through Q1 and this current will probably destroy Q1.

A Typical Power Supply

Fig. 6-9 is the schematic of a handy variable-output voltage-regulated power supply that can provide an output-voltage range of 6 to 25 volts at a maximum current rating of 1 ampere. The voltage ap-

pearing across the secondary of T1 is rectified by X1, X2, X3, and X4 in a bridge-rectifier configuration. The output from the filter is applied to the collector of transistor Q1. The emitter of Q1 is connected to the negative output terminal. Zener diode X5 and current-limiting resistor R1 provide the reference voltage for the base of Q1.
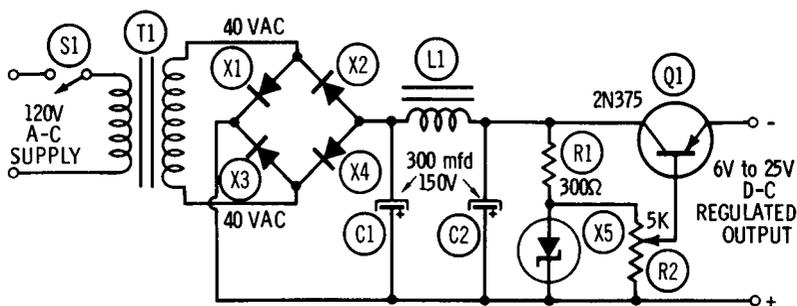

Fig. 6-9. Variable-voltage regulated power supply.

Parts List for Fig. 6-9

Item No.	Description
C1	Capacitor, 300 mfd, 150 volts, electrolytic
C2	Capacitor, 300 mfd, 150 volts, electrolytic
L1	Choke, .035 hy, 1 amp (Knight 54D2343, or equivalent)
Q1	Transistor, PNP, 2N375
R1	Resistor, 300 ohms, 1 watt
R2	Resistor, variable, 5000 ohms
S1	Switch, spst
T1	Transformer, power, 40 volts, 1 amp (Knight 54D4735, or equivalent)
X1	Rectifier, silicon, 1N2482
X2	Rectifier, silicon, 1N2482
X3	Rectifier, silicon, 1N2482
X4	Rectifier, silicon, 1N2482
X5	Diode, zener, 1N921

The stabilized voltage appearing across X5 is applied to voltage-control potentiometer R2, the slider of which is connected to the base of Q1. Thus, by adjusting R2, the amount of base bias applied to Q1 can be varied, and the value of the regulated output voltage changes.

Series control transistor Q1 should be provided with a suitable heat sink in this circuit. The case of Q1 must be insulated from the chassis; this can be accomplished as shown in Fig. 6-10. When this regulated power supply is used, extreme care must be taken not to short-circuit its output terminals because this will quickly destroy the transistor.
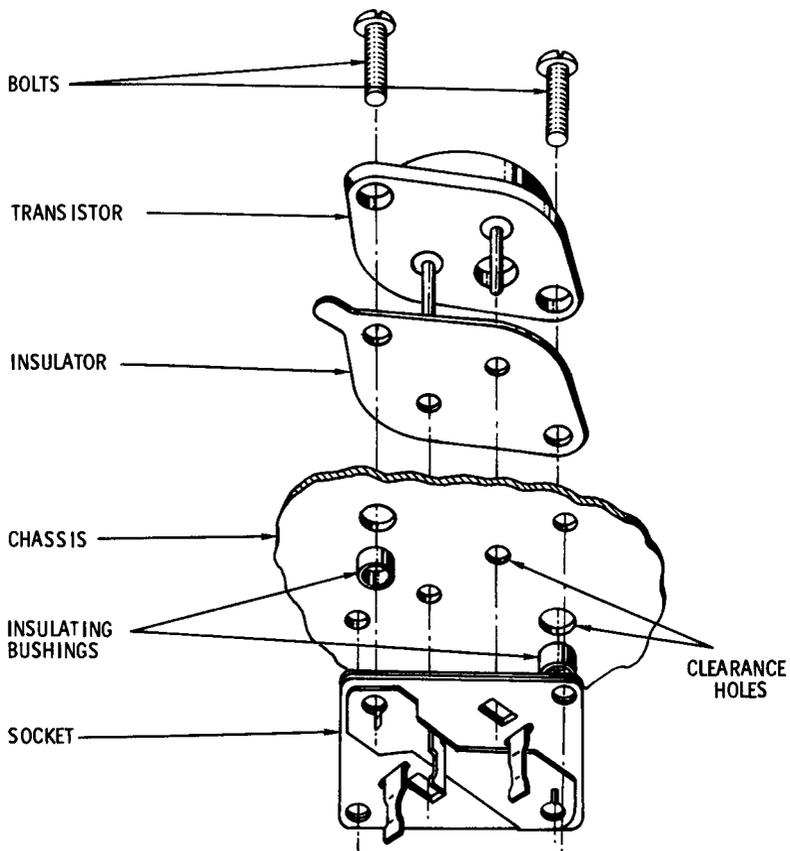
81

BOLTS

TRANSISTOR

INSULATOR

CHASSIS

INSULATING
BUSHINGS

CLEARANCE
HOLES

SOCKET

Fig. 6-10. Mounting of power transistors.

TO
OUTPUT
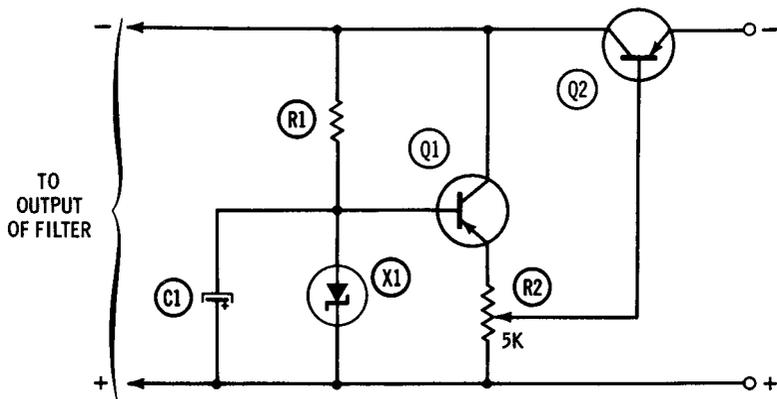OF FILTER

R1

Q1

Q2

C1

X1

R2

5K

Fig. 6-11. Improved series regulator.

An Improved Regulator

While the basic series voltage regulator employed in the power supply described previously will provide a voltage regulation on the order of 1.5% for extreme changes in load current, there is room for improvement in the basic circuit. Take a look at Fig. 6-11. Notice that transistor Q1, connected as an emitter follower, is placed between the output of the zener diode and base of the series-control transistor, Q2. The purpose of Q1 is to amplify the error signal obtained by comparing the regulated voltage from X1 with the unregulated voltage. The emitter of Q1 is connected to the base of series-control transistor Q2 through potentiometer R2.

Ripple Reduction

Notice that capacitor C1 is connected across the zener diode in the circuit of Fig. 6-11. The presence of this capacitor greatly reduces the ripple in the regulator output. Placed in the base circuit of Q1, C1 has an effective value roughly equal to its capacitance times the beta of Q1. Thus, if C1 has a capacitance of 1000 mfd and Q1 has a d-c beta of 50, the effective value of C1 will be 50,000 mfd.

This electronic filtering action can be put to good use in reducing the ripple output of an unregulated power supply, as shown in Fig. 6-12. Although this filter does not provide regulation, it is very effective in reducing the ripple. This circuit can be added to the output of a low-voltage (up to 24 volts) power supply to greatly reduce the ripple content of the output.
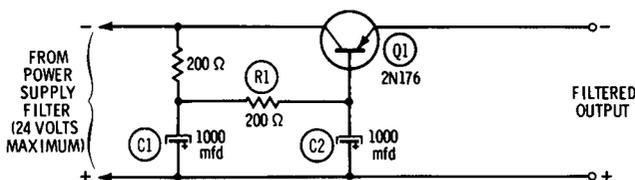

Fig. 6-12. Simple electronic filter.

In operation, Q1 is connected in series between the negative terminal of the power supply and the negative output terminal of the electronic filter. C1, R1, and C2 form a pi-section filter, applying ripple-free base bias to Q1. Any ripple appearing on the collector of Q1 is smoothed out so that almost none appears on the emitter of Q1. This is due to the amplifying action of Q1.

When this electronic filter is used, care must be taken not to short-circuit the output terminals because this will destroy Q1. Also, the power supply feeding the electronic filter must have some filtering built into it—at least a 100-mfd capacitor across its output terminals.
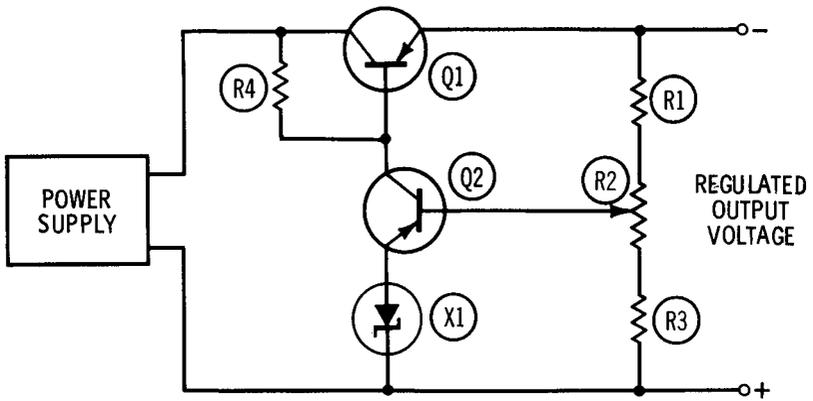
Fig. 6-13. Modified series voltage regulator.

Other Regulator Circuits

Fig. 6-13 shows another type of closed-loop regulator circuit. Notice that it is quite similar to one discussed in an earlier chapter dealing with vacuum-tube types.

The operation of the regulator shown in Fig. 6-13 is as follows. When the voltage across the external load drops, the voltage at the tap of voltage divider R1-R2-R3 will drop proportionally. Since zener diode X1 holds the emitter of Q2 at a fixed reference voltage, the base of Q2 will become less negative with respect to the emitter. This will decrease the amount of collector current in Q2, and decrease the voltage drop across the Q2 collector load, resistor R3. The resulting increase in negative voltage is applied to the base of Q1, the series-control transistor. Since the base of Q1 is now more negative with respect to its emitter, Q1 will pass more current to the external load, raising
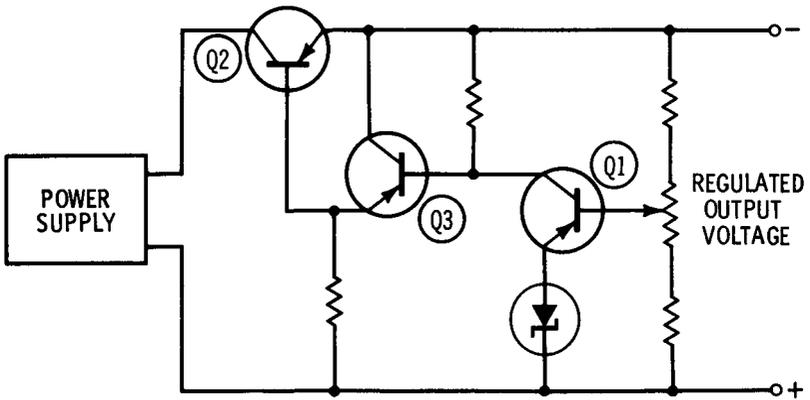

Fig. 6-14. Closed-loop series voltage regulator with two-stage error-signal amplifier.

the regulated voltage back to normal. An increase in external load voltage causes the regulator to operate in the opposite fashion.

