One of the more interesting and useful array of ICs is the RCA CA3102E. It contains two differential pairs and two current-source transistors. The device is ideally suited for use in doubly balanced mixers, modulators, and product detectors. The CA3102E is excellent for use in the following additional applications: vhf amplifiers, vhf mixers, rf amp./mixer/oscillator combinations, i-f amplifiers (differential and/or cascode mode), synchronous detectors, and sense amplifiers. This IC is similar in configuration to the CA3049T array, but has an independent substrate connection which is common to an internal shield that separates the two differential amplifiers. The shield helps assure good isolation in applications where that feature is required.

F_T for CA3102E is in excess of 1000 MHz. Noise figure at 100 MHz single transistor is 1.5 dB, R_s = 500 ohms. Noise figure at 200 MHz cascode mode is 4.6 dB. Additional specifications can be found in *RCA Data File* No. 611. The CA3102E offers almost limitless possibilities for applications in amateur radio design work. The chip is manufactured in a 14-lead DIP package. The CA3049T comes encased in a standard TO-5 package.

DIGITAL-LOGIC INTEGRATED CIRCUITS

Digital logic is the term used to describe an overall design procedure for electronic systems in which "on" and "off" are the important words, not "amplification," "detection," and other terms commonly applied to most amateur equipment. It is "digital" because it deals with discrete events that can be characterized by digits or integers, in contrast with linear systems in which an infinite number of levels may be encountered. It is "logic" because it follows mathematical laws, in which "effect" predictably follows "cause."

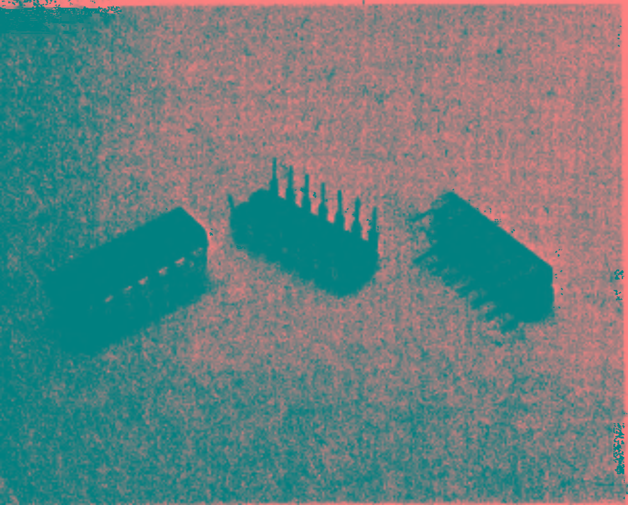
Just like linear integrated circuits, digital ICs are manufactured in such a way that the internal components are interconnected for particular applications. Packaging of the digital ICs is the same for their linear counterparts, with the full package range pictured earlier being used. From outward appearances, it would be impossible to tell the difference between the two types of ICs except from the identification numbers.

Linear ICs are constructed to respond to continuously variable or analog signals, such as in an amplifier. Digital devices, on the other hand, generally have active components operating only in either of two conditions – cutoff or saturation. Digital ICs find much application in on-off switching circuits, as well as in counting, computation, memory-storage, and display circuits. Operation of these circuits is based on binary mathematics, so words such as "one" and "zero" have come into frequent use in digital-logic terminology. These terms refer to specific voltage levels, and vary between manufacturers and devices. Nearly always, a "0" means a voltage near ground, while "1" means whatever the manufacturer specifies. One must distinguish between "positive logic" and "negative logic." In positive logic, a 1 is more positive than a 0, though both may be negative voltages. In negative logic, the reverse is true. Often the terms "high" and "low" are used in reference to these voltage levels. The definitions of these terms are the same for both positive and negative logic. A "high" is the most positive or least negative potential, while a "low" is the least positive or most negative.

For practical use in some applications it is desirable to convert binary data into decimal equivalents, such as in electronic counting and display systems. In other applications, such as the graphic recording or metering of summations or products of integers, it is convenient to convert the digital data into analog equivalents. Specialized integrated circuits designed to perform these functions are also considered to be included in the digital-IC category.

LOGIC SYMBOLS

With modern microcircuit technology, hundreds of components can be packaged in a single case. Rather than showing a forest of transistors, resistors, and diodes, logic diagrams show symbols based on the four distinctive shapes given in Fig. 4-28 at A through D. These shapes may be "modified" or altered slightly, according to



From outward appearances, these three ICs appear to be identicel. Although each is a *J-K* flip-flop, there are differences in their characteristics. Pictured at the left is a Texas Instruments SN74H72N integrated circuit, called a *J–K* master-slave flip-flop. Shown in the center is a Motorola MC1927P IC, which is a 120-MHz ac-coupled *J-K* flip-flop. Both of these ICs might be considered "universal" flip-flops, for they may be used in a variety of ways. Shown at the right is a Motorola MC726P, a simple *J-K* flip-flop.

specific functions performed. Examples are shown at E through H of Fig. 4-28.

The square, Fig. 4-28D and H, may appear on logic diagrams as a rectangle. This symbol is a somewhat universal one, and thus must be identified with supplemental information to indicate the exact function. Internal labels are usually used. Common identification labels are:

FF – Flip-flop
FL – Flip-flop latch
SS – Single shot
ST – Schmitt trigger.

Other logic functions may also be represented by the square or rectangle, and the label should adequately identify the function performed. Unique identifying shapes are used for gates and inverters, so these need no labels to identify the *function*. Hardware- or package-identification information may appear inside any of the symbols on logic diagrams.

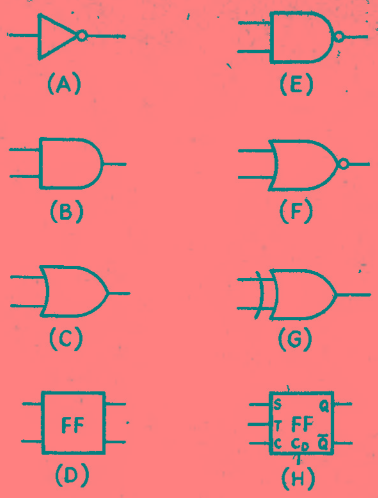


Fig. 4-28 – Distinctive symbols for digital logic diagrams. At A is shown an inverter, at B an AND gate, at C an OR gate, and at D a flip-flop. Additions to these basic symbols indicate specific functions performed. A small circle, for example, placed at the output point of the symbol, denotes that inversion occurs at the output of the device. Shown at E is an inverting AND or NAND gate, and at F is an inverting OR or NOR gate. At G is the symbol for an exclusive OR gate. The symbol at H represents a J-K flip-flop.

TYPES OF DIGITAL ICs

Digital integrated circuits perform a variety of functions, but these functions can generally be cataloged into just a few categories: gates, inverters, flip-flops, drivers and buffers, adders and subtractors, registers, and memories, plus the special-purpose ICs as mentioned earlier – decoders and converters. Some of these types, such as adders and subtractors, registers, and memories, find use primarily in computer systems. More universally used types of ICs are the inverters, gates and flip-flops.

Inverters

A single chip in one IC package may be designed to perform several functions, and these functions can be independent of each other. One example of an IC of this type is Motorola's MC789P, which bears the name, "hex inverter." This IC contains six identical inverter sections. The schematic diagram of one section is shown in Fig. 4-29A. In operation, 3.0 to 3.6 volts are applied between +Vcc and ground. For this device in positive-logic applications, a 0 is defined as any potential less than approximately 0.6 volt, and a 1 is any voltage greater than about 0.8. With a logic 0 applied at the input, the transistor will be at or near cutoff. Its output will be a potential near +Vcc, or a logic 1. If the 0 at the input is replaced by a 1, the transistor goes into saturation and its output drops nearly to ground potential; a 0 appears at the output. The output of this device is always the opposite or *complement* of the input logic level. This is sometimes called a NOT gate, because the input and output logic levels are *not* the same, under any conditions of operation.

Shown at the right in Fig. 4-29A is the logic symbol for the inverter. In all logic symbols, the connections for +Vcc and the ground return are omitted, although they are understood to be made. The proper connections are given in the manufacturer's data sheets, and, of course, must be made before the device will operate properly. In the case of all multiple-function ICs, such as the hex inverter, a single ground connection and a single +Vcc connection suffice for all sections contained in the package.

Gates

Another example of an IC containing several independent functions in one package is Motorola's MC724P, a quad 2-input gate. Four gates are contained in one chip. The schematic diagram and logic symbols for a gate section are shown at B in Fig. 4-29. As with the MC789P, a supply of 3.0 to 3.6 volts is used; for positive logic a 0 is a potential less than 0.6 volt, and a 1 is a potential greater than 0.8 volt. It may be seen from the schematic diagram that the two transistors have an independent input to each base, but they share a common collector resistor. Either transistor will be saturated with a logic 1 applied at its input, and a 0 output will result. A 0 at the input of either transistor will cause that transistor to be cut off, but a 1 at the opposite input will hold the output at 0. Thus, a 1 at either Input 1 *or* Input 2 will cause a 0 (or a NOT 1) to appear at the output. The NOT functions are usually written with a bar over them, so $\overline{1}$ means the same thing as NOT 1,

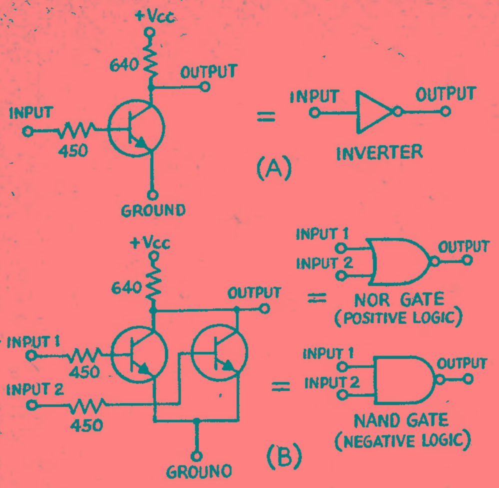


Fig. 4-29 — Digital circuits and their equivalent logic symbols. See text. Indicated resistor values are typical.

and is expressed as NOT 1 when reading the term. Logic-circuit operation can be expressed with equations. Boolean algebra, a form of binary mathematics, is used. These equations should not be confused with ordinary algebraic equations. The logic equation for the operation of the circuit in Fig. 4-28A is $1 \; v \; 1 = \overline{1}$. The little *v* means OR. Sometimes "+" is used instead of "*v*." In plain words, the equation says that a 1 at Input 1 *or* Input 2 will yield a NOT 1 at the output. This is equivalent of saying the circuit is an inverting OR gate, or a NOT OR gate. This latter name is usually contracted to NOR gate, the name by which the circuit is known.

If the circuit of Fig. 4-29B is used with negative logic, circuit operation remains the same; only the definitions of terms are changed. A logic 1, now, is a voltage level less than 0.6, and a 0 is a level greater than 0.8 volt. If a logic 1 is applied at both inputs, 1 *and* 2, both transistors will be cut off. The output is near +Vcc, which is a logic 0 or $\overline{\text{NOT}}$ 1. The equation for this operation is $1 \cdot 1 = \overline{1}$, where the dot means AND. In this way, with negative logic, the circuit becomes an inverting AND gate, or a NOT AND gate or, more commonly, a NAND gate. Manufacturers' literature frequently refers to this type of device as a NAND/NOR gate, because it performs either function.

Flip-Flops

It is not necessary for the various functions on a single chip to be identical. Motorola's MC780P IC, a decade up-counter, contains four flip-flops, an inverter, and a 2-input gate. These functions are interconnected to provide divide-by-10 operation, with ten input pulses required for every output pulse which appears. Intermediate outputs are also provided (in binary-coded form) so that the number of pulses which have entered the input can be determined at all times. These binary-coded decimal (BCD) outputs, after decoding, may be used to operate decimal-readout indicators.

The term, medium-scale integration (MSI) is frequently applied to ICs such as this decade up-counter, which contains the equivalent of 15 or more gates on a single chip. Large-scale integration (LSI) describes ICs containing the equivalent of 100 or more gates on a single chip. These terms, when applied to a particular IC, convey an idea of the complexity of the circuitry.

A flip-flop is a device which has two outputs that can be placed in various 1 and 0 combinations by various input schemes. Basically, one output is a 1 when the other is a 0, although situations do occur (sometimes on purpose) where both outputs are alike. One output is called the Q output, or "set" output, while the other is the $\overline{Q}$ (NOT Q) or "reset" output. If $Q = 1$ and $\overline{Q} = 0$, the flip-flop is said to be "set" or in the "1 state," while for the reverse, the flip-flop is "reset," or "cleared," or in the "0 state." A variety of inputs exist; from which the flip-flops derive their names.

The *R-S* flip-flop is the simplest type. Its outputs change directly as a result of changes at its inputs. The type *T* flip-flop "toggles," "flips," or changes its state during the occurrence of a *T* pulse, called a clock pulse. The *T* flip-flop can be considered as a special case of the *J-K* flip-flop described later. The type *D* flip-flop acts as a storage element. When a clock pulse occurs, the complementary status of the *D* input is transferred to the *Q* output. The flip-flop remains in this state even though the input may change, as it can change states only when a clock pulse occurs.

Although there is some disagreement in the nomenclature, a *J-K* flip-flop is generally considered to be a toggled or clocked *R-S* flip-flop. It may also be used as a storage element. The *J* input is frequently called the "set" or *S* input; the *K* is called the "clear" or *C* input (not to be confused with the clock input). The clock input is called *T*, as in the type *T* flip-flop. A clear-direct or C_D input which overrides all other inputs to clear the flip-flop to 0 is provided in most *J-K* flip-flop packages. The logic symbol for the *J-K* flip-flop is shown in Fig. 4-28H. A simple *J-K* flip-flop circuit contains 13 or 14 transistors and 16 or 18 resistors.

There are essentially two types of flip-flop inputs, the dc or level-sensitive type, and the "ac" or transistion-sensitive type. It should not be concluded that an ac input is capacitively coupled. This was true for the discrete-component flip-flops, but capacitors just do not fit into microcircuit dimensions. The construction of an ac input uses the "master-slave" principle, where the actions of a master flip-flop driving a slave flip-flop are combined to produce a shift in the output level during a transit of the input.

DIGITAL-LOGIC IC FAMILIES

There are seven categories or families of which nearly all semiconductor digital ICs are members.

Each family has its own inherent advantages and disadvantages. Each is geared to its own particular market, meeting a specific set of needs.

Resistor-Transistor Logic – RTL

RTL is known primarily for its economy. It is well named, since it contains resistors and transistors exclusively. The circuits of Fig. 4-29 are RTL. Advantages of the RTL family are economy, ease of use in system designs, ease of interface with discrete components, and high speed–power product. There are a wide number of functions available in this family. Disadvantages are low immunity to voltage noise (transients, rf pickup, and the like), and relatively low fanout (the number of loads that may be connected to an output before performance is degraded). The RTL family requires a supply of 3.0 to 3.6 volts.

Diode-Transistor Logic – DTL

DTL ICs contain diodes, as well as resistors and transistors. Early DTL ICs used design criteria carried over from the use of discrete components, where diodes were inexpensive compared to transistors. These ICs required negative and positive voltage sources. Later DTL ICs are of a modified design which lends itself more easily to IC processing. Performance characteristics are also enhanced, with less input current being required, and only a single voltage source needed. Members of the DTL family are limited generally to gates. Advantages of this family are low power dissipation, compatibility with TTL (see later section), low cost, ease of use in system design, ease of interface with discrete circuits, and relatively high fanout. DTL disadvantages are low noise immunity, especially in the high state where the input impedance is relatively high, rapid change in voltage thresholds with temperature, speed slowdown with capacitive loading, and lower speed capabilities than some other families. The DTL family requires a supply voltage of 5.