Fig. 6-14 shows substantially the same circuit as in Fig. 6-13, except that a second stage of error-signal amplification has been added by the use of Q3, which is operated as an emitter follower. This additional stage, amplifying the error signal, considerably improves the voltage regulation of the circuit.

CHAPTER 7

Current Regulation

Just as there are many electronic devices which must be operated from a source of constant voltage, so are there many types of circuitry and equipment which require a source of constant current for their operation. In this chapter the various methods of obtaining a constant-current source are examined. Both vacuum-tube and semiconductor current regulators are described.

One application of a constant-current source is the testing of certain types of semiconductor devices. For example, in the evaluation of zener diodes, it is important to use a constant-current source. Also, most tunnel-diode circuits perform at their best when operated from a source possessing constant-current characteristics.

REGULATING WITH A SERIES RESISTOR

The process of voltage regulation consists of maintaining a constant voltage across a load in spite of variations in the load and the current through it. By contrast, current regulation is achieved when the current through a load remains the same although the resistance of the load and/or the voltage across it may change.

Perhaps the simplest method of obtaining a relatively constant current source is to place a resistance in series between the source of operating voltage and the load, as shown in Fig. 7-1. The value of series resistor R1 should be about ten times that of the load. Under these conditions resistor R1 is the factor that limits the current in the circuit. Variation in the resistance of the load has an almost negligible effect. This can be seen more easily by studying an example. If the operating voltage is 100 volts, R1 is 1000 ohms, and the load is 10 ohms, current in the circuit will be

$$I = \frac{E}{R} = \frac{100}{1000 + 10} = .099 \text{ amp}$$

If the load changes to zero ohms, the current will be

$$I = \frac{100}{1000 + 0} = 0.1 \text{ amp}$$

If the load doubles, to 20 ohms, the current will be

$$I = \frac{100}{1000 + 20} = .098 \text{ amp}$$

Thus a change of $\pm 100\%$ in the load resulted in a current change of $\pm 1\%$.

The disadvantage of this method is that it is very wasteful. All the power dissipated by R1, which is nearly all the power in the circuit, serves no useful purpose. However, there are circumstances under which this method is useful.
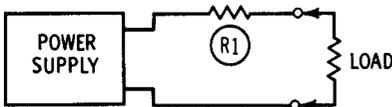

Fig. 7-1. Simple method of obtaining a constant-current source.
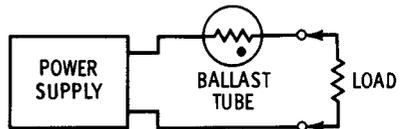
Fig. 7-2. Use of ballast tube to obtain constant current.

Another simple type of current regulator is shown in Fig. 7-2. Known as a "ballast tube," this current regulator was widely used at one time to maintain a constant current to a load connected to the 120-volt power line.

The ballast tube consists of an iron-alloy wire element enclosed in a special gas atmosphere. In operation, current variations through the ballast-tube element cause it to change temperature. This heating and cooling varies the resistance of the element proportionally—as the temperature increases, so does the resistance, and vice versa. When the ballast tube is connected in series with the load, an increase in current will cause an increase in temperature and, hence, resistance of the ballast-tube element. This greater resistance reduces the current in the load, keeping it close to its original value. Conversely, a decrease in current lowers the temperature of the ballast-tube element, and more current will be delivered to the load.

A modified version of the ballast tube, called a surgistor, is found in many television receivers. The surgistor is connected in series with the tube-heater string of the tv receiver. When the receiver is first turned on, the tube heaters have a cold resistance that is much less than their operating-temperature resistance. The surgistor limits the initial inrush of current by having a high resistance when it is cold. This high resistance limits the initial current through the tube heaters to safe values. As the tube heaters warm up, so does the surgistor

because of the passage of current through it. The resistance of the surgistor drops, and there is normal operating current in the tube heaters.

A constant-current power supply that provides exactly 25 milliamperes in spite of wide variations in load and input voltage.

ELECTRONIC METHODS

Although the ballast tube is capable of providing some current regulation, its reaction time is relatively slow. The reason for this is the thermal lag of the element—it takes a second or so for the ballast-tube element to change temperature after the current through it has changed. As a result, the ballast tube cannot correct for rapid changes in current through it.

This problem can be solved by using an electronic current-regulator system. Let us examine a vacuum-tube regulator first, to get the feel of electronic current regulation. Fig. 7-3 is the family of plate curves for a typical pentode. Notice that above the knee, point A, the plate current remains essentially constant for large changes in plate voltage.
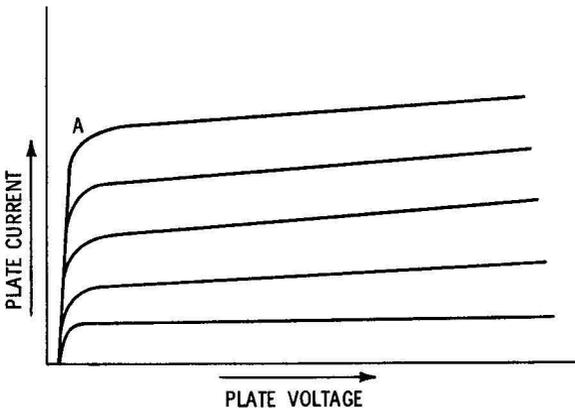
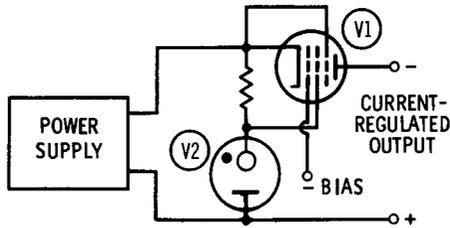Fig. 7-3. Pentode characteristic curves for various control-grid voltages.

Fig. 7-4. Pentode current regulator.

Fig. 7-4 shows how these pentode characteristics can be put to use in a practical current regulator. Pentode V1 is connected so that the external load is in its plate circuit. Proper values of control-grid bias and screen voltages are used to operate the pentode in the region where the plate-current characteristic is constant. Since the plate current of a pentode is highly dependent on the value of screen voltage, the latter is held at a constant potential by gas-filled voltage regulator V2.

Fig. 7-5 is the transistorized version of the above circuit. Transistor Q1 is biased for constant collector current, and the external load is connected in series with the collector. Zener diode X1 holds the base of Q1 at a fixed potential. If the collector current begins to change, the resulting change in base-emitter voltage returns the load current to its original value.
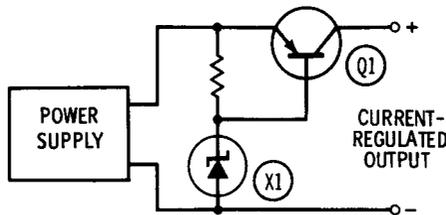

Fig. 7-5. Transistor current regulator.

Another current regulator is shown in Fig. 7-6. Notice that this circuit is similar to the voltage regulator shown in Fig. 6-13. Referring to Fig. 7-6, assume that the current drawn by the external load increases. This causes a greater current through R1, resulting in a greater voltage drop across it. The base of Q2 will now become more negative with respect to its emitter, which is held at a constant voltage by zener diode X1. The collector current of Q2 will increase, thereby causing the collector to become less negative. In turn, the base of Q1 will become less negative with respect to its emitter, and as a result, Q1 will pass less current to the external load—bringing the load current back down to its original value.

90

A decreasing load current will have the reverse action. The reduced voltage drop across R1 will cause the base of Q2 to become less negative with respect to its emitter, thus increasing the negative collector voltage of Q2. Since the collector of Q2 is direct-coupled to the base of Q1, base current in the latter will increase, increasing the current passed on to the load.
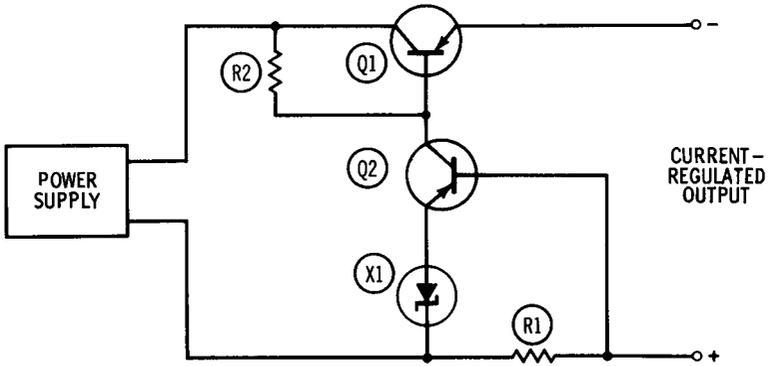

Fig. 7-6. Current regulator with error-amplifying stage.

Notice that although current regulation was obtained with this circuit, it is actually the voltage drop across series resistor R1 that supplied the error signal. This, of course, is satisfactory because the voltage drop across a resistor is directly proportional to the current through it.

CHAPTER 8

Batteries

No book on power supplies would be complete without a discussion of batteries as a source of power for electronic circuits. In this chapter we will take a look at the various types of batteries, their application to electronic circuits, their advantages, and their limitations.

Before launching into our discussion of batteries, there are several basic points to keep in mind. First, the term "battery" is frequently used incorrectly. By definition a battery is a source of d-c power consisting of two or more chemical, nuclear, solar, or thermal cells. A single unit such as is common referred to as a flashlight "battery" is actually a "cell"; if two or more cells are connected together, they form a battery of cells, or "battery." A 12-volt auto storage battery, for example, consists of 6 2-volt cells connected in series to provide a total of 12 volts.

There are two basic types of cells: primary and secondary. The primary cell is exhausted after its internal chemicals have been consumed in their electricity-producing chemical reaction. Normally one or more of the products of the reaction are lost. On the other hand the secondary cell may be reactivated, when it is exhausted, by passing direct current through it. This current, in the opposite direction from that originally developed by the cell, reverses the electrochemical action and restores the chemicals to their original state.

PRIMARY-CELL OPERATION

The first practical primary cell was produced in the 1800's by Volta, an Italian scientist. He discovered that two dissimilar metals immersed in an electrolyte start a chemical reaction which produces a potential difference between the two metal electrodes. A typical voltaic cell, as shown in Fig. 8-1, consists of a strip of copper and one of zinc, placed in an electrolyte made up of a weak sulfuric-acid solution.

If current is to be produced, there are certain requirements which must be met in the primary cell. These include:

1. The two electrodes must be made of dissimilar materials.
2. The electrolyte must be an acid, a salt, or an alkali that will react with the electrodes.
3. The electrolyte must be a good conductor of electricity.

There are certain definite characteristics that are common to all types of primary cells. The current that can be delivered by a cell is primarily determined by the active area of its electrodes—where the electrode and the electrolyte can react. The terminal voltage developed by the cell is not determined by the size or spacing of its electrodes, but rather by the materials used in its construction.

To understand the basic electrochemical action of a simple primary cell, refer again to Fig. 8-1. In a weak solution the sulfuric acid (H_2SO_4) breaks down into three charged particles. The sulfate portion takes on two additional electrons to become a negatively charged sulfate ion ($SO_4=$). The two hydrogen atoms lose electrons to become two positive ions (H^+).

As the zinc strip dissolves in the surfuric-acid electrolyte, zinc ions (Zn^+) enter the solution, leaving free electrons from their valence rings on the zinc electrodes. The zinc electrode now has a net negative charge due to its surplus of free electrons.

The chemical reaction between the electrolyte and copper electrode is basically the same, although not as intense. Thus, while the copper electrode also develops a negative charge, it is not so large as that produced on the zinc electrode. Since the latter is more negative than the former, a voltage difference exists between the zinc and copper electrodes.
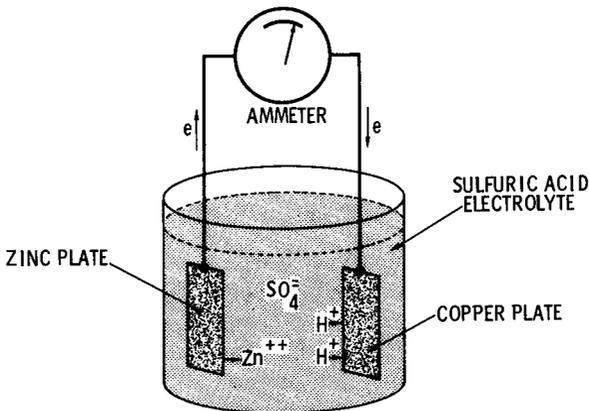

Fig. 8-1. Simple primary cell.

When a conductor is provided between the copper and zinc electrodes, the surplus of free electrons on the zinc electrode flow to the less negative copper electrode. Here hydrogen ions combine with electrons to form hydrogen gas on the surface of the copper electrode. Thus there is a complete electrical circuit; positive zinc ions are formed at the zinc plate at the same time positive hydrogen ions leave the solution, and electrons move through the conductor from the zinc plate to the copper plate. The action continues until the surface of the copper electrode is completely covered with hydrogen gas. When this point is reached, hydrogen ions cannot approach the copper plate, so electrons no longer flow. The cell is said to be "polarized."

While the simple zinc–copper–sulfuric-acid cell serves to illustrate the basic electrochemical action of a primary cell, it leaves much to be desired from a practical standpoint. Back in 1880, the first practical primary cell was developed by a Dr. Gassner. Because its electrolyte is in the form of a paste rather than being a liquid, it is termed a "dry cell."

Fig. 8-2 shows the internal construction of a typical dry cell. The outer zinc can serves as both the negative electrode and the container for the mix core (paste electrolyte). The can is produced from special zinc that is 99.9 percent pure. The positive electrode consists of a carbon rod placed in the center of the zinc can. The area between the carbon rod and the zinc shell is filled with the paste electrolyte consisting of manganese dioxide, acetylene black, ammonium chloride, zinc chloride, chrome inhibitor, and water. The manganese dioxide serves as a depolarizer, absorbing the hydrogen gas as it accumulates around the carbon rod (positive electrode) during periods of discharge. The open-circuit voltage developed by a carbon-zinc dry cell is approximately 1.5 volts.

The exact details of the internal construction of the zinc-carbon cell can be varied depending upon its intended use. For example, for flashlight service a cell must be capable of supplying a current of approximately 0.25 to 0.5 ampere, depending upon the type of bulb employed. Periods of usage may range from several seconds to several minutes at a time. Cells designed for photoflash service must deliver a high surge of current (in the range from 2 to 10 amperes) lasting less than one second. On the other hand, cells designed for transistor-radio service must furnish a relatively steady current of 10 to 100 ma for several hours. Proper design of the dry cell can provide optimum service for each application.

Environmental temperature plays an important role in the performance of a zinc-carbon cell. Optimum operating temperature for the zinc-carbon cell is approximately 70°F. Prolonged exposure to temperatures above 130°F may cause premature failure of the cell. Cells operating at temperatures of 0°F or lower will have their current

capability greatly decreased. This is due to the fact that the chemical action within the cell is greatly retarded at low temperatures. On the other hand, storage of zinc-carbon cells at low temperatures will extend their shelf life because the chemical reaction that takes place even when the cell is not connected is slowed. Zinc-carbon cells can be stored for a number of years with little sign of deterioration at temperatures near 0°F. (They must not be allowed to freeze, however.) High-temperature storage greatly reduces their shelf life since the chemical action is accelerated and moisture is lost from within the cell.
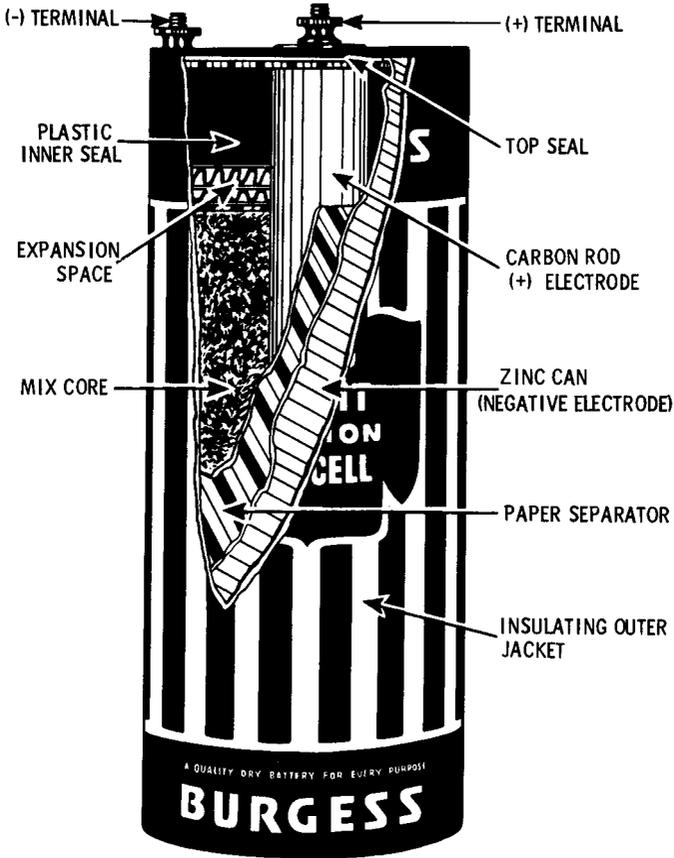
Fig. 8-2. Construction of a carbon-zinc dry cell.

INTERNAL IMPEDANCE

All cells have a certain internal impedance which may be considered as a resistance placed in series with the cell when it is in a circuit

(Fig. 8-3). The effect of this resistance is to limit the amount of current which a cell can deliver to an external load. As the current increases, the voltage drop across the internal impedance also increases, reducing the voltage available at the terminals.

A fresh carbon-zinc cell will exhibit a low internal resistance (a fraction of an ohm). During its period of service, the internal impedance gradually increases, causing the voltage across its terminals to drop with the application of the load. As the cell nears the end of its useful life, its internal impedance will be so great that its output voltage will drop to an unacceptable value when a load is applied. Because of this internal impedance, the terminal voltage of a cell should always be checked with the normal load connected. Without a load the terminal voltage will be at its maximum, giving an erroneous indication that the cell is still in satisfactory condition.
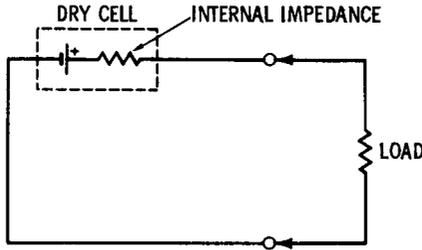
Fig. 8-3. Internal impedance of a cell.

MERCURY CELLS

The mercury cell is capable of providing the most stable output voltage over a given period of time of any conventional primary cell. The terminal voltage of the mercury cell is 1.350 volts plus or minus one-half of one percent. As indicated by Fig. 8-4, this voltage drops less than one percent of its initial value after the cell has been stored for several years. Mercury cells exhibit excellent shelf-life characteristics; cells over 14 years old are practically as good as new. Because of this, the mercury cell is often employed as an inexpensive secondary-voltage standard.

Fig. 8-5 illustrates the relatively flat voltage-decay characteristic of a typical mercury cell. Notice that its voltage remains nearly constant over most of its operating life when used with relatively light loads.

The basic mercury cell (Fig. 8-6) consists of an amalgamated zinc anode formed from highly purified compressed zinc powder, a cathode of mercuric oxide, and an electrolyte consisting of potassium hydroxide. The cathode and anode are separated by a porous material which has absorbed the electrolyte. It is possible for ions to flow between these two electrodes.
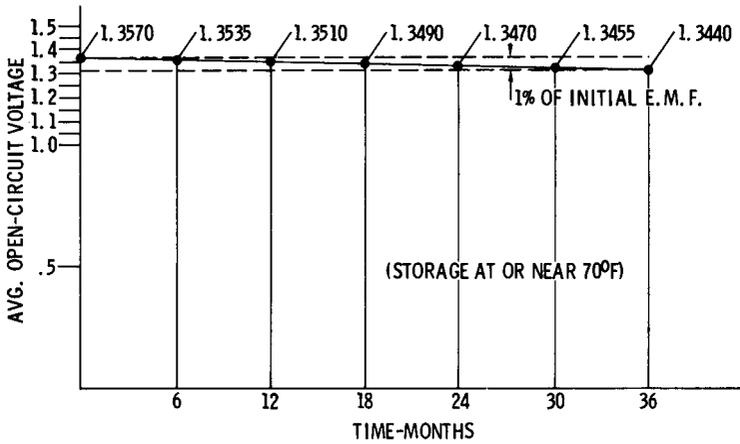
Fig. 8-4. Voltage of mercury cells after storage.

Some mercury cells employ a depolarizer consisting of a small amount of manganese dioxide; the initial no-load voltage of these cells is 1.45 volts. This higher value of voltage drops shortly after initial use of the cell.
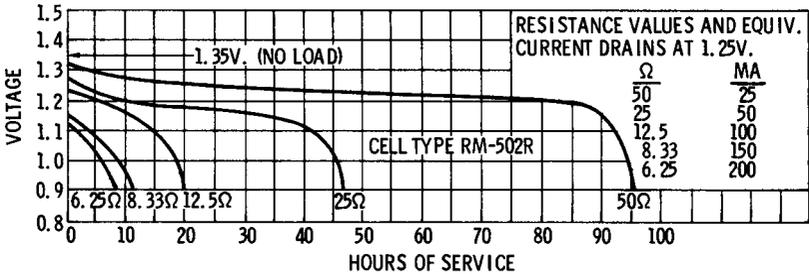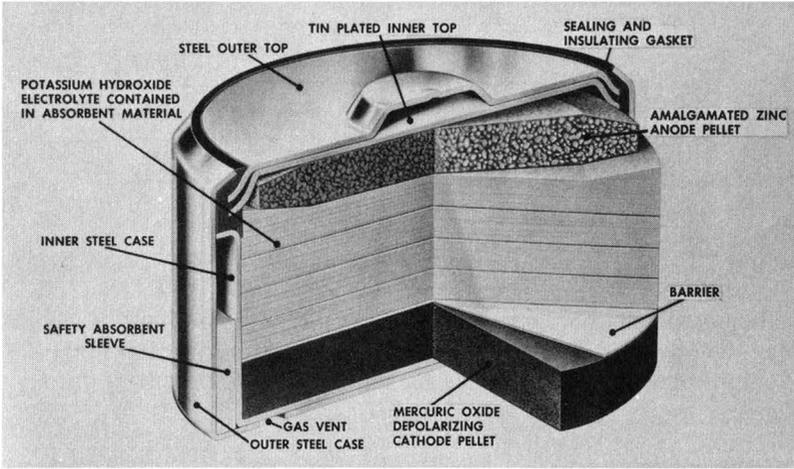

Fig. 8-5. Voltage output of loaded mercury cells.