High-Threshold Logic – HTL

HTL devices are designed for high noise immunity. The circuit form is the same as DTL except that breakdown (Zener) diodes are used at the inputs. Higher supply voltages and higher power dissipations accompany the HTL family. These ICs find applications in industrial environments and locations likely to have high electrical noise levels. Advantages are high noise immunity, stable operation over very large temperature ranges, interfaces easily with discrete components, electromechanical components, and linear functions (operational amplifiers and multipliers), and a constant threshold-versus-temperature characteristic. Disadvantages are higher cost than other families, and relatively high power dissipation. The HTL family requires a supply voltage of 15.

Transistor-Transistor Logic – TTL

TTL has characteristics that are similar to DTL, and is noted for many complex functions and the highest available speed of any saturated logic. TTL may be thought of as a DTL modification that results in higher speed and driving capability. It is noted for better noise immunity than that offered by DTL, and is more effective for driving high-capacitance loads because of its low output impedance in both logic states. TTL ICs fall into two major categories – medium speed and high speed. Various manufacturing techniques are used to increase the speed, including gold doping and incorporation of high-speed Schottky diodes on the chip. Another advantage of TTL is that it is compatible with various other families. Multiple sources and extensive competition have resulted in low prices for TTL devices. Disadvantages are that more care is required in the layout and mechanical design of systems because of its high speed, and additional capacitors are required for bypassing because of switching transients. The TTL family requires a supply of 5 volts.

Emitter-Coupled Logic – ECL

ECL has the highest speed of any of the logic forms. It is sometimes called current-mode logic. This family is different from standard saturating logic in that circuit operation is analogous to that of some linear devices. In this case, the transistors do not saturate and the logic swings are reduced in amplitude. Very high speeds can be attained because of the small voltage swings and the use of nonsaturating transistors. The input circuitry of ECL devices is of the nature of a differential amplifier, resulting in much higher input impedances than saturated-logic devices. Emitter-follower outputs are of low impedance with high fanout capabilities, and are suited for driving 50-ohm transmission lines directly. Disadvantages are higher power dissipation, less noise immunity than some saturated logic, translators are required for interfacing with saturated logic, and slowed-down operation with heavy capacitive loading. The ECL family requires a supply of -5.2 volts.

Metal-Oxide Semiconductor (MOS)

Digital MOS devices are gaining significance in industrial applications, with p-channel or P-MOS ICs being the most popular. Large, complex repetitive functions, such as long shift registers and high-capacity memories, have proved very practical. Gates and basic logic circuits have not become as popular, because they exhibit lower drive capability than other IC families. Input impedances to these devices are essentially capacitive (an open circuit for dc). This feature allows very high fanout where speed is not a consideration. Bidirectional devices give more flexibility to the circuit designer. P-MOS technology results in the lowest cost per bit for memories and long shift registers, because many more functions can be contained on a given chip size than in bipolar devices. Disadvantages are that devices must be handled more carefully than bipolar ICs because excessive static electricity can destroy the narrow gate oxide, even with internal breakdown-diode input protection. Drive capability is limited because of the high output impedances characteristic of these devices. Two power supplies are usually required. The P-MOS family requires supplies of -13 and -27 volts.

Complementary Metal-Oxide Semiconductor — CMOS

CMOS technology employs both p-channel and n-channel devices on the same silicon substrate. Both types are enhancement-mode devices; that is, gate voltage must be increased in the direction that inverts the surface in order for the device to conduct. Only one of the two complementary devices of a circuit section is turned on at a time, resulting in extremely low power dissipation. Dissipation is primarily from the switching of devices through the active region and the charging and discharging of capacitances. Advantages are low power dissipation, good noise immunity, very wide power supply voltage variations allowed, high fanout to other CMOS devices, and full temperature-range capabilities. Disadvantages are restricted interfacing capabilities because of high output impedance, and medium to high cost. The CMOS family requires a supply of 1.5 to 16 volts, 10 volts being nominal.

IC Family Groups

The popular digital-logic families have several groups where basic designs have been modified for medium speed, high speed, or low power consumption. The TTL family ICs have single-letter designators added to the part number to identify the group: S – Schottky high speed, H – medium speed, L – low power. ECL logic, as yet, has no such simple identification system. Manufacturers group their ECL products by propagation delay, an expression of the maximum speed at which the logic device will operate. Motorola, for example, calls the ECL group with 8-ns delay MECL. MECL II has a speed of 4 ns; MECL 10,000, 2 ns; and MECL III, 1.1 ns. With a propagation delay of 1 ns, operation at 300 MHz is possible.

Special Digital ICs

In addition to the logic families, many special-purpose digital ICs are available to accomplish specific tasks. A divide-by-10 circuit, such as the Fairchild U6B95H9059X, operates up to 320 MHz and is used as a prescaler to extend the range of a frequency counter. This IC has been designed to operate with low-level input signals, typically 100 mV at 150 MHz.

Large MOS arrays are being used for a number of applications which require the storage of logic instructions. These ICs are called memories. Instructions are stored in the memory by a process named programming. Some memories can be programmed only once; they are called ROMs (Read-Only Memory). ROMs must be read in sequence, but another group of devices called RAMs (Random-Access Memory) can be used a section at a time. Both ROMs and RAMs are also made in reprogrammable versions, where the information stored in the memory can be changed as desired. These models are named PROMs and PRAMs, respectively.

Large memory arrays are often used for the generation and conversion of information codes. One IC can be programmed to convert the 5-level RTTY code to the 8-level ASCII code popular in computer devices. National Semiconductor manufactures a single IC which generates the entire 56-character 8-level code. Several ICs are now available for character generation where letters and numerals are produced for display on an oscillograph screen.

OTHER DEVICES

THE UNIJUNCTION TRANSISTOR

Unijunction transistors (UJT) are being used by amateurs for such applications as side-tone oscillators, sawtooth generators, pulse generators, and timers.

Structurally, the UJT is built on an n-type silicon bar which has ohmic contacts – base one (B1) and base two (B2) – at opposite ends of the bar. A rectifying contact, the emitter, is attached between B1 and B2 on the bar. During normal operation B1 is grounded and a positive bias is supplied to B2. When the emitter is forward biased, emitter current will flow and the device will conduct. The symbol for a UJT is given in Fig. 4-30 at C. A circuit showing a typical application in which a UJT is employed is shown in Fig. 4-30.

SILICON CONTROLLED RECTIFIERS

The silicon controlled rectifier, also known as a Thyristor, is a four-layer (p-n-p-n or n-p-n-p) three-electrode semiconductor rectifier. The three terminals are called anode, cathode and gate, Fig. 4-28B.

The SCR differs from the silicon rectifier in that it will not conduct until the voltage exceeds the *forward breakover* voltage. The value of this voltage can be controlled by the gate current. As the gate current is increased, the value of the forward breakover voltage is decreased. Once the rectifier conducts in the forward direction, the gate current no longer has any control, and the rectifier behaves as a low-forward-resistance diode. The gate regains controls when the current through the rectifier is cut off, as during the other half cycle.

The SCR finds wide use in power-control applications and in time-delay circuits. SCRs are available in various voltage and wattage ratings.

TRIACS

The triac, similar to the SCR, has three electrodes – the main terminal (No. 1), another

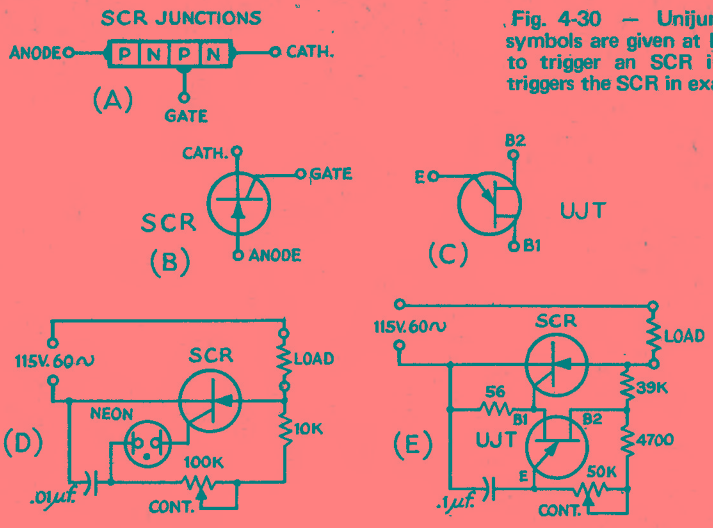


Fig. 4-30 — Unijunction transistor and SCR symbols are given at B and C. A neon lamp is used to trigger an SCR in the circuit at D. A UJT triggers the SCR in example E.

main terminal (No. 2), and a gate. The triac performs in the same manner as the SCR, but for either polarity of voltage applied to its main terminals. The SCR, as mentioned in the foregoing, conducts only during one half the sine-wave cycle. When an SCR is used in a motor-speed control, therefore, the motor cannot be brought up to full speed. The triac, however, does trigger on both halves of the cycle. Therefore, triacs are preferred to SCRs in many control circuits. The triac can be regarded as a device in which two SCRs are employed in parallel and oriented in opposite directions as shown in the drawing of Fig. 4-30. An example of a motor-speed control which uses a triac is given in the construction chapter of this book.

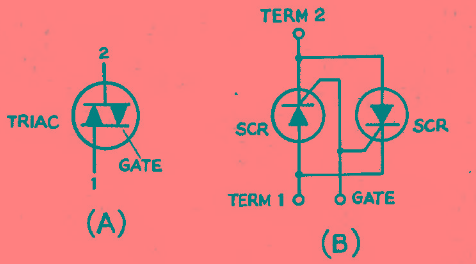


Fig. 4-31 — The symbol for a triac is given at A. The illustration at B shows how a triac compares to two SCRs connected for the same performance offered by a triac, thus permitting conduction during both halves of the cycle.

OPERATIONAL AMPLIFIERS

Early analog computers used amplifier blocks which became known as **operational amplifiers,** or simply **op amps.** Operational amplifiers can be constructed using tubes or transistors, and as hybrid or monolithic integrated circuits. The monolithic IC has become the most popular type of op amp. Today op-amp ICs cost approximately one dollar for the preferred types. They are used as building blocks in many circuit applications.

The op amp is a dc-coupled multistage linear amplifier which, in an ideal device, would have infinite input impedance and infinite gain. While the ideal op amp remains an unobtainable goal, voltage gains of 100,000 or more can be achieved. FET-input op amps have sufficiently high input impedance that the current required from the driving source is measured in pA (μμA).

Gain and Feedback

The internal circuit of a popular op-amp IC, the Fairchild μA741 (also produced by most other semiconductor manufacturers) is shown in Fig. 4-32. Two inputs are provided, one the complement or inverse of the other. An amplifier with two such inputs is known as a **differential amplifier.** If a small positive voltage is applied to the noninverting (+) terminal, it will produce a positive output. The same positive voltage applied to the inverting (–) terminal will result in a negative output. If the same voltage was applied to both terminals, the output would be zero. Both inputs can be used, called the differential connection, or one can be returned to ground for single-ended operation. In practical ICs, the output may not be exactly zero when both inputs are at zero potential. Any output under these conditions is called **offset** – some op amps have provision for connections to an external control which compensates for any offset voltage by applying bias current to the input transistors. The offset connections for the μA741 are shown in Fig. 4-32. Op amps are available in all of the popular IC packages; consult

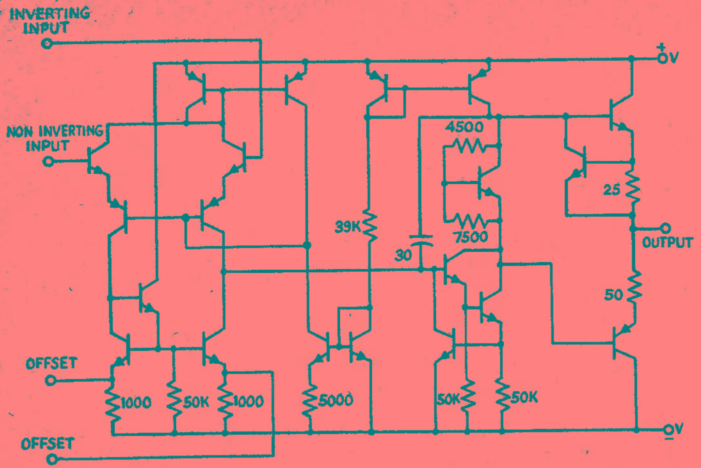


Fig. 4-32 — Internal circuit of a μA741 operational amplifier.

the manufacturer's literature for pin connections. Usually the pin connections are not the same for a particular device when it is made up in different package styles.

For most applications the full gain of the op amp is not used. Feedback is employed, as shown in Figs. 4-34A and B.. The addition of a resistive divider network, Ro-Ri, causes negative feedback by allowing part of the output voltage to be applied to the inverting input. The gain of the device will be equal to the sum of Ro and Ri, divided by the value of Ri. Feedback can be applied in a similar manner for a noninverting amplifier, Fig. 4-33B.. The voltage summer, Fig. 4-33C, provides an output voltage which is the sum of all input voltages multiplied by the gain of the operational amplifier. This circuit is often employed as an audio mixer. Fig. 4-33D shows the voltage-follower connections. The load at the output of this circuit can draw a large current while the input draws almost no current. The output voltage follows the level of the input potential almost exactly. The output of the differentiator (Fig. 4-33E) is proportional to the rate of change of the input voltage, while the integrator (Fig. 4-33F) averages the level of a voltage that varies over a short period of time. A differential connection of a single op amp is shown at G.

Stability

Because op amps are high-gain devices with frequency response from dc to several megahertz,

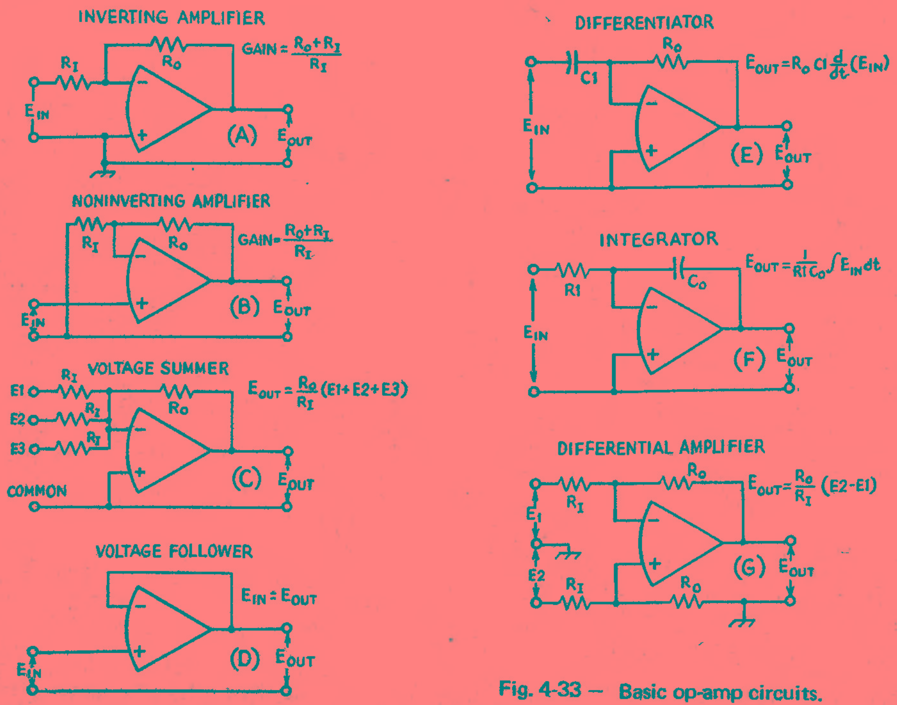


Fig. 4-33 — Basic op-amp circuits.