ALKALINE CELLS

There are several basic types of alkaline cells, including alkaline-manganese, silver oxide-zinc, and silver oxide-cadmium. Of these, the alkaline-manganese is the most widely used in electronic circuits.

An electrochemical action is involved in the alkaline cell, so in this respect it is similar to the carbon-zinc cell. However, the alkaline-manganese cell employs an alkaline electrolyte, whereas the carbon-zinc uses an acid electrolyte.

The alkaline-manganese cell has an open-circuit terminal voltage of about 1.45 volts; however, it delivers most of its available power below 1.25 volts. Alkaline-manganese cells are capable of a higher

98

Labels on figure:
STEEL OUTER TOP
TIN PLATED INNER TOP
SEALING AND INSULATING GASKET
POTASSIUM HYDROXIDE ELECTROLYTE CONTAINED IN ABSORBENT MATERIAL
AMALGAMATED ZINC ANODE PELLET
INNER STEEL CASE
BARRIER
SAFETY ABSORBENT SLEEVE
GAS VENT
OUTER STEEL CASE
MERCURIC OXIDE DEPOLARIZING CATHODE PELLET

Fig. 8-6. Construction of a typical mercury cell.

energy-discharge rate than zinc-carbon cells of comparable size. They can be continuously discharged without sacrificing electrical capacity. This is not the case with zinc-carbon cells; where they are used it is desirable to provide recovery time between periods of heavy current discharges.

It is possible, within limitations, to successfuly recharge alkaline-manganese cells. If it has not been discharged to below 40 percent of its capacity, and if the charging is done at a low rate, a typical alkaline manganese cell may be recharged 50 to 150 times.

SOLAR CELLS

Although the solar cell is not electrochemical in action, it deserves mention since it is becoming a practical source of power. Applications for the solar cell range from sun-powered portable radios to orbiting spacecraft.

Fig. 8-7 shows the basic construction of a solar cell; it consists of a P-N semiconductor "sandwich." In the absence of illumination, electrons in the N-type material and holes in the P-type material are kept from combining by the "barrier potential" present at the P-N junction. When the junction is illuminated, energy from the light splits valence electrons from some of the atoms, and these produce current in the cell.

Fig. 8-8 illustrates an application where solar cells are used to charge a nickel-cadmium battery. During periods of sunlight the solar
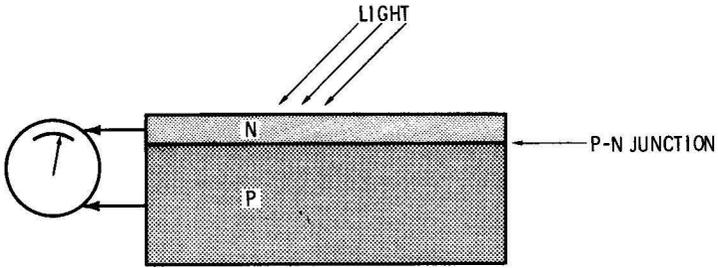
Fig. 8-7. Operation of a silicon solar cell.

cells provide charging current for the nickel-cadmium battery, which may then be used as a power supply during periods of darkness. The diode prevents discharge of the nickel-cadmium battery back through the solar cell.
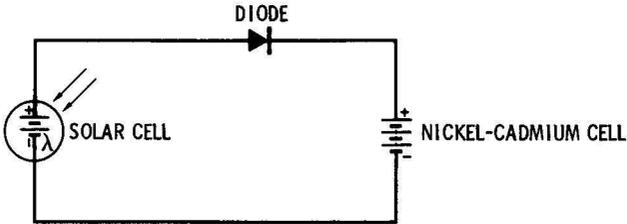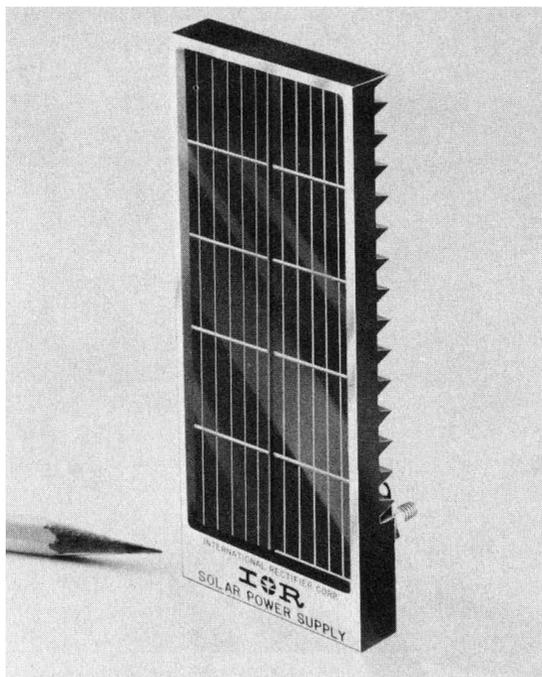

Fig. 8-8. Solar cell charging a nickel-cadmium cell.

A silicon solar cell for the conversion of radiant energy into electrical energy.

Courtesy International Rectifier Corp.

Solar power packs are available with outputs of 3.5 to 16 volts, 30 to 60 milliamperes.

SECONDARY CELLS

The chemical action within the primary cell cannot be reversed; that is, once the chemicals have been exhausted, the cell is no longer capable of generating electricity. Usually this happens because one or more of the reaction products are in a form that removes them from further activity, such as gas that disappears into the atmosphere.

By contrast, the secondary cell has the characteristic that its chemical action may be reversed. Current passing through it in the opposite direction causes a chemical action which restores the reactants to their original condition. Perhaps the most familiar example of the secondary cell is the lead-acid storage battery, which is widely used in automobiles.

Lead-Acid Cell

The following is a simplified description of the chemical reaction that takes place within a lead-acid cell when the cell is delivering current to a load. The sulfuric-acid electrolyte is broken down into posi-

101

tive hydrogen ions and negative sulfate ions. The spongy lead which comprises the negative electrode also dissolves slightly into electrolyte; the positive lead ions thus produced leave behind free electrons which can flow through the external load. The negative sulfate ions combine with the positive lead ions to form lead sulphate, which is deposited on the negative electrode.

The lead peroxide at the positive electrode reacts with the sulfuric-acid electrolyte to form positive lead ions; in additional reactions negative hydroxyl ions are produced. The positive ions combine with the negative sulfate ions in the electrolyte to form sulphate, which is deposited on the positive electrode.

During discharge of the lead-acid cell, hydrogen and hydroxyl ions combine as part of the electrochemical reaction to gradually replace part of the sulfuric acid in the electrolyte with water. This results in a lowering of the specific gravity of the electrolyte. It is possible, therefore, to determine the charge of the cell by measuring the specific gravity of its electrolyte with a hydrometer.

When the lead-acid cell is discharged, it may be recharged by sending a current through it in a direction opposite to its discharge current. During this charging process the chemical reactions involved in the discharge cycle are reversed. The lead sulphate which was deposited on the positive electrode during discharge is converted back into lead peroxide, and the negative plate is converted back to spongy lead. The open-circuit terminal voltage of the lead-acid cell is 2.1 volts.
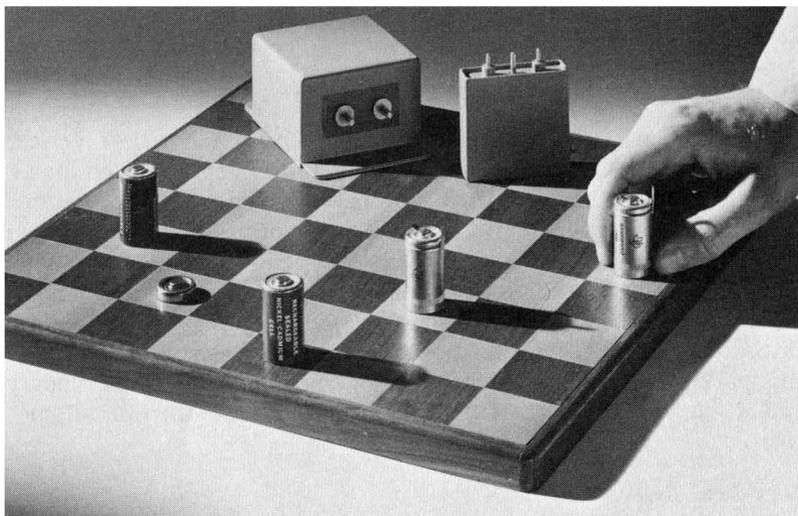
Courtesy Texas Instruments, Inc.

Rechargeable nickel-cadmium batteries are available in a wide variety of sizes and shapes.

Nickel-Cadmium Cells

The nickel-cadmium cell offers many of the most desirable characteristics of a secondary cell—sealed construction, excellent shelf life, and mechanical ruggedness. The negative electrode is made of a metallic cadmium, the positive electrode is nickel hydroxide, and potassium hydroxide is used for an electrolyte. When the cell is completely discharged, the positive electrode becomes nickel oxide, the negative electrode becomes cadmium hydroxide, and the electrolyte remains unchanged.

The terminal voltage of a fully charged nickel-cadmium cell is 1.2 volts. These cells can be discharged and recharged many times over a period of years before their usefulness is ended.

Silver-Cadmium Cell

The silver-cadmium cell is one of the most efficient—and most expensive—of all secondary cells. Basically it consists of a silver-oxide cathode, a cadmium anode, and an electrolyte of potassium hydroxide. This cell is capable of providing a considerably greater current than the nickel-cadmium cell. The chief drawback is the high cost of the silver used in its construction.

CHAPTER 9

Power Supplies Using SCR's

The silicon controlled rectifier (scr) is a semiconductor that is capable of providing efficient control of large amounts of a-c and d-c power. It is rapidly finding application in various types of power-supply circuits. The basic operation of the silicon controlled rectifier is explained in the following paragraph.

Fig. 9-1 aids in the basic understanding of the scr structure since the two transistors are equivalent to one scr. The two transistors are positioned back to back; the collector of transistor Q1 (an NPN unit) is connected to the base of transistor Q2 (a PNP unit), and the collector of Q2 is returned to the base of Q1. A meter placed in series between the emitter of Q2 and the supply voltage indicates current through the NPN-PNP combination. When there is no input current applied to the base of Q1, the meter indicates only a slight leakage current through the NPN-PNP pair. Note that the current applied to the gate lead (the base current of Q1) is multiplied by the beta (amplification factor) of Q1, and this becomes the base current of Q2. The base-emitter current of Q2 in turn is amplified by the beta of Q2 and fed back to the base of Q1. When there is an input current the betas of Q1 and Q2 increase until their product is greater than unity. At this point the current from Q2 exceeds the input current applied to the base of Q1. Regeneration causes the current through Q1 and Q2 to increase until both transistors are in a current-saturated condition. The meter then indicates a maximum current in the circuit. The important characteristic of the NPN-PNP combination is that, below a certain point, there is only a slight current through them. However, when sufficient current is available at the gate terminal, they snap into conduction almost instantaneously. As a result, this combination resembles a snap-action on-off switch—either passing no current or a maximum current, with no in-between state. This is in contrast to a conventional transistor amplifier, where the current may be smoothly varied from zero to maximum.
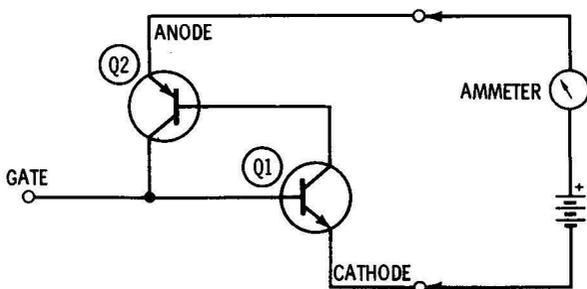
105

Fig. 9-1. Transistor equivalent of a silicon controlled rectifier.

The practical scr does not consist of two separate transistors. Rather, it is made up of a sandwich of alternate P-type and N-type semiconductor materials, as shown in Fig. 9-2A. Note how this corresponds to the equivalent scr circuit in Fig. 9-1. The electronic symbol for the scr is shown in Fig. 9-2B.
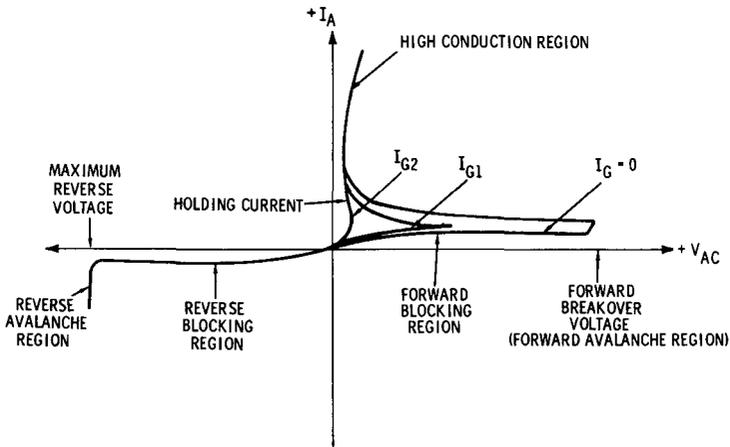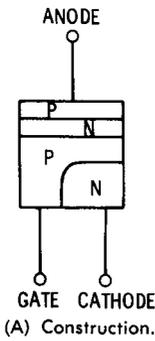
Fig. 9-2C shows the characteristic curve of a typical scr. If no current is applied to the scr gate electrode ($I_G = O$), the scr will not conduct until the forward breakover voltage ($I_G = O$) has been reached. At this time, the semiconductor will conduct heavily. If the anode current is reduced below the minimum holding current, the scr will revert to its nonconducting state.

When a current is applied to the gate electrode (I_{G1} or I_{G2}), the effect is to decrease the forward breakover voltage. This is indicated by the three curves, each of which represents a progressively higher value of gate current. The gate current can be increased to the point where the scr has forward-current characteristics very similar to those of a conventional semiconductor diode. In a sense the scr can be considered a form of current amplifier because a small value of gate current can control a large anode current. It is also important to note that once the gate triggers the scr into conduction, the gate loses all control over anode current. Reducing the gate current to zero, or even making it negative with respect to the cathode, will not cut off the anode current.

A 16-ampere silicon controlled rectifier having a peak reverse-voltage rating of 960 volts.

Courtesy Tung-Sol Electric Inc.

106

ANODE

P
N
P
N

GATE   CATHODE

(A) Construction.

A

G   C

(B) Symbol.

$+I_A$

HIGH CONDUCTION REGION

MAXIMUM
REVERSE
VOLTAGE

HOLDING CURRENT

I_{G2} I_{G1} $I_G = 0$

$+ V_{AC}$

REVERSE
AVALANCHE
REGION

REVERSE
BLOCKING
REGION

FORWARD
BLOCKING
REGION

FORWARD
BREAKOVER
VOLTAGE
(FORWARD AVALANCHE REGION)

(C) Characteristic curve.

Fig. 9-2. Silicon controlled rectifier.

TYPICAL SCR CIRCUITS

The scr is strictly an "on-off" device; variation in output is achieved by changing the length of the on and off times. Special techniques must be employed to utilize the scr in power-supply circuits.

Phase Control

One of the most common methods used to vary the turning on and off of scr's is phase control. Fig. 9-3 illustrates the basic phase-controlled scr power supply. The scr is arranged in a simple half-wave rectifier circuit with the gate connected to a phase-shift network which is capable of varying the phase difference between the gate and anode of the scr from 0 to 180 degrees. When the phase-shift network is adjusted for a zero-degree phase difference between the scr gate and anode, the scr will conduct during the entire half-cycle that the anode

107
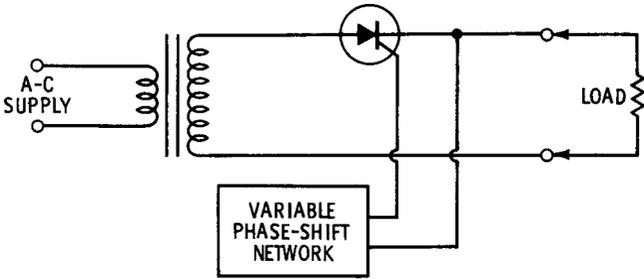
Fig. 9-3. Phase control of the scr supply.

is positive, as indicated in Fig. 9-4. If there is a 90-degree phase difference between the scr gate and the anode, the scr conducts for one-half of the half-cycle, as indicated in Fig. 9-4B. Increasing the phase difference between the scr gate and anode to 180 degrees keeps the scr from conducting (Fig. 9-4C). The output voltage of the power supply is determined by the *average* amount of power delivered to the load. This can be changed by varying the phase of the signal applied to the scr gate.
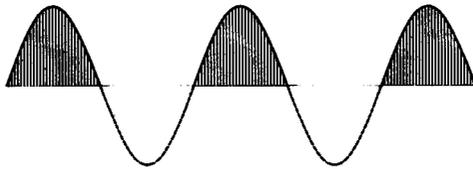
(A) 0° phase shift.
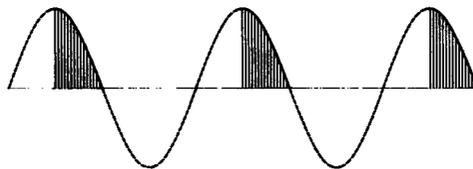
(B) 90° phase shift.
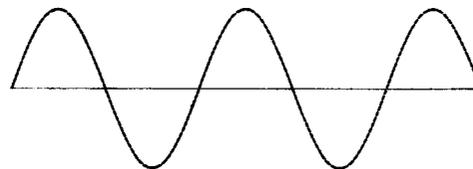
(C) 180° phase shift.

Fig. 9-4. Load waveform in an scr circuit.

108
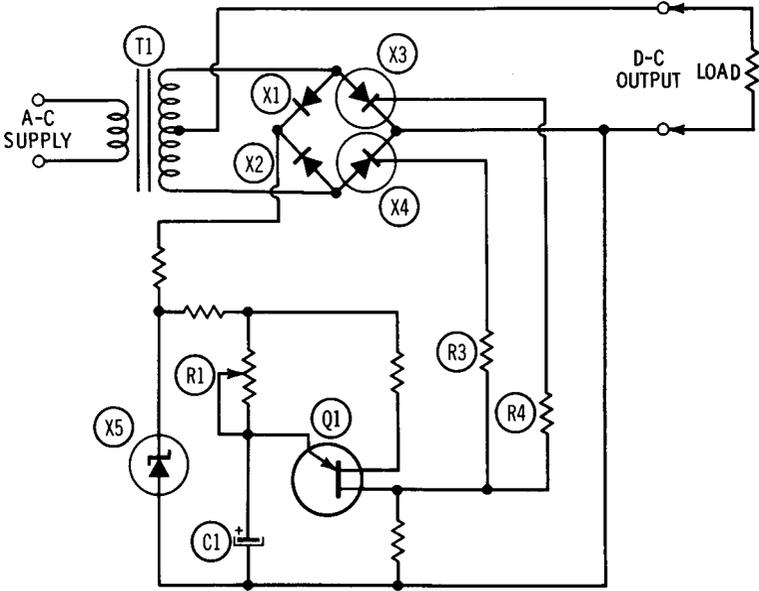
Fig. 9-5. Scr power supply with voltage control.

Unijunction Transistors

Fig. 9-5 shows a typical full-wave scr power supply incorporating a unijunction transistor in the phase-control circuitry. Before the circuit can be analyzed, however, the operation of a unijunction transistor (ujt) must be understood.

Basically, the ujt is constructed of a piece of N-type silicon with ohmic (nonrectifying) contacts at each end, as illustrated in Fig. 9-6A. A P-type rectifying contact, called the emitter, is formed on

(A) Construction.   (B) Equivalent circuit.
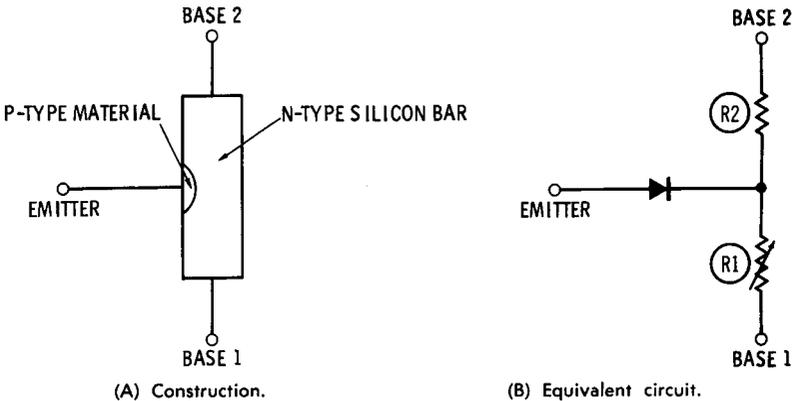
Fig. 9-6. Unijunction transistor.

109

one side in the middle of the N-type material. The N-type silicon material acts like a simple resistive voltage divider with a diode tied into its center. Refer to the equivalent circuit, Fig. 8-6B.

Fig. 9-7 shows the electrical characteristics of the ujt. When no current is applied to the emitter junction and a positive voltage is applied to base two, the voltage-divider action of the resistive N-type silicon material places a small reverse bias on the emitter junction.
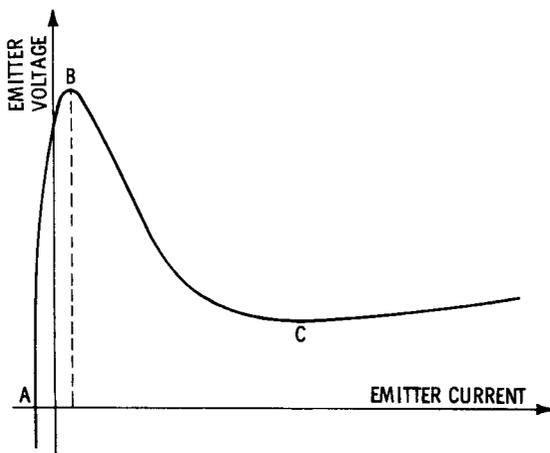
Fig. 9-7. Characteristic curve for a ujt.