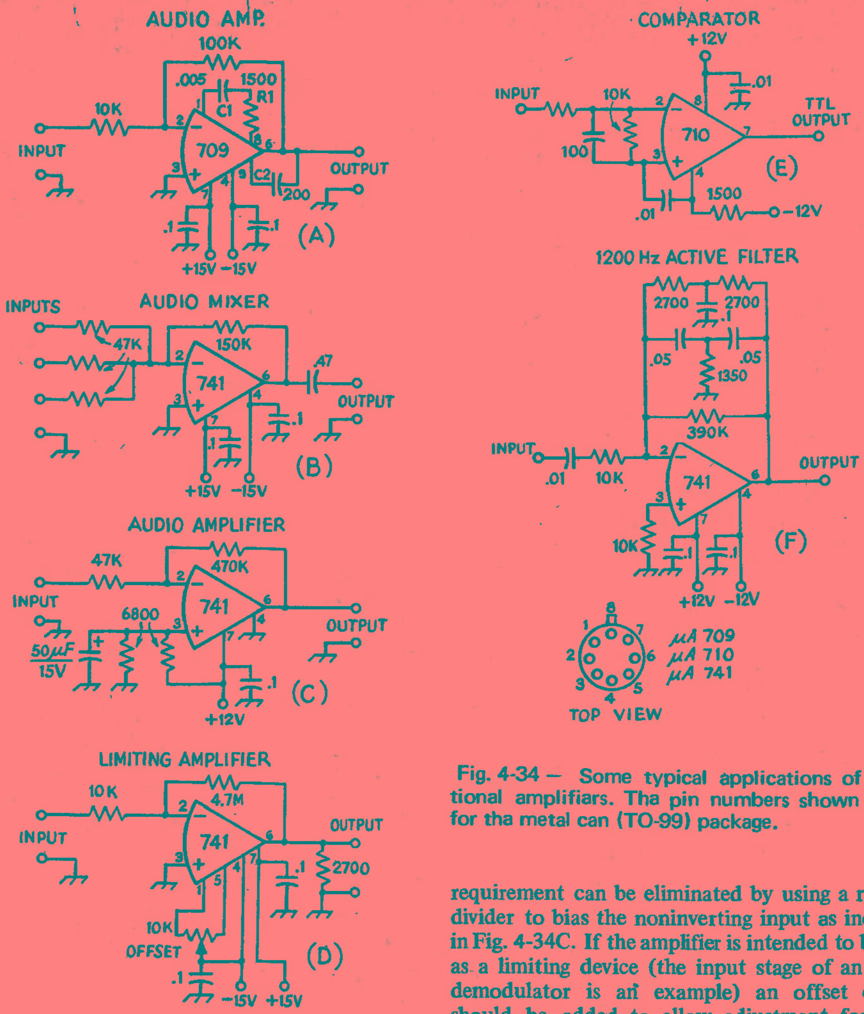


Fig. 4-34 – Some typical applications of operational amplifiers. The pin numbers shown are all for the metal can (TO-99) package.

oscillation can occur. In any op-amp circuit layout, the inputs should be well isolated from the output. Input leads should be kept as short as possible. Supply-voltage terminals should be bypassed with 0.1- or .01-μF capacitors. As the frequency is increased, the stages within an op amp will introduce phase shift. If the phase shift in the amplifier reaches 180 degrees before the gain has decreased to unity, the amplifier will be unstable. Some op amps, such as the μA709 of Fig. 4-34A. require an external compensation network, R1-C1, to reduce the gain of the device at hf. Others, the μA741 of Fig. 4-34B for example, contain internal compensation and, thus, require no additional components to assure stability.

Applications

Most monolithic op-amp ICs require supply voltages of plus 5 to 15 and minus 5 to 15. Practical examples of an audio amplifier and audio mixer are given in Fig. 4-33A and B,, respectively. In some amateur applications, the dual-polarity requirement can be eliminated by using a resistive divider to bias the noninverting input as indicated in Fig. 4-34C. If the amplifier is intended to be used as a limiting device (the input stage of an RTTY demodulator is an example) an offset control should be added to allow adjustment for equal clipping of the negative and positive peaks (Fig. 4-34D).

Another popular use for the op amp is as a comparator – see Fig. 4-34E. A comparator is used to indicate when a difference exists between a reference voltage and an input voltage. The output of the comparator will swing from its maximum positive voltage to maximum negative when the input exceeds the reference (zero voltage if the reference is zero). A number of op amps optimized for comparator service are available; they are often used as interface devices between linear and digital circuits. The operational amplifier is often employed in *active filters*, which use *RC* components to provide low-pass, high-pass, and bandpass characteristics. A simple illustration, an *RC* filter network tuned to 1200 Hz connected in parallel with the feedback resistor, is given in Fig. 4-34F. This design is for low *Q* giving a characteristic suitable for a cw receiver. The gain at resonance is approximately 40. Additional information about active filters and other op-amp circuits is available in the publications listed in the bibliography at the end of this chapter.

ABBREVIATED SEMICONDUCTOR SYMBOL LIST

BIPOLAR TRANSISTOR SYMBOLS

C_{ibo}	– Input capacitance, open circuit (common base)
C_{ieo}	– Input capacitance, open circuit (common emitter)
C_{obo}	– Output capacitance, open circuit (common base)
C_{oeo}	– Output capacitance, open circuit (common emitter)
f_c	– Cutoff frequency
f_T	– Gain-bandwidth product (frequency at which small-signal forward current-transfer ratio, common emitter, is unity, or 1)
g_{me}	– Small-signal transconductance (common emitter)
h_{FB}	– Static forward-current transfer ratio (common base)
h_{fb}	– Small-signal forward-current transfer ratio, short circuit (common base)
h_{FE}	– Static forward-current transfer ratio (common emitter)
h_{fe}	– Small-signal forward-current transfer ratio, short circuit (common emitter)
h_{IE}	– Static input resistance (common emitter)
h_{ie}	– Small-signal input impedance, short circuit (common emitter)
I_b	– Base current
I_c	– Collector current
I_{CBO}	– Collector-cutoff current, emitter open
I_{CEO}	– Collector-cutoff current, base open
I_E	– Emitter current
MAG	– Maximum available amplifier gain
P_{CE}	– Total dc or average power input to collector (common emitter)
P_{OE}	– Large-signal output power (common emitter)
R_L	– Load resistance
R_s	– Source resistance
V_{BB}	– Base-supply voltage
V_{BC}	– Base-to-collector voltage
V_{BE}	– Base-to-emitter voltage
V_{CB}	– Collector-to-base voltage
V_{CBO}	– Collector-to-base voltage (emitter open)
V_{CC}	– Collector-supply voltage
V_{CE}	– Collector-to-emitter voltage
V_{CEO}	– Collector-to-emitter voltage (base open)
$V_{CE(sat)}$	– Collector-to-emitter saturation voltage
V_{EB}	– Emitter-to-base voltage
V_{EBO}	– Emitter-to-base voltage (collector open)
V_{EE}	– Emitter-supply voltage
Y_{fe}	– Forward transconductance
Y_{ie}	– Input Admittance
Y_{oe}	– Output Admittance

FIELD-EFFECT TRANSFER SYMBOLS

A	– Voltage amplification
C_c	– Intrinsic channel capacitance
C_{ds}	– Drain-to-source capacitance (includes approximately 1-pF drain-to-case and interlead capacitance)
C_{gd}	– Gate-to-drain capacitance (includes 0.1-pF interlead capacitance)
C_{gs}	– Gate-to-source interlead and case capacitance
C_{iss}	– Small-signal input capacitance, short circuit
C_{rss}	– Small-signal reverse transfer capacitance, short circuit
g_{fs}	– Forward transconductance
g_{is}	– Input conductance
g_{os}	– Output conductance
I_D	– Dc drain current
$I_{DS(OFF)}$	– Drain-to-source OFF current
I_{GSS}	– Gate leakage current
r_c	– Effective gate series resistance
$r_{DS(ON)}$	– Drain-to-source ON resistance
r_{gd}	– Gate-to-drain leakage resistance
r_{gs}	– Gate-to-source leakage resistance
V_{DB}	– Drain-to-substrate voltage
V_{DS}	– Drain-to-source voltage
V_{GB}	– Dc gate-to-substrate voltage
V_{GB}	– Peak gate-to-substrate voltage
V_{GS}	– Dc gate-to-source voltage
V_{GS}	– Peak gate-to-source voltage
$V_{GS(OFF)}$	– Gate-to-source cutoff voltage
Y_{fs}	– Forward transadmittance $\approx g_{fs}$
Y_{os}	– Output admittance
Y_L	– Load admittance

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Chapter 5

AC-Operated Power Supplies

Power-line voltages have been "standardized" throughout the U.S. at 115 – 230 V in residential areas where a single voltage phase is supplied. These figures represent nominal voltages, however. "Normal" line voltage in a particular area may be between approximately 110 and 125 volts, but generally will be above 115 volts. In many states, the service is governed by the state's public utilities commission. The voltage average across the country is approximately 117 volts. Source of information: Edison Electric Company (an association of power companies), New York, NY.

The electrical power required to operate amateur radio equipment is usually taken from the ac lines when the equipment is operated where this power is available; in mobile operation the prime source of power is usually the storage battery.

The high-voltage dc for the plates of vacuum tubes used in receivers and transmitters is derived from the commercial ac lines by the use of a transformer-rectifier-filter system. The transformer changes the voltage of the ac to a suitable value, and the rectifier converts it to pulsating dc. The filter reduces the pulsations to a suitably low level, and may have either a capacitor input or a choke input, depending on whether a shunt capacitor or a series inductor is the first filter element. Essentially pure direct current is required to prevent hum in the output of receivers, speech amplifiers, modulators and transmitters. In the case of transmitters, a pure dc plate supply is also dictated by government regulations. If a constant supply voltage is required under conditions of changing load or ac line voltage, a regulator is used following the filter.

When the prime power source is dc (a battery), the dc is first changed to ac, and is then followed by the transformer-rectifier-filter system. Additional information on this type of supply is contained in Chapter 10.

The cathode-heating power can be ac or dc in the case of indirectly heated cathode tubes, and ac or dc for filament-type tubes if the tubes are operated at a high power level (high-powered audio and rf applications). Low-level operation of filament-type tubes generally requires dc on the filaments if undue hum is to be avoided.

Occasionally transformerless power supplies are used in some applications (notably in the ac-dc type of broadcast receiver). Such supplies operate directly from the power line, and it is necessary to connect the chassis or common-return point of the circuit directly to one side of the ac line. This type of power supply represents an extreme shock hazard when the equipment is interconnected with other apparatus in the amateur station, or when the chassis is exposed. For safety reasons, an isolation transformer should be used with such equipment when it is present in an amateur station.

POWER-LINE CONSIDERATIONS

POWER LINE CONNECTIONS

In most residential systems, three wires are brought in from the outside to the distribution board, while in other systems there are only two wires. In the three-wire system, the third wire is the neutral which is grounded. The voltage between the other two wires normally is 230, while half of this voltage (115) appears between each of these wires and neutral, as indicated in Fig. 5-1A. In systems of this type, usually it will be found that the 115-volt household load is divided as evenly as possible between the two sides of the circuit, half of the load being connected between one wire and the neutral, while the other half of the load is connected between the other wire and neutral. Heavy appliances, such as electric stoves and heaters, normally are designed for 230-volt operation and therefore are connected across the two ungrounded wires. While both ungrounded wires should be fused, a fuse should never be used in the wire to the neutral, nor should a switch be used in this side of the line. The reason for this is that opening the neutral wire does not disconnect the equipment. It simply leaves the equipment on one side of the 230-volt circuit in series with whatever load may be across the other side of the

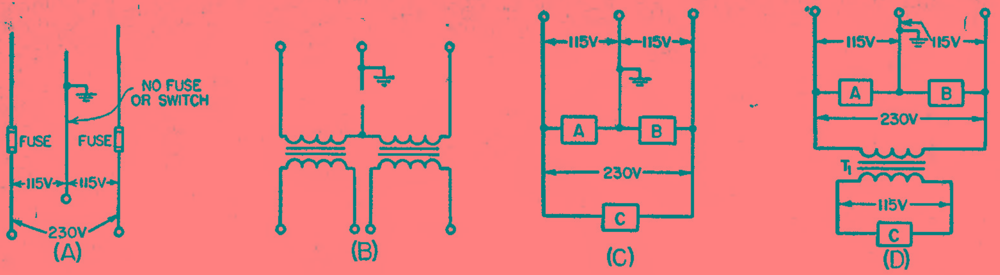


Fig. 5-1 — Three-wire power-line circuits. A — Normal 3-wire-line termination. No fuse should be used in the grounded (neutral) line. B — Showing that a switch in the neutral does not ramove voltage from either side of the line. C — Connections for both 115- and 230-volt transformers. D — Operating a 115-volt plate transformer from the 230-volt line to avoid light blinking. T1 is a 2-to-1 step-down transformer.

circuit, as shown in Fig. 5-1B. Furthermore, with the neutral open, the voltage will then be divided between the two sides in inverse proportion to the load resistance, the voltage on one side dropping below normal, while it soars on the other side, unless the loads happen to be equal.

The usual line running to baseboard outlets is rated at 15 amperes. Considering the power consumed by filaments, lamps, transmitter, receiver and other auxiliary equipment, it is not unusual to find this 15-A rating exceeded by the requirements of a station of only moderate power. It must also be kept in mind that the same branch may be in use for other household purposes through another outlet. For this reason, and to minimize light blinking when keying or modulating the transmitter, a separate heavier line should be run from the distribution board to the station whenever possible. (A three-volt drop in line voltage will cause noticeable light blinking.)

If the system is of the three-wire 230-V type, the three wires should be brought into the station so that the load can be distributed to keep the line balanced. The voltage across a fixed load on one side of the circuit will increase as the load current on the other side is increased. The rate of increase will depend upon the resistance introduced by the neutral wire. If the resistance of the neutral is low, the increase will be correspondingly small. When the currents in the two circuits are balanced, no current flows in the neutral wire and the system is operating at maximum efficiency.

Light blinking can be minimized by using transformers with 230-volt primaries in the power supplies for the keyed or intermittent part of the load, connecting them across the two ungrounded wires with no connection to the neutral, as shown in Fig. 5-1C. The same can be accomplished by the insertion of a step-down transformer with its primary operating at 230 volts and secondary delivering 115 volts. Conventional 115-volt transformers may be operated from the secondary of the step-down transformer (see Fig. 5-1D).

When a special heavy-duty line is to be installed, the local power company should be consulted as to local requirements. In some localities it is necessary to have such a job done by a licensed electrician, and there may be special requirements to be met. Some amateurs terminate the special line to the station at a switch box, while others may use electric-stove receptacles as the termination. The power is then distributed around the station by means of conventional outlets at convenient points. All circuits should be properly fused.

Three-Wire 115-V Power Cords

To meet the requirements of state and national codes, electrical tools, appliances and many items of electronic equipment now being manufactured to operate from the 115-volt line must be equipped with a 3-conductor power cord. Two of the conductors carry power to the device in the usual fashion, while the third conductor is connected to the case or frame.

When plugged into a properly wired mating receptacle, the 3-contact polarized plug connects this third conductor to an earth ground, thereby grounding the chassis or frame of the appliance and preventing the possibility of electrical shock to the user. All commercially manufactured items of electronic test equipment and most ac-operated amateur equipments are being supplied with these 3-wire cords. Adapters are available for use where older electrical installations do not have mating receptacles. For proper grounding, the lug of the green wire protruding from the adapter must be attached underneath the screw securing the cover plate of the outlet box where connection is made, and the outlet box itself must be grounded.