As a result, there is only a small reverse current in the emitter circuit. This is represented at point A in Fig. 9-7. As the forward bias applied to the emitter junction is increased, there is a decrease in the emitter reverse current, as indicated by the region between points A and B in Fig. 9-7. When point B is reached, the P-N junction becomes forward biased; forward emitter current starts and the resistance between the emitter and base one drops to a very low value. Since the emitter voltage decreases as the emitter current increases, a negative-resistance characteristic results, as indicated between points B and C in Fig. 9-7.

Take a look at Fig. 9-8A, which shows the unijunction transistor used in a relaxation-oscillator circuit. When an input voltage is first applied to the circuit, capacitor C1 acts like a short circuit, so the emitter is at ground potential. Because of the voltage-divider action of the silicon material, there is a positive voltage at base one, and the base-one–emitter junction is reverse biased. As capacitor C1 charges, the voltage across it can be represented as the line between points A and B in Fig. 9-8B. At point B the voltage is sufficient to forward-bias the emitter. The emitter junction now conducts, making the effective emitter–base-one resistance drop to a very low value. Capacitor C1 rapidly discharges through this low resistance, as indicated by the line

(A) Circuit.

(B) Waveform across C1.

(C) Waveform across R2.
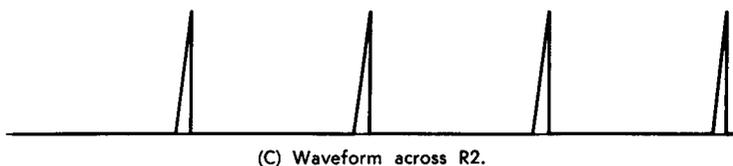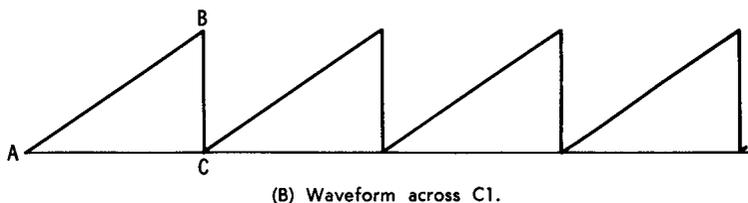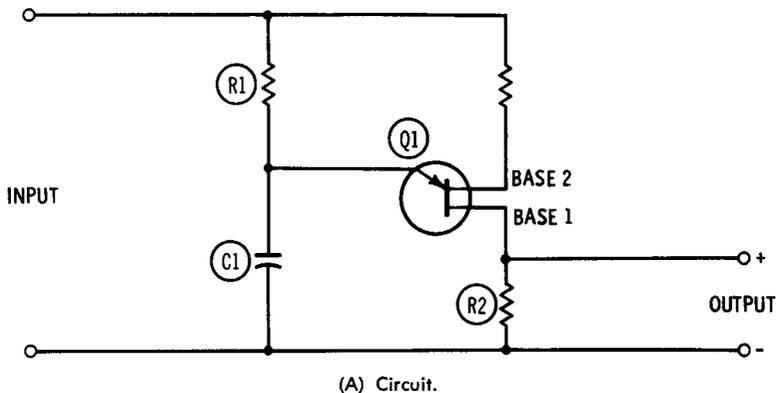
Fig. 9-8. Basic ujt relaxation oscillator.

between points B and C in Fig. 9-8B. When capacitor C1 is discharged, the whole cycle starts over again.

Fig. 9-8C shows the voltage pulses developed across resistor R2 each time C1 discharges through the forward-biased emitter junction. The frequency of the output pulses can be changed by varying the value of resistor R1. For a given value of C1, reducing the value of R1 will increase the frequency, and vice versa.

Fig. 9-9A shows how a ujt can be used as the phase control in an scr power supply. The ujt is connected as a relaxation oscillator with R1 as the charging resistor and C1 as the capacitor being charged. R1 is adjustable so the charging rate of C1 may be varied. The positive-going pulses developed at base one of the ujt are applied to the gate of the scr. In operation, as the positive half-cycle from the a-c input begins to increase in amplitude, the anode of the scr becomes increasingly positive with respect to the cathode, as shown in Fig. 9-9B. At

the same time the voltage applied to the ujt and the timing circuit R1-C1 is also increasing. When the voltage applied to the ujt emitter has risen to a point sufficient to forward-bias it, C1 discharges through the low-resistance emitter junction, developing a positive-going pulse across resistor R2, as shown in Fig. 9-9C. This pulse, applied to the
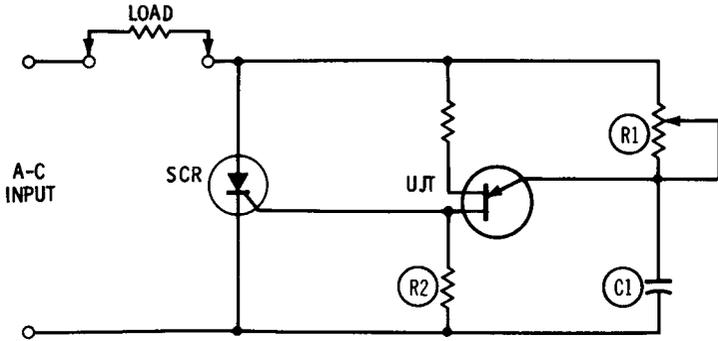
(A) Schematic.
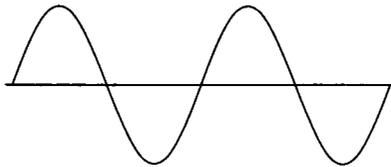
(B) Waveform at anode of scr.

(C) Waveform across R2.

(D) Load current.

Fig. 9-9. Ujt phase control.

gate of the scr, turns the scr on, and it conducts. There is current in the load for the portion of the positive half-cycle indicated in Fig. 9-9D. During the following half-cycle, the scr anode is negative so it will not conduct. As a result, current will be applied to the load only on positive half-cycles of the a-c input.

Fig. 9-10 shows the same operating conditions as Fig. 9-9 except that resistor R1 has been adjusted to charge C1 faster. This results in

112

C1 discharging through the ujt emitter junction earlier in the positive half-cycle of operation, as shown in Fig. 9-10B. The scr is turned on earlier in the cycle (Fig. 9-10C), and the scr will apply a greater portion of the positive half-cycle to the load. Thus, the point in the positive half-cycle at which the ujt fires determines the point at which the scr conducts. Since the timing of the ujt capacitor discharge, in turn, is determined by the value of the charging resistor, the power applied to the load by the scr can be easily controlled by varying the ujt charging resistor.

(A) Waveform at anode of scr.

(B) Waveform across R2.

(C) Load current.
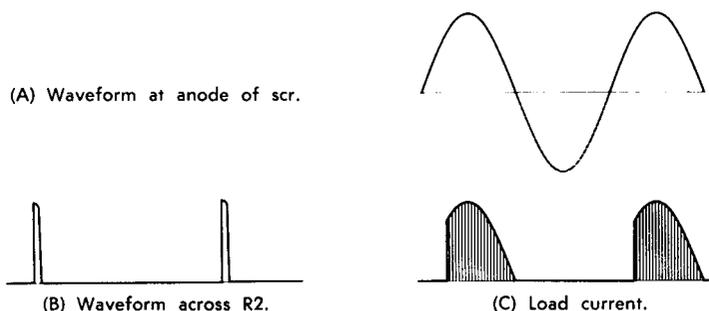
Fig. 9-10. Accelerated trigger.

Now return to the power-supply circuit of Fig. 9-5. The voltage appearing across the secondary of power transformer T1 is applied to diodes X1 and X2, which are connected to form a full-wave recti-fier. Although at first glance the presence of the scr's X3 and X4 sug-gests a bridge-rectifier configuration, they form a second full-wave rectifier for applying d-c power to the load.

The positive half-cycles from X1 and X2 are applied to the ujt circuitry; R1 and C1 form the charging network, with R1 being made variable to vary the charging rate of C1. The positive-going pulses at base one of the ujt are applied to the gates of the two scr's via isolat-ing resistors R3 and R4. These pulses switch on the scr's on alternate half-cycles of operation. The scr which has a positive anode at the time of application of the pulse from the ujt will conduct current to the load. By varying R1, the voltage control, the point in the cycle in which the ujt discharges may be varied, thus controlling the portion of the cycle in which the particular scr will conduct. Zener diode X5 stabilizes the voltage conditions under which the unijunction transistor works in order to provide consistent operation.

A PRACTICAL SCR POWER SUPPLY

Fig. 9-11 is the schematic of an scr-controlled variable-voltage power supply capable of providing from 0 to 40 volts at a current of
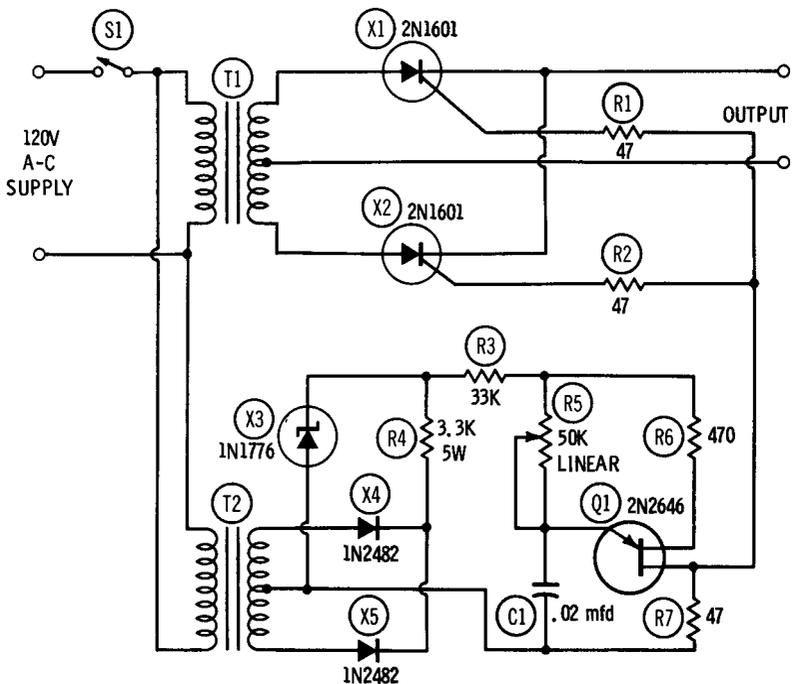
Fig. 9-11. Variable-voltage scr power supply.

Parts List for Fig. 9-11

Item No.	Description
C1	Capacitor, .02 mfd, mylar
R1	Resistor, 47 ohms, ½ watt
R2	Resistor, 47 ohms, ½ watt
R3	Resistor, 33K ohms, ½ watt
R4	Resistor, 3300 ohms, 5 watts
R5	Resistor, variable, 50K ohms, linear
R6	Resistor, 470 ohms, ½ watt
R7	Resistor, 47 ohms, ½ watt
S1	Switch, spst
T1	Transformer, power, 40 volts center-tapped, 1200 ma (Stancor P8196, or equivalent)
T2	Transformer, power, 120 volts, center-tapped, 50 ma (Knight 54D3708, or equivalent)
X1	Rectifier, silicon controlled, 2N1601
X2	Rectifier, silicon controlled, 2N1601
X3	Diode, zener, 1N1776
X4	Rectifier, silicon, 1N2482
X5	Rectifier, silicon, 1N2482
Q1	Transistor, unijunction, 2N2646

up to 1 ampere. The circuit is essentially the same as the one shown in Fig. 9-5, except that a separate ujt power supply is used.

When the output voltage of this supply is low, the output ripple will increase considerably. The reason for this is that at low voltage levels, only a small portion of the half-cycle is passed on to the load. Thus, there will be relatively wide gaps between successive output pulses. As a result, this supply is not recommended for loads requiring very low ripple.

REGULATED POWER SUPPLIES

Voltage-regulated power supplies using scr's have an advantage, in that these circuits dissipate very little power. In an all-transistor regulated supply, the current passed to the load is controlled by either a series or shunt control transistor whose effective internal resistance is varied by means of a control signal. The resistance of the control transistors represents a power loss (transistor heating). On the other
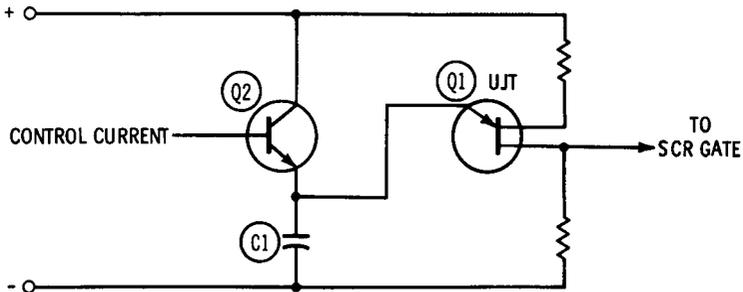
Fig. 9-12. Transistor control of ujt discharge rate.

hand, an scr in a regulated power supply is either in a state of full conduction or no conduction. When it is in full conduction, the scr has almost zero internal resistance and so dissipates little power. This, of course, means good efficiency. It boils down to the fact that, on an equal power-output basis, the scr-regulated power supply may use much smaller semiconductor devices, both electrically and physically.

How Scr Voltage Regulation Is Achieved

To understand the basic operation of scr voltage regulation, take a look at Fig. 9-12. Notice that this is the same basic ujt phase control described earlier except for the addition of transistor Q2, inserted in place of the charging resistor. This transistor is an electronically variable resistor, the effective resistance of which may be adjusted by controlling the base current. Thus, as the base current of Q1 is increased, the effective emitter-collector resistance will be decreased,

115

and vice versa. Since the charging rate of C1 depends on the value of the charging resistor, it is easy to see that the charging rate of C1, and hence the firing rate of the ujt, can be controlled by transistor Q1. Therefore, the firing rate of the ujt can be controlled by varying the base current applied to Q1 because this varies its effective internal resistance.

Fig. 9-13 illustrates an scr voltage-regulated power supply using the transistor-controlled ujt principle just described. The base of Q1 is connected to voltage divider R1-R2-R3, placed across the output terminals of the supply. When the voltage across the external load increases, the base of Q1 becomes more positive with respect to its
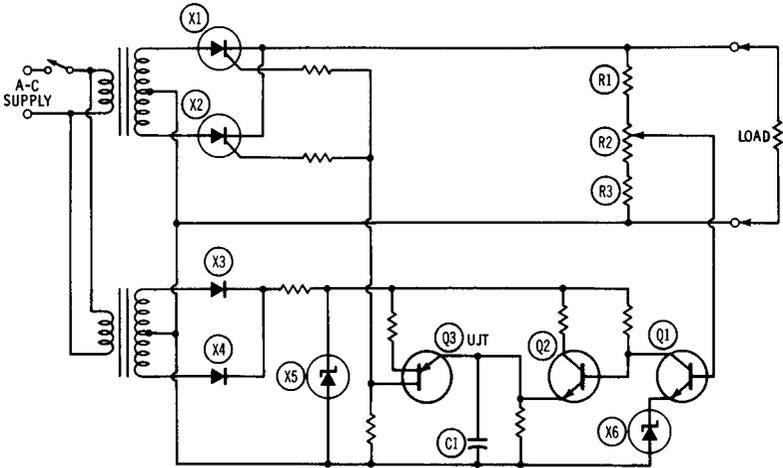
Fig. 9-13. Regulated power supply.

emitter since the latter is held at a constant voltage by zener diode X1. This increases the collector current of Q1, so the collector becomes less positive. Since the collector of Q1 is direct-coupled to the base of Q2, the base also becomes less positive with respect to the Q2 emitter. This decreases the collector current, thereby increasing the effective internal resistance. Since the emitter-collector circuit of Q2 forms part of the capacitor-charging circuit for the ujt, the increased resistance of Q2 decreases the charging rate of C1, and hence, the firing frequency of the ujt. As a result the scr's conduct later in their operating cycle, decreasing the average current applied to the load. The load voltage will drop to its original value.

A decrease in load voltage has exactly the reverse effect. The effective resistance of Q2 decreases, the ujt fires sooner, and the scr's will conduct earlier in their cycle. This increases the average current applied to the load, bringing the load voltage back up to normal.

Other SCR Circuits

In addition to the scr power-supply and voltage-regulator circuits described thus far, the scr finds many additional applications. Fig. 9-14 shows how a single scr can control the entire output of a full-wave bridge. Using this circuit the power applied to the load can be varied from 0 to 100%. Note that the scr (Q2) is in series with the load, so it is in a position to exercise complete control.
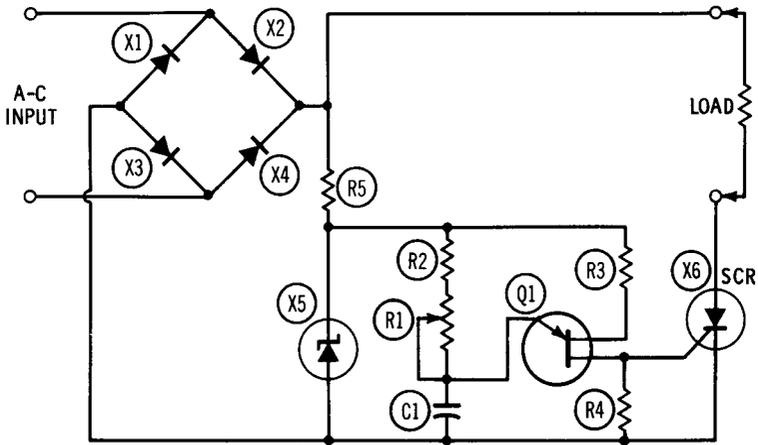

Fig. 9-14. Control of bridge rectifier.

The output of bridge rectifier X1, X2, X3, and X4 is a series of pulses; these are applied to both the load circuit and the trigger circuitry for the scr gate. Capacitor C1 is charged by current through R2 and R1. At a certain emitter voltage, unijunction transistor Q1 fires, and the resulting pulse across R4 triggers the scr. The scr then conducts until the end of that pulse from the bridge. By adjusting control R1 the charging time of capacitor C1 can be changed so the scr will conduct more or less of each half-cycle. Zener diode X5 stabilizes the operating conditions of the trigger circuitry in order to obtain consistent performance.

CONTROLLED A-C SWITCHES

In order to control both halves of the a-c cycle, it is necessary to use either a single scr in the output of a full-wave bridge rectifier (Fig. 9-14), or two scr's that alternately switch the output of a full-wave rectifier (Fig. 9-5). Also, two scr's may be connected "back to back" to achieve full-wave control, although this generally requires two isolated phase-control circuits.

117

FORWARD

ANODE

GATE CATHODE

(A) Symbol.

VOLTAGE

REVERSE

(B) Characteristic curve.
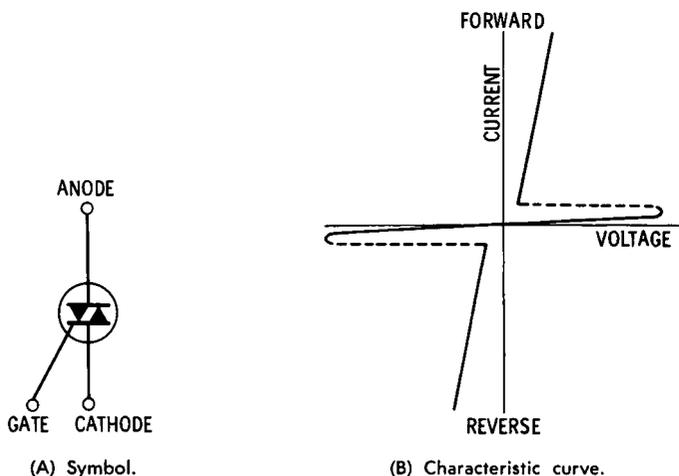
Fig. 9-15. Controlled a-c switch (triac).

In contrast, the controlled a-c switch (triac) permits the relatively simple full-wave control of power. Basically, the triac consists of two "back-to-back" scr's with a common gate electrode, as shown schematically in Fig. 9-15A. The electrical characteristics of the triac are shown in Fig. 9-15B. When connected in series with a load in an a-c
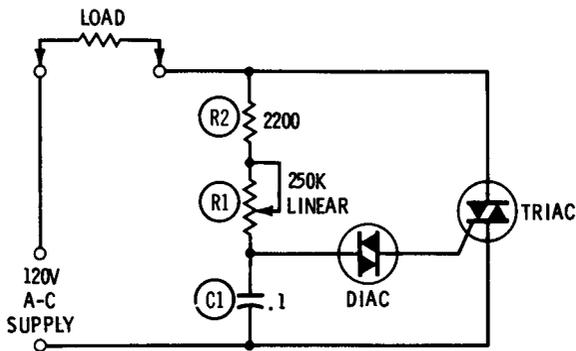

LOAD

R2 2200

R1 250K LINEAR

C1 .1 DIAC

TRIAC

120V
A-C
SUPPLY

Fig. 9-16. Triac control circuit.

circuit, the triac may be triggered into conduction during alternate half-cycles to obtain full-wave control, since its anodes become alternately positive with respect to the common gate during alternate applied half-cycles.

Fig. 9-16 shows a practical triac circuit. This provides full-wave power control and will handle loads up to 100 watts. The triac is phase-controlled by a relaxation oscillator consisting of the diac (neg-

118

ative-resistance diode), R1, R2, and C1. The basic operation of this phase control is the same as the ujt phase control described previously. The discharge rate of the relaxation oscillator is determined by setting the power control, R1. Unlike the ujt relaxation oscillator, however, the diac provides a gate trigger pulse from either negative or positive half-cycles.

CHAPTER 10

Miscellaneous Power-Supply Circuits

Not all power supplies involve the conversion of a 120-volt a-c power source to various values of direct current. Sometimes it is necessary to change low-voltage direct current to a higher voltage, or an a-c output may be required from a d-c source. This chapter examines several rather new and novel power-supply circuits.

TRANSISTOR POWER CONVERTERS AND INVERTERS

Before the advent of the transistor, low-voltage d-c to high-voltage d-c power converters (such as those used to operate auto radios) employed an electromechanical switch called a vibrator. It provided the necessary rapid interruption of current so that a step-up transformer could be used to produce a higher voltage. A simplified example of this type of supply is shown in Fig. 10-1. The electromechanical vibrator operates much like a door buzzer—an electromagnet causes the movable armature to vibrate rapidly between the two current-carrying contacts. This rapid switching action creates current pulses from the d-c power source in alternate halves of the primary winding. Pulsating direct current in the primary of the transformer induces across the secondary of T1 a high-voltage alternating current which is rectified and filtered.