Fusing

All transformer primary circuits should be properly fused. To determine the approximate current rating of the fuse to be used, multiply each current being drawn from the supply in amperes by the voltage at which the current is being drawn. Include the current taken by bleeder resistances and voltage dividers. In the case of series resistors, use the source voltage, not the voltage at the equipment end of the resistor. Include filament power if the transformer is supplying filaments. After multiplying the various voltages and currents, add the individual products. Then divide by the line voltage and add 10 or 20 percent. Use a fuse with the nearest larger current rating.

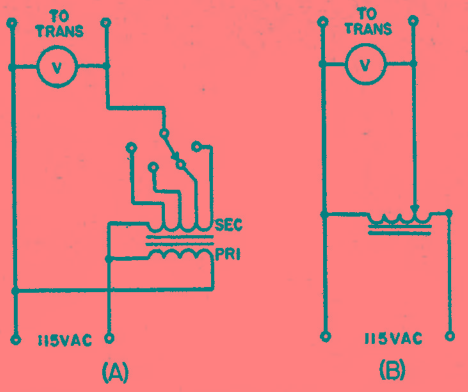


Fig. 5-2 — Two methods of transformer primary control. At A is a tapped toy transformer which may be connected so as to boost or buck the line voltage as required. At B is indicated a variable trensformer or autotransformer (Variac) which feeds the transformer primaries.

LINE-VOLTAGE ADJUSTMENT

In certain communities trouble is sometimes experienced from fluctuations in line voltage. Usually these fluctuations are caused by a variation in the load on the line. Since most of the variation comes at certain fixed times of the day or night, such as the times when lights are turned on at evening, they may be taken care of by the use of a manually operated compensating device. A simple arrangement is shown in Fig. 5-2A. A toy transformer is used to boost or buck the line voltage as required. The transformer should have a tapped secondary varying between 6 and 20 volts in steps of 2 or 3 volts and its secondary should be capable of carrying the full load current.

The secondary is connected in series with the line voltage and, if the phasing of the windings is correct, the voltage applied to the primaries of the transmitter transformers can be brought up to the rated 115 volts by setting the toy-transformer tap switch on the right tap. If the phasing of the two windings of the toy transformer happens to be reversed, the voltage will be reduced instead of increased. This connection may be used in cases where the line voltage may be above 115 volts. This method is preferable to using a resistor in the primary of a power transformer since it does not affect the voltage regulation as seriously. The circuit of 5-2B illustrates the use of a variable autotransformer (Variac) for adjusting line voltage.

Constant-Voltage Transformers

Although comparatively expensive, special transformers called constant-voltage transformers are available for use in cases where it is necessary to hold line voltage and/or filament voltage constant with fluctuating supply-line voltage. These are static-magnetic voltage regulating transformers operating on principles of ferroresonance. They have no tubes or moving parts, and require no manual adjustments. These transformers are rated over a range of less than one VA at 5 volts output up to several thousand VA at 115 or 230 volts. On the average they will hold their output voltages within one percent under an input voltage variation of ±15 percent.

SAFETY PRECAUTIONS

All power supplies in an installation should be fed through a single main power-line switch so that all power may be cut off quickly, either before working on the equipment, or in case of an accident. Spring-operated switches or relays are not sufficiently reliable for this important service. Foolproof devices for cutting off all power to the transmitter and other equipment are shown in Fig. 5-3. The arrangements shown in Fig. 5-3A and B are similar circuits for two-wire (115-volt) and three-wire (230-volt) systems. S is an enclosed double-throw switch of the sort usually used as the entrance switch in house installations. J is a standard ac outlet and P a shorted plug to fit the outlet. The switch should be located prominently in plain sight, and members of the household should be instructed in its location and use. I is a red lamp located alongside the switch. Its purpose is not so much to serve as a warning that the power is on as it is to help in identifying and quickly

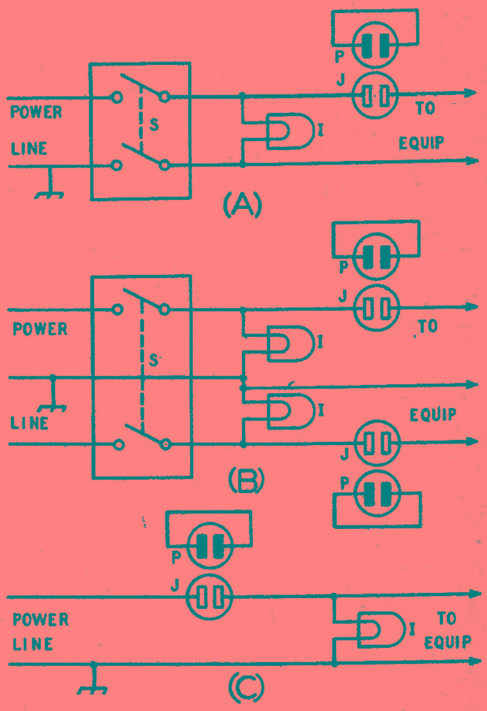


Fig. 5-3 — Reliable errangements for cutting off all power to the transmittar. S is an enclosed double-pole power switch, J a standard ac outlet, P a shorted plug to fit the outlet and I a red lamp.

A is for a two-wire 115-volt line, B for e three-wire 230-volt system, and C e simplified errangement for low-power stations.

locating the switch should it become necessary for someone else to cut the power off in an emergency.

The outlet J should be placed in some corner out of sight where it will not be a temptation for children or others to play with. The shorting plug can be removed to open the power circuit if there are others around who might inadvertently throw the switch while the operator is working on the rig. If the operator takes the plug with him, it will prevent someone from turning on the power in his absence and either hurting themselves or the equipment or perhaps starting a fire. Of utmost importance is the fact that the outlet J *must* be placed in the *ungrounded* side of the line.

Those who are operating low power and feel that the expense or complication of the switch isn't warranted can use the shorted-plug idea as the main power switch. In this case, the outlet should be located prominently and identified by a signal light, as shown in Fig. 5-3C.

The test bench should be fed through the main power switch, or a similar arrangement at the bench, if the bench is located remotely from the transmitter.

A bleeder resistor with a power rating which gives a considerable margin of safety should be used across the output of all transmitter power supplies, so that the filter capacitors will be discharged when the high-voltage is turned off.

PLATE AND FILAMENT TRANSFORMERS

Output Voltage

The output voltage which the plate transformer must deliver depends upon the required dc load voltage and the type of filter circuit.

With a choke-input filter (see Fig. 5-4), the required rms secondary voltage (each side of center-tap for a center-tap rectifier) can be calculated by the equation:

$$E_t = 1.1\ [E_o + I\,(R_1 + R_2 + R_s)]$$

where E_o is the required dc output voltage, I is the load current (including bleeder current) in amperes, R1 and R2 are the dc resistances of the chokes, and R_s is the series resistance (transformer and rectifier). E_t is the open-circuit rms voltage.

With a capacitive-input filter system, the approximate transformer output voltage required to give a desired dc output voltage with a given load can be calculated with the aid of Fig. 5-5.

Example:
Required dc output volts – 25
Load current to be drawn – 500 mA (0.5 ampere)
Input capacitor – 1000 μF

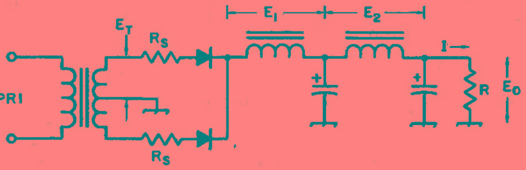


Fig. 5-4 — Diagram showing various voltage drops that must be taken into consideration in determining the required transformer voltage to deliver the desired output voltage.

Series resistance – 5 ohms
Load resistance = $\frac{25}{0.5}$ = 50 ohms
$RC = 50 \times 1000 = 50{,}000$
$R_s/R = 5/50 = 0.1$

Fig. 5-5 shows that the ratio of dc volts to the required transformer rms voltage is 1.07.

The required transformer terminal voltage under load is

$$E_{AC} = \frac{E_{DC} + I \times R_s}{1.07}$$

where I is the load current in amperes.

$$E_{AC} = \frac{25 + 0.5 \times 5}{1.07}$$

$$= \frac{27.5}{1.07} = 25.7 \text{ volts}$$

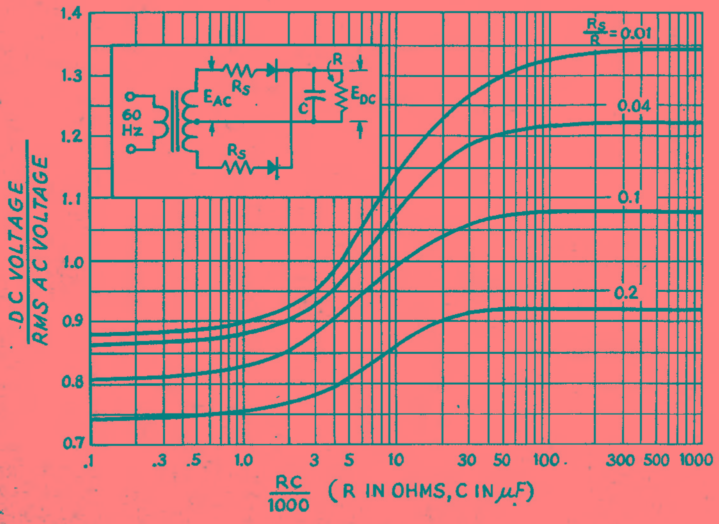


Fig. 5-5 — Dc output voltages from a full-wave rectifier circuit as a function of the filter capacitance and load resistance. R_s includes transformer winding resistance and rectifier forward resistance. For the retio R_s/R, both resistances are in ohms; for the RC product, R is in ohms and C is in μF.

The required transformer is one having a 51.4-V center-tapped secondary. A 50- or 55-V secondary would be entirely satisfactory. Should the filter section contain one or more filter chokes connected between the input capacitor and the load, the dc-resistance values of the chokes are added to the value of R_s in the equation before multiplying by the load-current value.

Volt-Ampere Rating

The number of volt-amperes delivered by a transformer depends upon the type of filter (capacitor or choke input) used, and upon the type of rectifier used (full-wave center tap, or full-wave bridge). With a capacitive-input filter the heating effect in the secondary is higher because of the high ratio of peak-to-average current. The volt-amperes handled by the transformer may be several times the watts delivered to the load. With a choke-input filter, provided the input choke has at least the critical inductance, the secondary volt-amperes can be calculated quite closely by the equation:

$$\text{(Full-wave ct)}\quad Sec.\ VA = \frac{.707\,EI}{1000}$$

$$\text{(Full-wave bridge)}\quad Sec.\ VA = \frac{EI}{1000}$$

where E is the *total* rms voltage of the secondary (between the outside ends in the case of a center-tapped winding) and I is the dc output current in milliamperes (load current plus bleeder current). The primary volt-amperes will be somewhat higher because of transformer losses.

BROADCAST & TELEVISION REPLACEMENT TRANSFORMERS

Small power transformers of the type sold for replacement in broadcast and television receivers are usually designed for service in terms of use for several hours continuously with capacitor-input filters. In the usual type of amateur transmitter service, where most of the power is drawn intermittently for periods of several minutes with equivalent intervals in between, the published ratings can be exceeded without excessive transformer heating.

With a capacitor-input filter, it should be safe to draw 20 to 30 percent more current than the rated value. With a choke-input filter, an increase in current of about 50 percent is permissible. If a bridge rectifier is used, the output voltage will be approximately doubled. In this case, it should be possible in amateur transmitter service to draw the rated current, thus obtaining about twice the rated output power from the transformer.

This does not apply, of course, to amateur transmitter plate transformers, which usually are already rated for intermittent service.

REWINDING POWER TRANSFORMERS

Although the home winding of power transformers is a task that few amateurs undertake, the rewinding of a transformer secondary to give some desired voltage for powering filaments or a solid-state device is not difficult. It involves a matter of only a small number of turns and the wire is large enough to be handled easily. Often a receiver power transformer with a burned-out high-voltage winding or the power transformer from a discarded TV set can be converted into an entirely satisfactory transformer without great effort and with little expense. The average TV power transformer for a 17-inch or larger set is capable of delivering from 350 to 450 watts, continuous duty. If an amateur transmitter is being powered, the service is not continuous, so the ratings can be increased by a factor of 40 or 50 percent without danger of overloading the transformer.

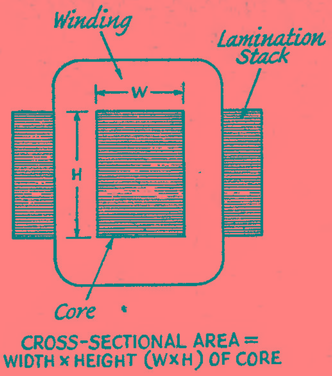


Fig. 5-6 — Cross-sectional drawing of a typical power transformer. Multiplying the height (or thickness of the laminations) times the width of the central core area in inches gives the value to be applied to Fig. 5-7.

The primary volt-ampere rating of the transformer to be rewound, if known, can be used to determine its power-handling capability. The secondary volt-ampere rating will be ten to twenty percent less than the primary rating. The power rating may also be determined approximately from the cross-sectional area of the core which is *inside* the windings. Fig. 5-6 shows the method of determining the area, and Fig. 5-7 may be used to convert this information into a power rating.

Before disconnecting the winding leads from their terminals, each should be marked for identification. In removing the core laminations, care should be taken to note the manner in which the core is assembled, so that the reassembling will be done in the same manner. Most transformers have secondaries wound over the primary, while in some the order is reversed. In case the secondaries are on the inside, the turns can be pulled out from the center after slitting and removing the fiber core.

The turns removed from one of the original filament windings of known voltage should be carefully counted as the winding is removed. This will give the number of turns per volt and the same figure should be used in determining the number of turns for the new secondary. For instance, if the

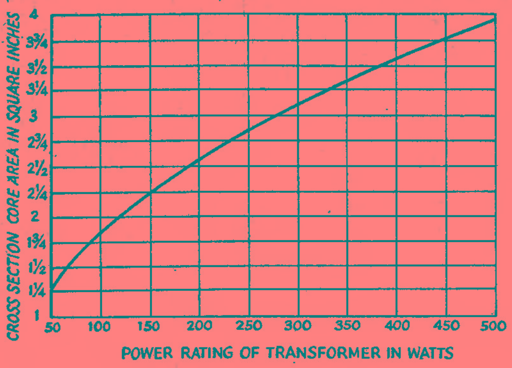


Fig. 5-7 — Power-handling capability of a transformer versus cross-sectional area of core.

old filament winding was rated at 5 volts and had 15 turns, this is 15/5 = 3 turns per volt. If the new secondary is to deliver 18 volts, the required number of turns on the new winding will be 18 X 3 = 54 turns.

In winding a transformer, the size of wire is an important factor in the heat developed in operation. A cross-sectional area of 1000 circular mils per ampere is conservative. A value commonly used in amateur-service transformers is 700 cmil/A. The larger the cmil/A figure, the cooler the transformer will run. The current rating in amperes of various wire sizes is shown in the copper-wire table in another chapter. If the transformer being rewound is a filament transformer, it may be necessary to choose the wire size carefully to fit the small available space. On the other hand, if the transformer is a power unit with the high-voltage winding removed, there should be plenty of room for a size of wire that will conservatively handle the required current.

After the first layer of turns is put on during rewinding, secure the ends with cellulose tape. Each layer should be insulated from the next; ordinary household waxed paper can be used for the purpose, a single layer being adequate. Sheets cut to size beforehand may be secured over each layer with tape. Be sure to bring all leads out the same side of the core so the covers will go in place when the unit is completed. When the last layer of the winding is put on, use two sheets of waxed paper, and then cover those with vinyl electrical tape, keeping the tape as taut as possible. This will add mechanical strength to the assembly.