Although the electromechanical vibrator did its job fairly well, it had limitations. Because it employed moving parts, it was subject to mechanical failure within a relatively short time. Also, the electrical contacts would wear and impair circuit efficiency.

With the advent of the transistor, the mechanical vibrator has frequently been replaced by transistor switching. Fig. 10-2 shows a typical transistorized direct-current to direct-current converter. Transistors Q1 and Q2, the center-tapped primary winding (L1), and the two feedback windings (L2 and L3) form an oscillator circuit. The
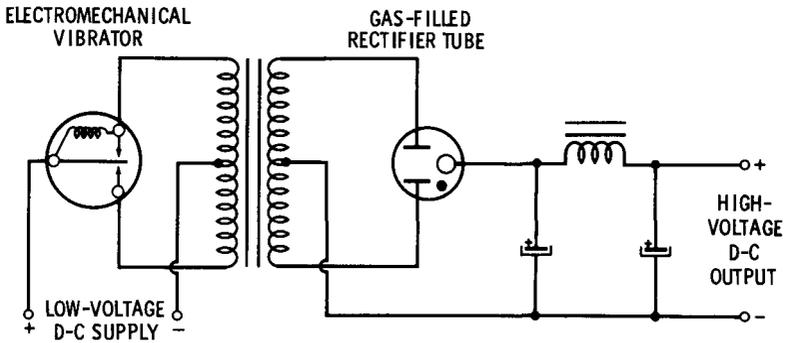
Fig. 10-1. Vibrator converter.

pattern of oscillations is such that when Q1 is saturated (has a maximum collector current) and thus has a very low internal resistance, Q2 is cut off (zero collector current). Likewise, Q1 is cut off while Q2 is saturated. This rapid switching from cutoff to saturation generates a square-wave current in center-tapped primary winding L1 of step-up transformer T1. Pulsating current through the primary induces a high voltage in secondary winding L4. The latter voltage is rectified and filtered to yield the desired d-c output voltage.

Mechanical-vibrator power supplies were generally designed with operating frequencies in the range of 60 to 300 Hz; transistor-converter operating frequencies range from 60 to 5000 Hz. Since tran-
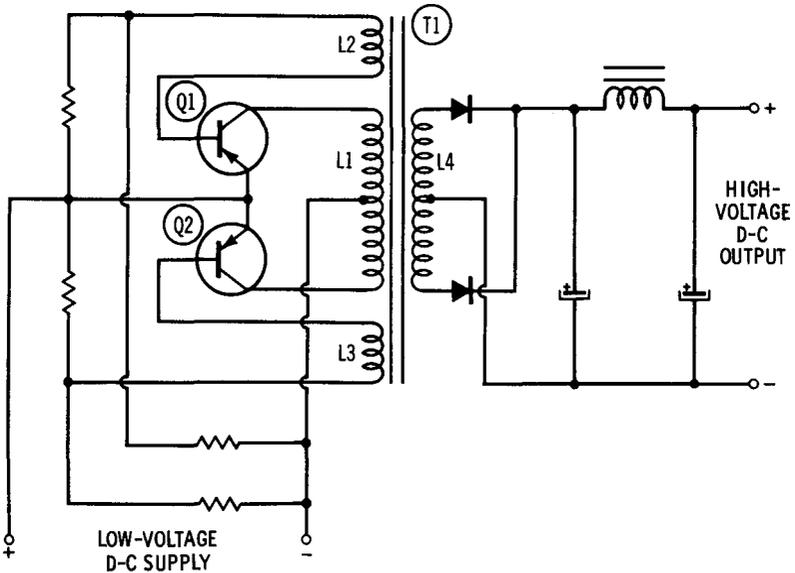
Fig. 10-2. Transistorized converter.

122

sistor converters employ no moving parts, they can operate at much higher frequencies. This permits smaller values of filter elements to be used. Also, at higher operating frequencies, the power transformer need not have as much inductance, which means that less iron and copper are required in its construction. Consequently it is much lighter in weight than a transformer designed for 60-Hz operation.

An inverter that supplies up to 300 watts at 115 volts a-c from a 12-volt battery.
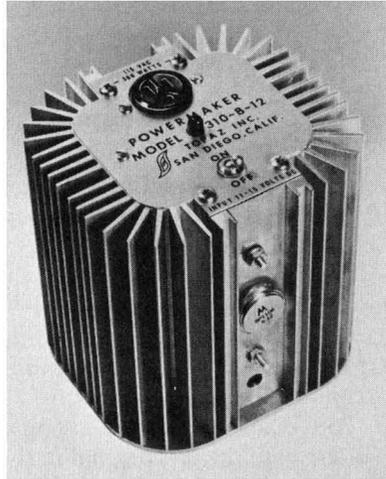
Courtesy Topaz Inc.

D-c to a-c power inverters operate basically in the same manner as the d-c to d-c converters just described. The major difference between the two is that the inverter is designed to provide an a-c output (most generally 60 Hz). That way the output may be used to operate equipment designed for regular house power.

RADIO-FREQUENCY POWER SUPPLIES

Fig. 10-3 is the schematic of a rather unusual type of power supply that is capable of efficiently providing very high voltages at low current. This circuit was widely used in the earlier tv receivers employing electrostatic-deflection picture tubes, and is still used in oscilloscopes and electrostatic dust precipitators.

As shown in Fig. 10-3, this supply consists of a radio-frequency oscillator, a high-voltage transformer, and a rectifier. The circuit values are selected to provide an oscillator frequency of approximately 80 kHz, with a power output of approximately 25 watts. The r-f energy developed in windings L1 and L2 is inductively coupled to the secondary, L3, which consists of many more turns than L1 and L2 so a high r-f voltage is induced in winding L3. This is applied to half-wave
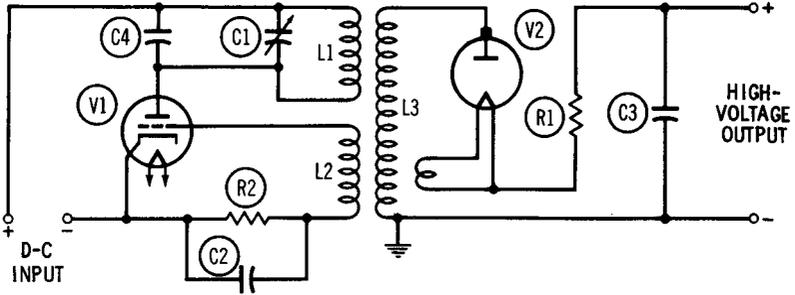
Fig. 10-3. Radio-frequency high-voltage power supply.

rectifier V2. The rectified voltage is filtered by R1 and C3. Because of the very high ripple frequency, the value of the filter capacitor is quite small, normally 500 pf.

The r-f power-supply output can be voltage-regulated by the closed-loop method shown in Fig. 10-4. A portion of the output voltage is sampled and compared with a fixed reference voltage. The resulting error signal is amplified and used to vary the screen-grid voltage of oscillator tube V1.

To see how this works, assume that the load current increases. This will increase the error signal in the positive direction, causing the voltage applied to the screen grid of V1 to increase. The amplitude of oscillation developed by V1 will likewise increase. In turn, this will
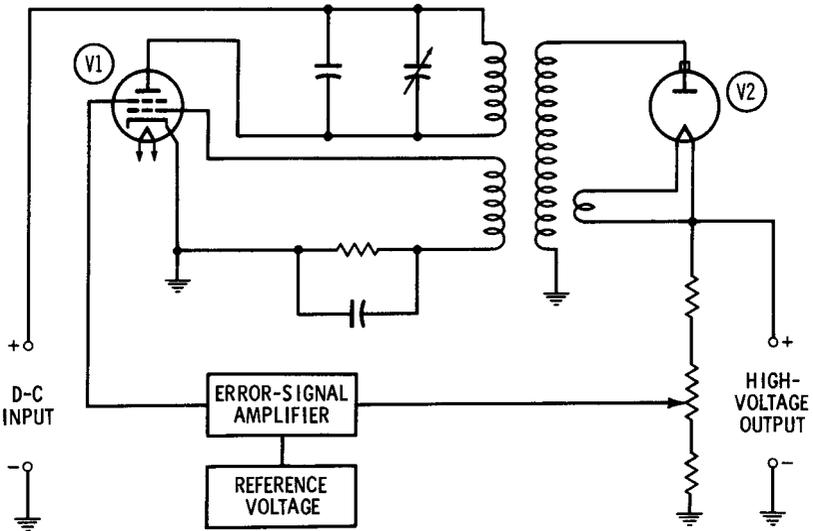
Fig. 10-4. Voltage-regulated r-f power supply.

124
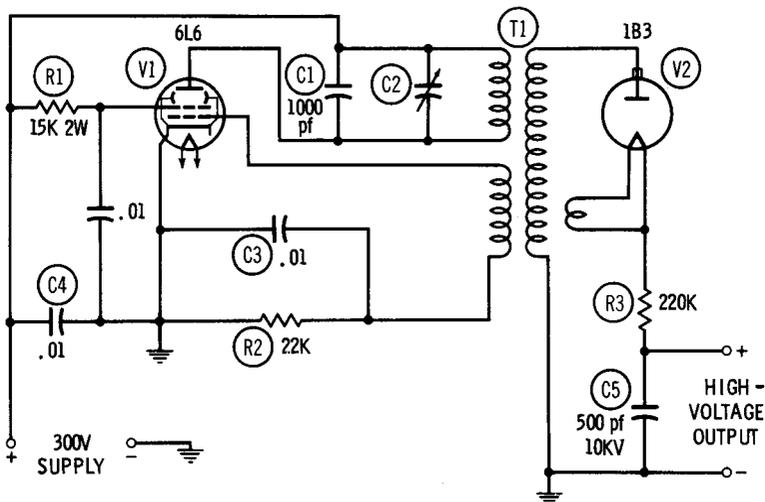
Fig. 10-5. Practical high-voltage power supply.

Parts List for Fig. 10-5

Item No.	Description
C1	Capacitor, 1000 pf, mica
C2	Capacitor, trimmer, 500-1000 pf, mica
C3	Capacitor, .01 mfd, mylar
C4	Capacitor, .01 mfd, mylar
C5	Capacitor, 500 pf, 10KV
R1	Resistor, 15K ohms, 2 watts
R2	Resistor, 22K ohms, ½ watt
R3	Resistor, 220K ohms, ½ watt
T1	Transformer, high-voltage (Spellman 10-15KV-1, or equivalent)
V1	Tube, 6L6
V2	Tube, 1B3

increase the voltage developed across the secondary of T1 and the rectified output voltage. If the output voltage should increase, the reverse action will occur—the screen voltage of V1 will decrease and the rectified output voltage will drop accordingly.

The 5KV d-c power supply shown in Fig. 10-5 is ideal for the high-voltage crt requirements of an oscilloscope, insulation tester, electronic

125

dust precipitator, etc. The supply is constructed around an inexpensive r-f high-voltage transformer that is commercially available. The operation of this supply is identical with the one shown in Fig. 10-4.

The construction is not particularly critical, although care must be taken that adequate insulation is used around high-voltage rectifier V2, its associated wiring, and filter capacitor C5.

Adjustment of the supply consists of setting C2 for maximum high-voltage output. Although, because of its low current output, this supply is not considered dangerous, care should be taken not to get directly across the output terminals when it is operating.

Index