The laminations and housing are assembled in just the opposite sequence to that followed in disassembly. Use a light coating of shellac between each lamination. During reassembly, the lamination stack may be compressed by clamping in a vise. If the last few lamination strips cannot be replaced, it is better to omit them than to force the unit together.

RECTIFIER CIRCUITS

Half-Wave Rectifier

Fig. 5-8 shows three rectifier circuits covering most of the common applications in amateur equipment. Fig. 5-8A is the circuit of a half-wave rectifier. The rectifier is a device that will conduct current in one direction but not in the other. During one half of the ac cycle the rectifier will conduct and current will flow through the rectifier to the load. During the other half of the cycle the rectifier does not conduct and no current flows to the load. The shape of the output wave is shown in (A) at the right. It shows that the current always flows in the same direction but that the flow of current is not continuous and is pulsating in amplitude.

The average output voltage – the voltage read by the usual dc voltmeter – with this circuit (no filter connected) is 0.45 times the rms value of the ac voltage delivered by the transformer secondary. Because the frequency of the pulses is relatively low (one pulsation per cycle), considerable filtering is required to provide adequately smooth dc output, and for this reason this circuit is usually limited to applications where the current involved is small, such as supplies for cathode-ray tubes and for protective bias in a transmitter.

The peak reverse voltage (PRV), the voltage the rectifier must withstand when it isn't conducting, varies with the load. With a resistive load it is the peak ac voltage (1.4 E_{RMS}) but with a capacitor load drawing little or no current it can rise to 2.8 E_{RMS}.

Another disadvantage of the half-wave rectifier circuit is that the transformer must have a considerably higher primary volt-ampere rating (approximately 40 percent greater), for the same dc power output, than in other rectifier circuits.

Full-Wave Center-Tap Rectifier

A commonly used rectifier circuit is shown in Fig. 5-8B. Essentially an arrangement in which the outputs of two half-wave rectifiers are combined, it makes use of both halves of the ac cycle. A transformer with a center-tapped secondary is required with the circuit.

The average output voltage is 0.9 times the rms voltage of half the transformer secondary; this is the maximum voltage that can be obtained with a suitable choke-input filter. The peak output voltage is 1.4 times the rms voltage of half the transformer secondary; this is the maximum voltage that can be obtained from a capacitor-input filter (at little or no load).

The peak reverse voltage across a rectifier unit is 2.8 times the rms voltage of half the transformer secondary.

As can be seen from the sketches of the output wave form in (B) to the right, the frequency of the output pulses is twice that of the half-wave rectifier. Therefore much less filtering is required.

Since the rectifiers work alternately, each handles half of the load current, and the load-current rating of each rectifier need be only half the total load current drawn from the supply.

Two separate transformers, with their primaries connected in parallel and secondaries connected in series (with the proper polarity) may be used in this circuit. However, if this substitution is made, the primary volt-ampere rating must be reduced to about 40 percent less than twice the rating of one transformer.

Full-Wave Bridge Rectifier

Another full-wave rectifier circuit is shown in Fig. 5-8C. In this arrangement, two rectifiers operate in series on each half of the cycle, one rectifier being in the lead to the load, the other being in the return lead. The current flows through two rectifiers during one half of the cycle and through the other two rectifiers during the other half of the cycle. The output wave shape (C), to the right, is the same as that from the simple center-tap rectifier circuit. The maximum output voltage into a resistive load or a properly designed choke-input filter is 0.9 times the rms voltage delivered by the transformer secondary; with a capacitor-input filter and a very light load the output voltage is 1.4 times the secondary rms voltage. The peak reverse voltage per rectifier is 1.4 times the secondary rms voltage. Each rectifier in a bridge circuit should have a minimum load-current rating of one-half the total load current to be drawn from the supply.

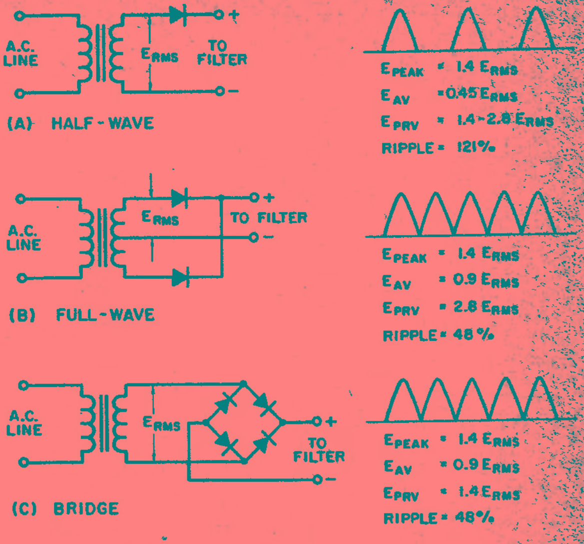


Fig. 5-8 — Fundamental rectifier circuits. A — Half-wave (E_{PRV} = 1.4 E_{RMS} with resistive load, = 2.8 E_{RMS} with capacitor-input filter). B — Full-wave. C — Full-wave bridge. Output voltage values do not include rectifier voltage drops.

RECTIFIER RATINGS

All rectifiers are subject to limitations as to breakdown voltage and current-handling capability. Some tube types are rated in terms of the maximum rms voltage that should be applied to the rectifier plate. This is sometimes dependent on whether a choke- or capacitive-input filter is used. Others, particularly mercury-vapor and semiconductor types, are rated according to maximum peak reverse voltage.

Rectifiers are rated also as to maximum dc load current, and some may carry peak-current ratings in addition. To assure normal life, all ratings should be carefully observed.

HIGH-VACUUM RECTIFIERS

High-vacuum rectifiers depend entirely upon the thermionic emission from a heated filament and are characterized by a relatively high internal resistance. For this reason, their application usually is limited to low power, although there are a few types designed for medium and high power in cases where the relatively high internal voltage drop may be tolerated. This high internal resistance makes them less susceptible to damage from temporary overload and they are free from the bothersome electrical noise sometimes associated with other types of rectifiers.

Some rectifiers of the high-vacuum full-wave type in the so-called receiver-tube class will handle up to 275 mA at 400- to 500-volts dc output. Those in the higher power class can be used to handle up to 500 mA at 2000 volts dc in full-wave circuits. Most low-power high-vacuum rectifiers are produced in the full-wave type, while those for greater power are invariably of the half-wave type, two tubes being required for a full-wave rectifier circuit. A few of the lower voltage types have indirectly heated cathodes, but are limited in heater-to-cathode voltage rating.

SEMICONDUCTOR RECTIFIERS

Silicon rectifiers are being used almost exclusively in power supplies for amateur equipment. Types are available to replace high-vacuum and mercury-vapor rectifiers. The semiconductors have the advantages of compactness, low internal voltage drop, low operating temperature and high current-handling capability. Also, no filament transformers are required.

Silicon rectifiers are available in a wide range of voltage and current ratings. In peak reverse voltage ratings of 600 or less, silicon rectifiers carry current ratings as high as 400 amperes, and at 1000 PRV the current ratings may be 1.5 amperes or so. The extreme compactness of silicon types makes feasible the stacking of several units in series for higher voltages. Standard stacks are available that will handle up to 10,000 PRV at a dc load current of 500 mA, although the amateur can do much better, economically, by stacking the rectifiers himself.

PROTECTION OF SILICON POWER DIODES

The important specifications of a silicon diode are:

1) PRV (or PIV), the peak reverse (or peak inverse) voltage,

2) I_o, the average dc current rating.

3) I_{REP}, the peak repetitive forward current, and

4) I_{SURGE}, the peak one-cycle surge current. The first two specifications appear in most catalogs. The last two often do not, but they are very important.

Since the rectifier never allows current to flow more than half the time, when it does conduct it has to pass at least twice the average direct current. With a capacitor-input filter, the rectifier conducts much less than half the time, so that when it does conduct, it may pass as much as ten to twenty times the average dc current, under certain conditions. This peak current is I_{REP}, the peak repetitive forward current.

Also, when the supply is first turned on, the discharged input capacitor looks like a dead short, and the rectifier passes a very heavy current. This is I_{SURGE}. The maximum I_{SURGE} rating is usually for a duration of one cycle (at 60 Hz), or about 16.7 milliseconds.

If a manufacturer's data sheet is not available, an educated guess about a diode's capability can be made by using these rules of thumb for silicon diodes of the type commonly used in amateur power supplies:

Rule 1) The maximum I_{REP} rating can be assumed to be approximately four times the maximum I_o rating.

Rule 2) The maximum I_{SURGE} rating can be assumed to be approximately twelve times the maximum I_o rating. (This should provide a reasonable safety factor. Silicon rectifiers with 750-mA dc ratings, as an example, seldom have 1-cycle surge ratings of less than 15 amperes; some are rated up to 35 amperes or more.) From this then, it can be seen that the rectifier should be selected on the basis of I_{SURGE} and not on I_o ratings.

Thermal Protection

The junction of a diode is quite small, hence it must operate at a high current density. The heat-handling capability is, therefore, quite small. Normally, this is not a prime consideration in high-voltage, low-current supplies. When using high-current rectifiers at or near their maximum ratings (usually 2-ampere or larger stud-mount rectifiers), some form of heat sinking is necessary. Frequently, mounting the rectifier on the main chassis – directly, or by means of thin mica insulating washers – will suffice. If insulated from the chassis, a thin layer of silicone grease should be used between the diode and the insulator, and between the insulator and the chassis to assure good heat conduction. Large high-current rectifiers often require special heat sinks to maintain a safe operating temperature. Forced-air cooling is sometimes used as a further aid. Safe case temperatures are usually given in the manufacturer's data sheets and should be observed if the maximum capabilities of the diode are to be realized.

Surge Protection

Each time the power supply is activated, assuming the input filter capacitor has been discharged, the rectifiers must look into what represents a dead short. Some form of surge protection is usually necessary to protect the diodes until the input capacitor becomes nearly charged. Although the dc resistance of the transformer secondary can be relied upon in some instances to provide ample surge-current limiting, it is seldom enough on high-voltage power supplies to be suitable. Series resistors can be installed between the secondary and the rectifier strings as illustrated in Fig. 5-4, but are a deterrent to good

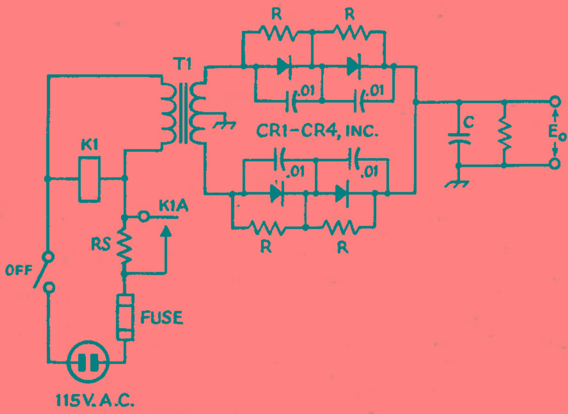


Fig. 5-9 – The primary circuit of T1 shows how a 115-volt ac relay and a series dropping resistor, R_S, can provide surge protection while C charges. When silicon rectifiers are connected in series for high-voltage operation, the inverse voltage does not divide equally. The reverse voltage drops can be equalized by using equalizing resistors, as shown in the secondary circuit. To protect against voltage "spikes" that may damage an individual rectifier, each rectifier should be bypassed by a .01-µF capacitor. Connected as shown, two 400-PRV silicon rectifiers can be used as an 800-PRV rectifier, although it is preferable to include a safety factor and call it a "750-PRV" rectifier. The rectifiers, CR1 through CR4, should be the same type (same type number and ratings).

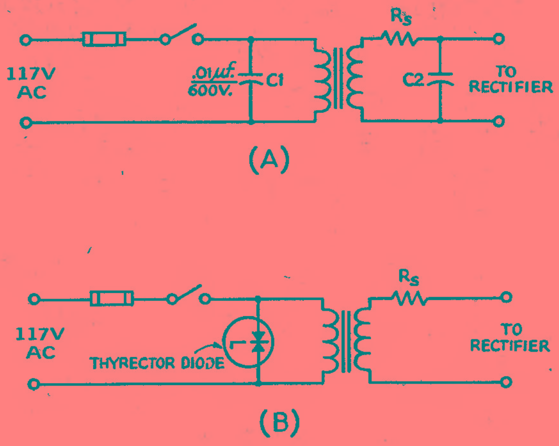


Fig. 5-10 — Methods of suppressing line transients. See text.

voltage regulation. By installing a surge-limiting device in the primary circuit of the plate transformer, the need for series resistors in the secondary circuit can be avoided. A practical method for primary-circuit surge control is shown in Fig. 5-9. The resistor, R_s introduces a voltage drop in the primary feed to T1 until C is nearly charged. Then, after C becomes partially charged, the voltage drop across R_s lessens and allows K1 to pull in, thus applying full primary power to T1 as K1A shorts out R_s.R_s is usually a 25-watt resistor whose resistance is somewhere between 15 and 50 ohms, depending upon the power supply characteristics.

Transient Problems

A common cause of trouble is transient voltages on the ac power line. These are short spikes, mostly, that can temporarily increase the voltage seen by the rectifier to values much higher than the normal transformer voltage. They come from distant lightning strokes, electric motors turning on and off, and so on. Transients cause unexpected, and often unexplained, loss of silicon rectifiers.

It's always wise to suppress line transients, and it can be easily done. Fig. 5-10A shows one way. C1 looks like 280,000 ohms at 60 Hz, but to a sharp transient (which has only high-frequency components), it is an effective bypass. C2 provides additional protection on the secondary side of the transformer. It should be .01μF for transformer voltages of 100 or less, and .001μF for high-voltage transformers.

Fig. 5-10B shows another transient-suppression method using selenium suppressor diodes. The diodes do not conduct unless the peak voltage becomes abnormally high. Then they clip the transient peaks. General Electric sells protective diodes under the trade name, "Thyrector." Sarkes-Tarzian uses the descriptive name, "Klip-volt."

Transient voltages can go as high as twice the normal line voltage before the suppressor diodes clip the peaks. Capacitors cannot give perfect suppression either. Thus, it is a good idea to use power-supply rectifiers rated at about twice the expected PRV.

Diodes in Series

Where the PRV rating of a single diode is not sufficient for the application, similar diodes may be used in series. (Two 500-PRV diodes in series will withstand 1000 PRV, and so on.) When this is done, a resistor and a capacitor should be placed across each diode in the string to equalize the PRV drops and to guard against transient voltage spikes, as shown in Fig. 5-9. Even though the diodes are of the same type and have the same PRV rating, they may have widely different back resistances when they are cut off. The reverse voltage divides according to Ohm's Law, and the diode with the higher back resistance will have the higher voltage developed across it. The diode may break down.

If we put a swamping resistor across each diode, R as shown in Fig. 5-9, the resultant resistance across each diode will be almost the same, and the back voltage will divide almost equally. A good rule of thumb for resistor size is this: Multiply the PRV rating of the diode by 500 ohms. For example, a 500-PRV diode should be shunted by 500 X 500, or 250,000 ohms.

The shift from forward conduction to high back resistance does not take place instantly in a silicon diode. Some diodes take longer than others to develop high back resistance. To protect the "fast" diodes in a series string until all the diodes are properly cut off, a .01-μF capacitor should be placed across each diode. Fig. 5-9 shows the complete series-diode circuit. The capacitors should be noninductive, ceramic disk, for example, and should be well matched. Use 10-percent-tolerance capacitors if possible.

Diodes in Parallel

Diodes can be placed in parallel to increase current-handling capability. Equalizing resistors should be added as shown in Fig. 5-11. Without the resistors, one diode may take most of the current. The resistors should be selected to have about a 1-volt drop at the expected peak current.

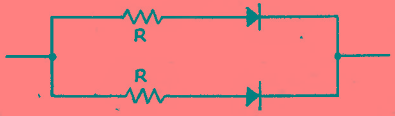


Fig. 5-11 — Diodes in parallel should have equalizing resistors. See text for appropriate value.

FILTERING

The pulsating dc waves from the rectifiers are not sufficiently constant in amplitude to prevent hum corresponding to the pulsations. Filters are required between the rectifier and the load to smooth out the pulsations into an essentially constant dc voltage. Also, upon the design of the filter depends to a large extent the dc voltage output, the voltage regulation of the power supply, and the maximum load current that can be drawn from the supply without exceeding the peak-current rating of the rectifier. Power supply filters are low-pass devices using series inductors and shunt capacitors.

Load Resistance

In discussing the performance of power-supply filters, it is sometimes convenient to express the load connected to the output terminals of the supply in terms of resistance. The load resistance is equal to the output voltage divided by the total current drawn, including the current drawn by the bleeder resistor.

Voltage Regulation

The output voltage of a power supply always decreases as more current is drawn, not only because of increased voltage drops on the transformer, filter chokes and the rectifier (if high-vacuum rectifiers are used) but also because the output voltage at light loads tends to soar to the peak value of the transformer voltage as a result of charging the first capacitor. By proper filter design the latter effect can be eliminated. The change in output voltage with load is called *voltage regulation* and is expressed as a percentage.

$$\text{Percent regulation} = \frac{100\,(E1 - E2)}{E2}$$

Example: No-load voltage = E1 = 1550 volts.
Full-load voltage = E2 = 1230 volts.

$$\text{Percentage regulation} = \frac{100\,(1550 - 1230)}{1230}$$

$$= \frac{32{,}000}{1230} = 26 \text{ percent}$$

A steady load, such as that represented by a receiver, speech amplifier or unkeyed stages of a transmitter, does not require good (low) regulation as long as the proper voltage is obtained under load conditions. However, the filter capacitors must have a voltage rating safe for the highest value to which the voltage will soar when the external load is removed.

A power supply will show more (higher) regulation with long-term changes in load resistance than with short temporary changes. The regulation with long-term changes is often called the static regulation, to distinguish it from the dynamic regulation (short temporary load changes). A load that varies at a syllabic or keyed rated, as represented by some audio and rf amplifiers, usually requires good dynamic regulation (15 percent or less) if distortion products are to be held to a low level. The dynamic regulation of a power supply is improved by increasing the value of the output capacitor.

When essentially constant voltage regardless of current variation is required (for stabilizing an oscillator, for example), special voltage-regulating circuits described elsewhere in this chapter are used.

Bleeder

A bleeder resistor is a resistance connected across the output terminals of the power supply. Its functions are to discharge the filter capacitors as a safety measure when the power is turned off and to improve voltage regulation by providing a minimum load resistance. When voltage regulation is not of importance, the resistance may be as high as 100 ohms per volt. The resistance value to be used for voltage-regulating purposes is discussed in later sections. From the consideration of safety, the power rating of the resistor should be as conservative as possible, since a burned-out bleeder resistor is more dangerous than none at all!

Ripple Frequency and Voltage

The pulsations in the output of the rectifier can be considered to be the resultant of an alternating current superimposed upon a steady direct current. From this viewpoint, the filter may be considered to consist of shunting capacitors which short-circuit the ac component while not interfering with the flow of the dc component, and series chokes which pass dc readily but which impede the flow of the ac component.

The alternating component is called the ripple. The effectiveness of the filter can be expressed in terms of percent ripple, which is the ratio of the rms value of the ripple to the dc value in terms of percentage. Any multiplier or amplifier supply in a code transmitter should have less than 5 percent ripple. A linear amplifier can tolerate about 3 percent ripple on the plate voltage. Bias supplies for linear amplifiers, and modulator and modulated-amplifier plate supplies, should have less than 1 percent ripple. VFOs, speech amplifiers and receivers may require a ripple reduction to .01 percent.

Ripple frequency is the frequency of the pulsations in the rectifier output wave – the number of pulsations per second. The frequency of the ripple with half-wave rectifiers is the same as the frequency of the line supply – 60 Hz with 60-Hz supply. Since the output pulses are doubled with a full-wave rectifier, the ripple frequency is doubled – to 120 Hz with a 60-Hz supply.

The amount of filtering (values of inductance and capacitance) required to give adequate smoothing depends upon the ripple frequency, with more filtering being required as the ripple frequency is lowered.

Type of Filter

Power-supply filters fall into two classifications, capacitor input and choke input. Capacitor-input filters are characterized by relatively high output voltage in respect to the transformer voltage. Advantage of this can be taken when silicon rectifiers are used or with any rectifier when the load resistance is high. Silicon rectifiers have a higher allowable peak-to-dc ratio than do thermionic rectifiers. This permits the use of capacitor-input filters at ratios of input capacitor to load resistance that would seriously shorten the life of a thermionic rectifier system. When the series resistance through a rectifier and filter system is appreciable, as when high-vacuum rectifiers are used, the voltage regulation of a capacitor-input power supply is poor.

The output voltage of a properly designed choke-input power supply is less than would be obtained with a capacitor-input filter from the same transformer.

CAPACITIVE-INPUT FILTERS

Capacitive-input filter systems are shown in Fig. 5-12. Disregarding voltage drops in the chokes, all have the same characteristics except in respect to ripple. Better ripple reduction will be obtained when LC sections are added, as shown in Figs. 5-12B and C.

Output Voltage

To determine the approximate dc voltage output when a capacitive-input filter is used, reference should be made to the graph of Fig. 5-5.

Example:

Transformer rms voltage – 350
Load resistance – 2000 ohms

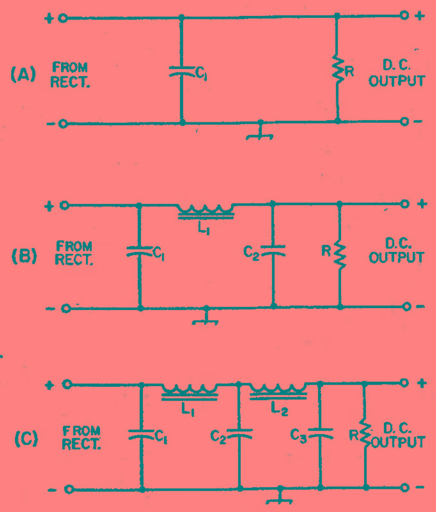


Fig. 5-12 — Capacitive-input filter circuits. A — Simple capacitive. B — Single-section. C — Double-section.

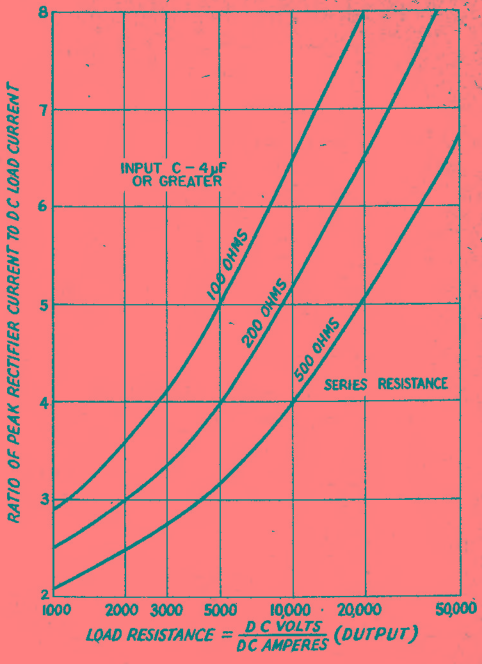


Fig. 5-13 — Graph showing the ralationship between the dc load current and the rectifier peak current with capacitive input for various values of load and input resistance.

Series resistance – 200 ohms
200 ÷ 2000 = 0.1
Input capacitor $C = 20\ \mu F$

$$\frac{RC}{1000} = \frac{2000 \times 20}{1000} = 40$$

From curve 0.1 and $RC = 40$, dc voltage = 350 × 1.06 = 370.

Regulation

If a bleeder resistance of 20,000 ohms is used in the example above, when the load is removed and R becomes 20,000, the dc voltage will rise to 470. For minimum regulation with a capacitor-input filter, the bleeder resistance should be as high as possible, or the series resistance should be low and the filter capacitance high, without exceeding the transformer or rectifier ratings.

Maximum Rectifier Current

The maximum current that can be drawn from a supply with a capacitive-input filter without exceeding the peak-current rating of the rectifier may be estimated from the graph of Fig. 5-13. Using values from the preceding example, the ratio of peak rectifier current to dc load current for 2000 ohms, as shown in Fig. 5-13, is 3. Therefore, the maximum load current that can be drawn without exceeding the rectifier rating is 1/3 the peak rating of the rectifier. For a load current of 185 mA, as above (370 V ÷ 2000 Ω), the rectifier peak current rating should be at least 3 × 185 = 555 mA.

With bleeder current only, Fig. 5-13 shows that the ratio will increase to 6.5. But since the bleeder draws 23.5 mA dc, the rectifier peak current will be only 153 mA.

CHOKE-INPUT FILTERS

With thermionic rectifiers better voltage regulations results when a choke-input filter, as shown in Fig. 5-4, is used. Choke input permits better utilization of the thermionic rectifier, since a higher load current usually can be drawn without exceeding the peak current rating of the rectifier.

Minimum Choke Inductance

A choke-input filter will tend to act as a capacitive-input filter unless the input choke has at least a certain minimum value of inductance called the critical value. This critical value is given by

$$L_{\text{crit}}\ (\text{henrys}) = \frac{E\ (\text{volts})}{I\ (\text{mA})}$$

where E is the output voltage of the supply, and I is the current being drawn through the filter.

If the choke has at least the critical value, the output voltage will be limited to the average value of the rectified wave at the input to the choke (see Fig. 5-8) when the current drawn from the supply is small. This is in contrast to the capacitive-input filter in which the output voltage tends to soar toward the peak value of the rectified wave at light loads.

Minimum-Load – Bleeder Resistance

From the formula above for critical inductance, it is obvious that if no current is drawn from the supply, the critical inductance will be infinite. So that a practical value of inductance may be used, some current must be drawn from the supply at all times the supply is in use. From the formula we find that this minimum value of current is

$$I\ (\text{mA}) = \frac{E\ (\text{volts})}{L_{\text{crit}}}$$

In the majority of cases it will be most convenient to adjust the bleeder resistance so that the bleeder will draw the required minimum current. From the formula, it may be seen that the value of critical inductance becomes smaller as the load current increases.

Swinging Chokes

Less costly chokes are available that will maintain at least the critical value of inductance over the range of current likely to be drawn from practical supplies. These chokes are called swinging chokes. As an example, a swinging choke may have an inductance rating of 5/25 H and a current rating of 200 mA. If the supply delivers 1000 volts, the minimum load current should be 1000/25 = 40 mA. When the full load current of 200 mA is drawn from the supply, the inductance will drop to 5 H. The critical inductance for 200 mA at 1000 volts is 1000/200 = 5 H. Therefore the 5/25 H choke maintains the critical inductance at the full current rating of 200 mA. At all load currents between 40 mA and 200 mA, the choke will adjust its inductance to the approximate critical value.

Output Voltage

Provided the input-choke inductance is at least the critical value, the output voltage may be calculated quite close by the following equation:

$$E_o = 0.9E_t - (I_B + I_L)(R1 + R2) - E_r$$

where E_o is the output voltage; E_t is the rms voltage applied to the rectifier (rms voltage between center-tap and one end of the secondary in the case of the center-tap rectifier); I_B and I_L are the bleeder and load currents, respectively, in amperes; R_1 and R_2 are the resistances of the first and second filter chokes; and E_r is the voltage drop across the rectifier. The various voltage drops are shown in Fig. 5-4. At no load I_L is zero; hence the no-load voltage may be calculated on the basis of bleeder current only. The voltage regulation may be determined from the no-load and full-load voltages using the formula previously given.

OUTPUT CAPACITOR

Whether the supply has a choke- or capacitor-input filter, if it is intended for use with a Class A af amplifier, the reactance of the output capacitor should be low for the lowest audio frequency; 16 μF or more is usually adequate. When the supply is used with a Class B amplifier (for modulation or for ssb amplification) or a cw transmitter, increasing the output capacitance will result in improved dynamic regulation of the supply. However, a region of diminishing returns can be reached, and 20 to 30 μF will usually suffice for any supply subjected to large changes at a syllabic (or keying) rate.

RESONANCE

Resonance effects in the series circuit across the output of the rectifier, formed by the first choke and first filter capacitor, must be avoided, since the ripple voltage would build up to large values. This not only is the opposite action to that for which the filter is intended, but may also cause excessive rectifier peak currents and abnormally high peak-reverse voltages. For full-wave rectification the ripple frequency will be 120 Hz for a 60-Hz supply, and resonance will occur when the product of choke inductance in henrys times capacitor capacitance in microfarads is equal to 1.77. At least twice this product of inductance and capacitance should be used to ensure against resonance effects. With a swinging choke, the minimum rated inductance of the choke should be used.

RATINGS OF FILTER COMPONENTS

In a power supply using a choke-input filter and properly designed choke and bleeder resistor, the no-load voltage across the filter capacitors will be about nine-tenths of the ac rms voltage. Nevertheless, it is advisable to use capacitors rated for the *peak* transformer voltage. This large safety factor is suggested because the voltage across the capacitors can reach this peak value if the bleeder should burn out and there is no load on the supply.

In a capacitive-input filter, the capacitors should have a working-voltage rating at least as high, and preferably somewhat higher, than the peak voltage from the transformer. Thus, in the case of a center-tap rectifier having a transformer delivering 550 volts each side of the center tap, the minimum safe capacitor voltage rating will be 550 X 1.41 or 775 volts. An 800-volt capacitor should be used, or preferably a 1000-volt unit.

Filter Capacitors in Series

Filter capacitors are made in several different types. Electrolytic capacitors, which are available for peak voltages up to about 800, combine high capacitance with small size, since the dielectric is an extremely thin film of oxide on aluminum foil. Capacitors of this type may be connected in series for higher voltages, although the filtering capacitance will be reduced to the resultant of the two capacitances in series. If this arrangement is used, it is important that *each* of the capacitors be shunted with a resistor of about 100 ohms per volt of supply voltage applied to the individual capacitors, with an adequate power rating. These resistors may serve as all or part of the bleeder resistance. Capacitors with higher voltage ratings usually are made with a dielectric of thin paper impregnated with oil. The working voltage of a capacitor is the voltage that it will withstand continuously.

Filter Chokes

Filter chokes or inductances are wound on iron cores, with a small gap in the core to prevent magnetic saturation of the iron at high currents. When the iron becomes saturated its permeability decreases, and consequently the inductance also decreases. Despite the air gap, the inductance of a choke usually varies to some extent with the direct current flowing in the winding; hence it is necessary to specify the inductance at the current which the choke is intended to carry. Its inductance with little or no direct current flowing in the winding will usually be considerably higher than the value when full load current is flowing.

NEGATIVE-LEAD FILTERING

For many years it has been almost universal practice to place filter chokes in the positive leads of plate power supplies. This means that the insulation between the choke winding and its core (which should be grounded to chassis as a safety measure) must be adequate to withstand the output voltage of the supply. This voltage requirement is removed if the chokes are placed in the negative lead as shown in Fig. 5-14. With this connection, the capacitance of the transformer secondary to ground appears in parallel with the filter chokes tending to bypass the chokes. However, this effect will be negligible in practical application except in cases where the output ripple must be reduced to a very low figure. Such applications are usually limited to low-voltage devices such as receivers, speech amplifiers and VFOs where insulation is no problem and the chokes may be placed in the positive side in the conventional manner. In higher voltage applications, there is no reason why the filter chokes should not be placed in the negative lead to reduce insulation requirements. Choke terminals, negative capacitor terminals and the transformer center-tap terminal should be well protected against accidental contact, since these will assume full supply voltage to chassis should a choke burn out or the chassis connection fail.

THE "ECONOMY" POWER SUPPLY

In many transmitters of the 100-watt class, an excellent method for obtaining plate and screen voltages without wasting power in resistors is by the use of the "economy" power-supply circuit. Shown in Fig. 5-15, it is a combination of the full-wave and bridge-rectifier circuits. The voltage at E1 is the normal voltage obtained with the full-wave circuit, and the voltage at E2 is that obtained with the bridge circuit (see Fig. 5-8). The *total* dc power obtained from the transformer is, of course, the same as when the transformer is used in its normal manner. In cw and ssb applications, additional power can usually be drawn without excessive heating, especially if the transformer has a rectifier filament winding that isn't being used.

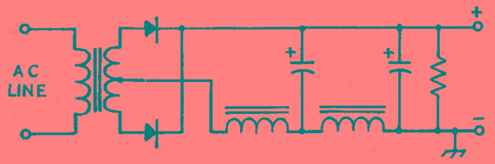


Fig. 5-14 — In most applications, the filter chokes may be placed in the negative instead of the positive side of the circuit. This reduces the danger of a voltage breakdown between the choke winding and core.

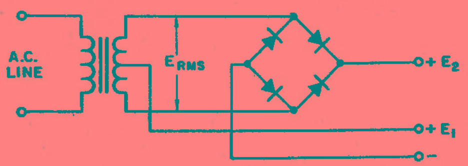


Fig. 5-15 — The "economy" power supply circuit is a combination of the full-wave and bridge-rectifier circuits.

VOLTAGE-MULTIPLYING CIRCUITS

Although vacuum-tube rectifiers can be used in voltage-multiplying circuits, semiconductor rectifiers are recommended.

A simple half-wave rectifier circuit is shown in Fig. 5-16. Strictiy speaking this is not a voltage-multiplying circuit. However, if the current demand is low (a milliampere or less), the dc output voltage will be close to the peak voltage of the source, or $1.4E_{rms}$. A typical application of the circuit would be to obtain a low bias voltage from a heater winding; the + side of the output can be grounded by reversing the polarity of the rectifier and capacitor. As with all half-wave rectifiers, the output voltage drops quickly with increased current demand.

The resistor R1 in Fig. 5-16 is included to limit the current through the rectifier, in accordance with the manufacturer's rating for the diode. If the resistance of the transformer winding is sufficient, R1 can be omitted.

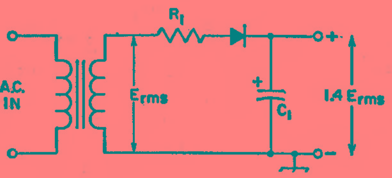


Fig. 5-16 — If the current demand is low, a simple half-wave rectifier will deliver a voltage increase. Typical values, for E_{RMS} = 117 and a load current of 1 mA:
C1 — 50-μF, 250-V electrolytic.
E_{output} — 160 volts.
R1 — 22 ohms.

VOLTAGE DOUBLERS

Several types of voltage-doubling circuits are in common use. Where it is not necessary that one side of the transformer secondary be at ground potential, the voltage-doubling circuit of Fig. 5-17 is used. This circuit has several advantages over the voltage-doubling circuit to be described later. For a given output voltage, compared to the full-wave rectifier circuit (Fig. 5-8B), this full-wave doubler circuit requires rectifiers having only half the PRV rating. Again for a given output voltage, compared to a full-wave bridge circuit (Fig. 5-8C) only half as many rectifiers (of the same PRV rating) are required.

Resistors R1 in Fig. 5-17 are used to limit the surge currents through the rectifiers. Their values are based on the transformer voltage and the rectifier surge-current rating, since at the instant the power supply is turned on the filter capacitors look like a short-circuited load. Provided the limiting resistors can withstand the surge current, their current-handling capacity is based on the maximum load current from the supply.

Output voltages approaching twice the peak voltage of the transformer can be obtained with the voltage-doubling circuit of Fig. 5-17. Fig. 5-18 shows how the voltage depends upon the ratio of the series resistance to the load resistance, and the product of the load resistance times the filter capacitance.

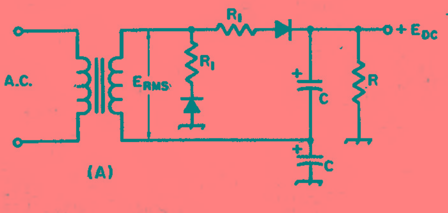
When one side of the transformer secondary must be at ground potential, as when the ac is derived from a heater winding, the voltage-multiplying circuits of Fig. 5-19 can be used. In the voltage-doubling circuit at A, C1 charges through the left-hand rectifier during one half of the ac cyle; the other rectifier is nonconductive during this time. During the other half of the cycle the right-hand rectifier conducts and C2 becomes charged; they see as the source the transformer plus the voltage in C1. By reversing the polarities of the capacitors and rectifiers, the + side of the output can be grounded.

VOLTAGE TRIPLING AND QUADRUPLING

A voltage-tripling circuit is shown in Fig. 5-19B. On one half of the ac cycle C1 is charged to the source voltage through the left-hand rectifier. On the opposite half of the cycle the middle rectifier conducts and C2 is charged to twice the source voltage, because it sees the transformer plus the charge in C1 as its source. (The left-hand rectifier is cut off on this half cycle.) At the same time the right-hand rectifier conducts and, with the transformer and the charge in C2 as the source, C3 is charged to three times the transformer voltage. The + side of the output can be grounded if the polarities of all of the capacitors and rectifiers are reversed.

The voltage-quadrupling circuit of Fig. 5-19C works in substantially similar fashion.

In any of the circuits of Fig. 5-19, the output voltage will approach an exact multiple (2, 3 or 4, depending upon the circuit) of the peak ac voltage when the output current drain is low and the capacitance values are high.



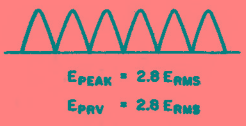


Fig. 5-17 — Full-wave voltage-doubling circuit. Values of limiting resistors, R1, depend upon allowable surge currents of rectifiers.

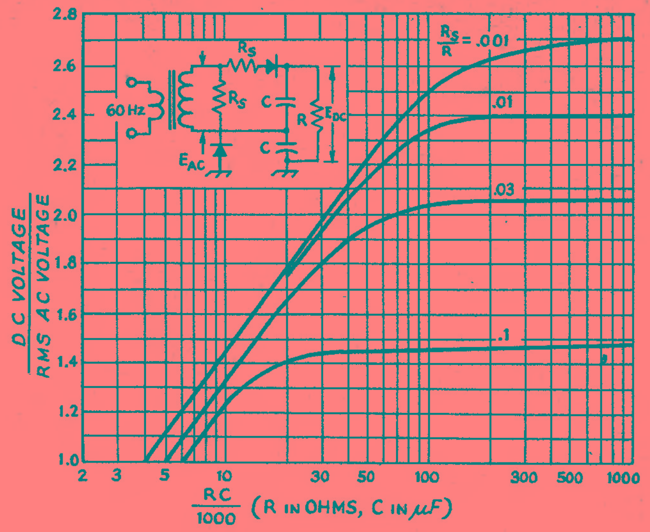


Fig. 5-18 — Dc output voltages from a full-wave voltage-doubling circuit as a function of the filter capacitances and load resistance. For the ratio R_s/R and for the RC product, resistances are in ohms and capacitance is in microfareds. Equal resistance values for R_s and equal capacitance values for C are assumed.

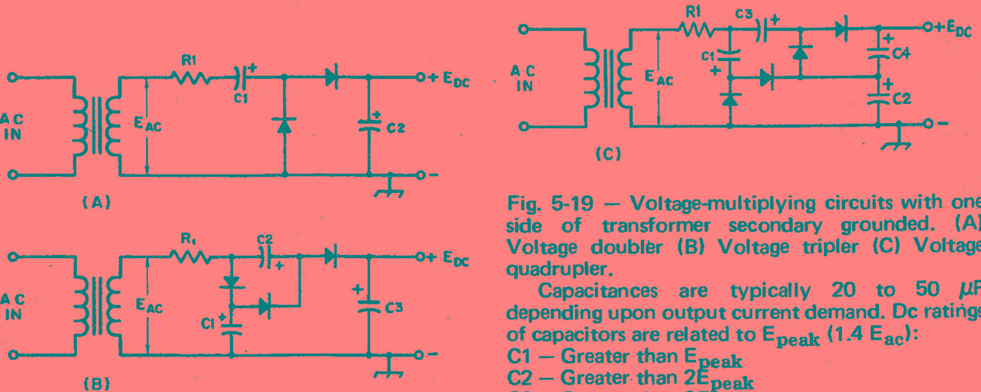


Fig. 5-19 — Voltage-multiplying circuits with one side of transformer secondary grounded. (A) Voltage doubler (B) Voltage tripler (C) Voltage quadrupler.

Capacitances are typically 20 to 50 µF depending upon output current demand. Dc ratings of capacitors are related to E_{peak} (1.4 E_{ac}):

C1 — Greater than E_{peak}
C2 — Greater than $2E_{peak}$
C3 — Greater than $3E_{peak}$
C4 — Greater than $4E_{peak}$

VOLTAGE DROPPING

Series Voltage-Dropping Resistor

Certain plates and screens of the various tubes in a transmitter or receiver often require a variety of operating voltages differing from the output voltage of an available power supply. In most cases, it is not economically feasible to provide a separate power supply for each of the required voltages. If the current drawn by an electrode (or combination of electrodes operating at the same voltage) is reasonably constant under normal operating conditions, the required voltage may be obtained from a supply of higher voltage by means of a voltage-dropping resistor in series, as shown in Fig. 5-20A. The value of the series, resistor, R1, may be obtained from Ohm's Law,

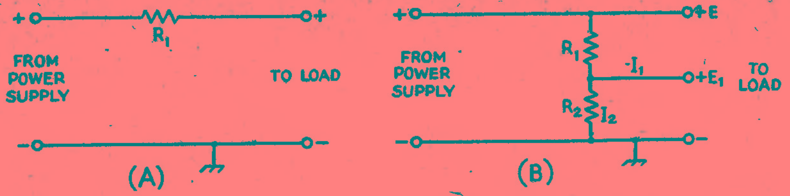
$$R = \frac{E_d}{I}$$

where E_d is the voltage *drop* required from the supply voltage to the desired voltage and I is the total rated current of the load.

Example: The plate of the tube in one stage and the screens of the tubes in two other stages require an operating voltage of 250. The nearest available supply voltage is 400 and the total of the rated plate and screen currents is 75 mA. The required resistance is

$$R = \frac{400 - 250}{.075} = \frac{150}{.075} = 2000 \text{ ohms}$$

The power rating of the resistur is obtained from P (watts) = I^2R = $(0.075)^2 \times (2000)$ = 11.2 watts. A 20-watt resistor is the nearest safe rating to be used.



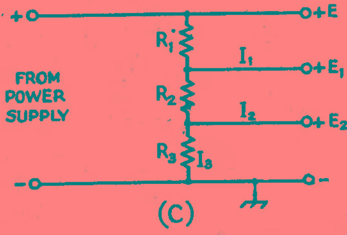


Fig. 5–20 — A — Series voltage-dropping resistor. B — Simple voltage divider.

$$R2 = \frac{E1}{I2}\,;\; R1 = \frac{E - E1}{I1 + I2}$$

$I2$ must be assumed.

C — Multiple divider circuit.

$$R3 = \frac{E2}{I3};\; R2 = \frac{E1 - E2}{I2 + I3};\; R1 = \frac{E - E1}{I1 + I2 + I3}$$

$I3$ must be assumed.

Voltage Dividers

The regulation of the voltage obtained in this manner obviously is poor, since any change in current through the resistor will cause a directly proportional change in the voltage drop across the resistor. The regulation can be improved somewhat by connecting a second resistor from the low-voltage end of the first to the negative power-supply terminal, as shown in Fig. 5-20B. Such an arrangement constitutes a voltage divider. The second resistor, R2, acts as a constant load for the first, R1, so that any variation in current from the tap becomes a smaller percentage of the total current through R1. The heavier the current drawn by the resistors when they alone are connected across the supply, the better will be the voltage regulation at the tap.

Such a voltage divider may have more than a single tap for the purpose of obtaining more than one value of voltage. A typical arrangement is shown in Fig. 5-20C. The terminal voltage is E, and two taps are provided to give lower voltages, E1 and E2, at currents I1 and I2 respectively. The smaller the resistance between taps in proportion to the total resistance, the lower is the voltage between the taps. The voltage divider in the figure is made up of separate resistances, R1, R2 and R3. R3 carries only the bleeder current, I3; R2 carries I2 in addition to I3; R1 carries I1, I2 and I3. To calculate the resistances required, a bleeder current, I3, must be assumed; generally it is low compared with the total load current (10 percent or so). Then the required values can be calculated as shown in the caption of Fig. 5-20, I being in decimal parts of an ampere.

The method may be extended to any desired number of taps, each resistance section being calculated by Ohm's Law using the needed voltage drop across it and the total current through it. The power dissipated by each section may be calculated by multiplying I and E or I^2 and R.

VOLTAGE STABILIZATION

Gaseous Regulator Tubes

There is frequent need for maintaining the voltage applied to a low-voltage low-current circuit at a practically constant value, regardless of the voltage regulation of the power supply or variations in load current. In such applications, gaseous regulator tubes (0B2/VR105, 0A2/VR150, etc.) can be used to good advantage. The voltage drop across such tubes is constant over a moderately wide current range. Tubes are available for regulated voltages near 150, 105, 90 and 75 volts.

The fundamental circuit for a gaseous regulator is shown in Fig. 5-21. The tube is connected in series with a limiting resistor, R1, across a source of voltage that must be higher than the starting voltage. The starting voltage is about 30 to 40 percent higher than the operating voltage. The load is connected in parallel with the tube. For stable operation, a minimum tube current of 5 to 10 mA is required. The maximum permissible current with most types is 40 mA; consequently, the load current cannot exceed 30 to 35 mA if the voltage is to be stabilized over a range from zero to maximum load. A single VR tube may also be used to regulate the voltage to a load current of almost any value as long as the *variation* in the current does not exceed 30 to 35 mA. If, for example, the average load current is 100 mA, a VR tube may be used to hold the voltage constant provided the current does not fall below 85 mA or rise above 115 mA.

The value of the limiting resistor must lie between that which just permits minimum tube current to flow and that which just passes the maximum permissible tube current when there is no load current. The latter value is generally used. It is given by the equation:

$$R = \frac{(E_S - E_r)}{I}$$

where R is the limiting resistance in ohms, E_S is the voltage of the source across which the tube and resistor are connected, E_r is the rated voltage drop across the regulator tube, and I is the maximum tube current in amperes (usually 40 mA, or .04 A).

Two tubes may be used in series to give a higher regulated voltage than is obtainable with one, and also to give two values of regulated voltage. Regulation of the order of 1 percent can be obtained with these regulator tubes when they are operated within their proper current range. The capacitance in shunt with a VR tube should be limited to 0.1 μF or less. Larger values may cause the tube drop to oscillate between the operating and starting voltages.

ZENER DIODE REGULATION

A Zener diode (named after Dr. Carl Zener) can be used to stabilize a voltage source in much the same way as when the gaseous regulator tube is used. The typical circuit is shown in Fig. 5-22A. Note that the cathode side of the diode is connected to the positive side of the supply. The electrical characteristics of a Zener diode under conditions of forward and reverse voltage are given in Chapter 4.

Zener diodes are available in a wide variety of voltages and power ratings. The voltages range from less than 2 to a few hundred, while the power ratings (power the diode can dissipate) run from less than 0.25 watt to 50 watts. The ability of the Zener diode to stabilize a voltage is dependent upon the conducting impedance of the diode, which can be as low as one ohm or less in a low-voltage high-power diode to as high as a thousand ohms in a low-power high-voltage diode.

Diode Power Dissipation

Unlike gaseous regulator tubes, Zener diodes of a particular voltage rating have varied maximum current capabilities, depending upon the power ratings of each of the diodes. The power dissipated in a diode is the product of the voltage across it and the current through it. Conversely, the maximum current a particular diode may safely conduct equals its power rating divided by its voltage rating. Thus, a 10-V 50-W Zener diode, if operated at its maximum dissipation rating, would conduct 5 amperes of current. A 10-V 1-W diode, on the other hand, could safely conduct no more than 0.1 A, or 100 mA. The conducting impedance of a diode is its voltage rating divided by the current flowing through it, and in the above examples would be 2 ohms for the 50-W diode, and 100 ohms for the 1-W diode. Disregarding small voltage changes which may occur, the conducting impedance of a given diode is a function of the current flowing through it, varying in inverse proportion.

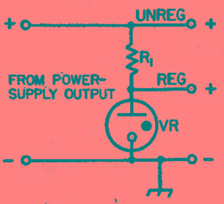


Fig. 5-21 — Voltage stabilization circuit using a VR tube. A negative-supply output may be regulated by reversing the polarity of the power-supply connections and the VR-tube connections from those shown here.

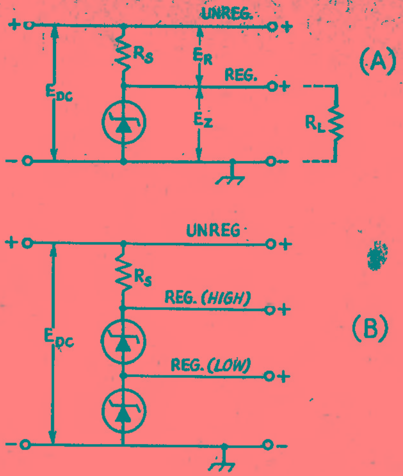


Fig. 5-22 — Zener-diode voltage regulation. The voltage from a negetive supply may be regulated by reversing the power-supply connections and the diode polarities.

The power-handling capability of most Zener diodes is rated at 25 degrees C, or approximately room temperature. If the diode is operated in a higher ambient temperature, its power capability must be derated. A typical 1-watt diode can safely dissipate only 1/2 watt at 100 degrees C.

Limiting Resistance

The value of R_S in Fig. 5-22 is determined by the load requirements. If R_S is too large the diode will be unable to regulate at large values of I_L, the current through R_L. If R_S is too small, the diode dissipation rating may be exceeded at low values of I_L. The optimum value for R_S can be calculated by:

$$R_S = \frac{E_{DC}\,(\text{min}) - E_Z}{1.1\, I_L\,(\text{max})}$$

When R_S is known, the maximum dissipation of the diode, P_D, may be determined by:

$$P_D = \left[\frac{E_{DC}\,(\text{max}) - E_Z}{R_S} - I_L\,(\text{min})\right] E_Z$$

In the first equation, conditions are set up for the Zener diode to draw 1/10 the maximum load current. This assures diode regulation under maximum load.

Example: A 12-volt source is to supply a circuit requiring 9 volts. The load current varies between 200 and 350 mA.

$E_Z = 9.1$ V (nearest available value).

$$R_S = \frac{12 - 9.1}{1.1 \times 0.35} = \frac{2.9}{0.385} = 7.5 \text{ ohms}$$

$$P_D = \left[\frac{12 - 9.1}{7.5} - 0.2\right] 9.1 = .185 \times 9.1 = 1.7 \text{ W}$$

The nearest available dissipation rating above 1.7 W is 5; therefore, a 9.1-V 5-W Zener diode should be used. Such a rating, it may be noted, will cause the diode to be in the safe dissipation range even though the load is completely disconnected [I_L (min) = 0].

Obtaining Other Voltages

Fig. 5-22B shows how two Zener diodes may be used in series to obtain regulated voltages not normally obtainable from a single Zener diode, and also to give two values of regulated voltage. The diodes need not have equal breakdown voltages, because the arrangement is self equalizing. However, the current-handling capability of each diode should be taken into account. The limiting resistor may be calculated as above, taking the sum of the diode voltages as E_Z, and the sum of the load currents as I_L.

ELECTRONIC VOLTAGE REGULATION

Several circuits have been developed for regulating the voltage output of a power supply electronically. While more complicated than the VR-tube and Zener-diode circuits, they will handle higher voltage and current variations, and the output voltage may be varied continuously over a wide range.

Voltage regulators fall into two basic types. In the type most commonly used by amateurs, the dc supply delivers a voltage higher than that which is available at the output of the regulator, and the regulated voltage is obtained by dropping the voltage down to a lower value through a dropping "resistor." Regulation is accomplished by varying either the current through a fixed dropping resistance as changes in input voltage or load currents occur (as in the VR-tube and Zener-diode regulator circuits), or by varying the equivalent resistive value of the dropping element with such changes. This latter technique is used in electronic regulators where the voltage-dropping element is a vacuum tube or a transistor, rather than an actual resistor. By varying the dc voltage at the grid or current at the base of these elements, the conductivity of the device may be varied as necessary to hold the output voltage constant. In solid-state regulators the series-dropping element is called a pass transistor. Power transistors are available which will handle several amperes of current at several hundred volts, but solid-state regulators of this type are usually operated at potentials below 100 volts.

The second type of regulator is a switching type, where the voltage from the dc source is rapidly switched on and off (electronically). The average dc voltage available from the regulator is proportional to the duty cycle of the switching wave form, or the ratio of the ON time to the total period of the switching cycle. Switching frequencies of several kilohertz are normally used to avoid the need for extensive filtering to smooth the switching frequency from the dc output.

The above information pertains essentially to voltage regulators. A circuit can also be constructed to provide current regulation. Such regulation is usually obtained in the form of current limitation – to a maximum value which is either preset or adjustable, depending on the circuit. Relatively simple circuits, such as described later,

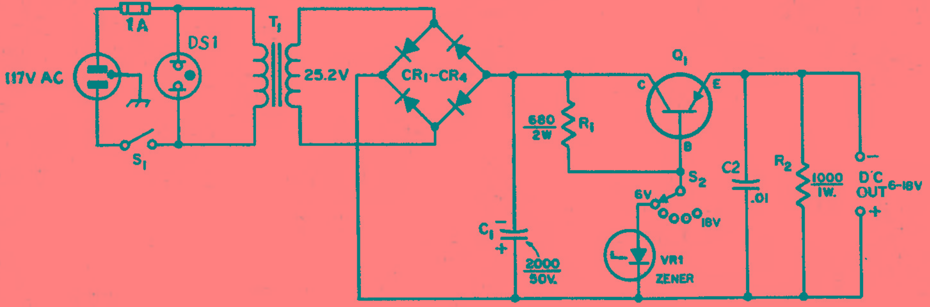


Fig. 5-23 – Schematic diagram of the power supply. Capacitances are in µF; capacitors marked with a polarity are electrolytic. Resistances are in ohms; R1 and R2 are composition.

C1 – 2000-µF 50 volts dc electrolytic (Mallory CG23U50C1).

C2 – .01-µF disk ceramic.

CR1-CR4, incl. – 50 PRV 3-A silicon diode (Motorola 1N4719).

DS1 – Neon lamp assembly with resistor (Leecraft 32-2111).

Q1 – 2N1970.

S1 – Spst toggle switch.

S2 – Phenolic rotary, 1 section, 2-pole (1 used), 6-position, shorting (Mallory 3126J).

T1 – Filament transformer, 25.2 V, 2 A (Knight 54 D 4140 or similar).

VR1 – Voltage regulator diode.

can be used to provide current limiting only. Current limiting circuitry may also be used in conjunction with voltage regulators.

Solid-State Regulators

One of the simplest forms of solid-state regulation is shown at Fig. 5-23. A bridge rectifier supplies 25 volts dc to a series regulator transistor, Q1, whose base bias is established by means of a Zener diode, VR1, providing a voltage reference of a fixed level. C1 is the input capacitor for the filter. R1 is chosen to establish a safe Zener-diode current, which is dependent upon the wattage rating of the diode. A 1-watt Zener diode is adequate for the circuit of Fig. 5-23. R2 is a bleeder resistor and C2 is an rf bypass. If several output voltages are desired, say from 6 to 18 volts, Zener diodes from 6 to 18 volts can be wired to S2 as shown. When a 2N1970 is used at Q1, the value of R1 will be 680 ohms. This value offers a compromise for the 5 reference diodes used (6,9,12,15, and 18 volts).

The output of the supply is equal to the Zener voltage minus the emitter-to-base bias voltage of Q1. Both the Zener voltage and bias voltage will be approximately zero with only R2 as a load, but will rise to roughly 0.3 volt with a 1-A load connected to the output. An increase in load current lowers the unregulated dc input voltage which appears across VR1 and R1. Zener current is reduced, decreasing the voltage at which the diode regulates. How much the voltage drops depends upon the characteristics of the particular Zener employed.

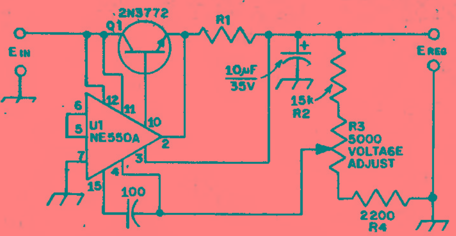
This power supply has very low output ripple. The main limitation of the circuit is the possibility of destroying Q1, the series-regulator transistor, when a dead short or heavy overload is connected across the output of the supply. To protect Q1 during normal operation, it should be mounted on a fairly large heat sink which is thermally coupled to the main chassis of the supply. The transistor should be insulated from the sink by means of a mica spacer and a thin layer of silicone grease. The sink can then be bolted directly to the chassis.

IC Regulators

The solid-state regulator described above provides only fixed voltages. Regulator circuits with the output voltage continuously variable over a wide range and with a very high degree of regulation can be built, but the number of circuit components is comparatively large when discrete components are used. Integrated-circuit devices can be used in a solid-state regulator circuit to replace many or all of the discrete components, depending on the output requirements. The voltage reference, control, shut-down (for current limiting) and pass-transistor driver elements are contained on a single silicon chip. The construction of a regulated power supply is simplified to a few interconnections if an IC regulator is used.

Fig. 5-24 is the diagram of a regulator using an IC and a single pass transistor. With a dc potential of 24 to 30 volts applied at E_{IN} the circuit as shown will provide an adjustable output voltage between 5 and 15. The circuit will handle up to 5 amperes of current, provided, of course, that the dc source will deliver this amount. If the load requires no more than 150 mA of current the pass transistor may be eliminated from the circuit altogether; in this case pins 2 and 10 of the IC should be interconnected.

The NE550 regulator will safely accept input voltages as high as 50, and output voltages may be adjusted by appropriate resistance values for R2, R3, and R4 from 2 to 40 volts. The value of R1 determines the shut-down current (maximum cur-



EXCEPT AS INDICATED, DECIMAL VALUES OF CAPACITANCE ARE IN MICROFARADS (µF); OTHERS ARE IN PICOFARADS (pF OR µµF); RESISTANCES ARE IN OHMS; k = 1000, M = 1000 000.

Fig. 5-24 — Schematic diagram of 15-V 5-A regulator (W1KLK, *QST* for November, 1971).

Q1 — Motorola power transistor; 30-cubic-inch heat sink required (Delco 7281366 rediator or equiv.).

R1 — 0.1-ohm resistor, made from 8 feet of No. 22 enam. copper wire.

R2, R4 — For text reference.

R3 — Linear taper.

U1 — Signetics IC.

Table 5-1

Voltage Divider			*Current Limit*	
V_{OUT}	R_A	R_B	I_{MAX}	R_1
3.6	6135	2967	.05	12
5	4417	3654	0.1	6
9	11,043	2442	0.5	1.2
12	14,724	2314	1.0	0.6
13.6	16,687	2272	1.5	0.4
15	18,405	2243	2	0.3
20	24,540	2177	2.5	0.24
28	34,356	2122	3.0	0.20
			5	0.12
			10	.006

Table 5-1 — Resistance values for various voltage and current outputs from the regulator of Fig. 5-24. These values were determined by mathematical calculation and are not necessarily available from stock supplies. The figures given do indicate the practical values which may be used along with an appropriate-value control for R2 in the circuit of Fig. 5-24.

R_A — R2 plus top portion of R3.

R_B — R4 plus bottom portion of R3.

rent which the circuit will deliver into a short circuit) and is usually selected to protect either the pass transistor or the power supply transformer, whichever has the lower current rating. Table 5-1 gives resistance values for various levels of voltage and current from the regulator.

The use of a high-gain pass device improves the output regulation, and a Darlington-connected pair is frequently employed. Of course it is easy to purchase a ready-made Darlington transistor, but the enterprising amateur can make his own, as shown in Fig. 5-25A. However, some of the IC regulators which are available on the market have so much internal gain that it is difficult to avoid oscillation with a high-gain pass transistor.

High-Current-Output Regulators

When a single pass transistor is not available to handle the current which may be required from a regulator, the current-handling capability may be increased by connecting two or more pass transistors in parallel. The circuits at B and C of Fig. 5-25 show the method of connection. The resistances in the emitter leads of each transistor are necessary to equalize the currents.

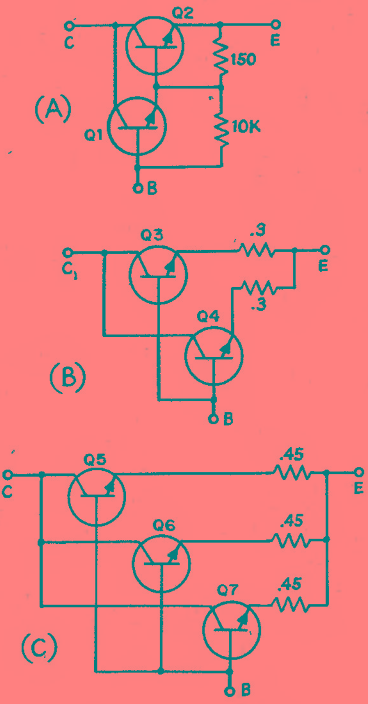


Fig. 5-25 — At A, a Darlington-connected pair for use as the pass element in a series-regulating circuit. At B and C, the method of connecting two or more transistors in parallel for high current output. Resistances are in ohms. The circuit at A may be used for load currents from 100 mA to 5 A, at B for currents from 6 to 10 A, and at C for currents from 9 to 15 A.

Q1 — Motorola MJE 340 or equivalent.

Q2-Q7, incl. — Power transistor such as 2N3055 or 2N3772.

Fixed-Voltage IC Regulators

IC regulators with all circuitry contained on a single silicon chip are becoming available for different values of fixed-voltage outputs. The LM309 five-volt regulator, manufactured by National Semiconductor and others, is one type of such ICs. These regulators are three-terminal devices, for making connections to the positive unregulated input, positive regulated output, and ground. They are designed for local regulation on digital-logic circuit-board cards to eliminate the distribution problems associated with single-point regulation. For this reason they are frequently called on-card regulators.

The LM309 is available in two common transistor packages. The LM309H in a TO-5 package can deliver output currents in excess of 200 mA if adequate heat sinking is provided, and the LM309K in the TO-3 power package can provide an output current greater than 1 A. The regulator is essentially blow-out proof, with current limiting included in the circuit. In addition, thermal shutdown is provided to keep the IC from overheating. If internal dissipation becomes too great, the regulator will shut down to prevent excessive heating.

It is not necessary to bypass the output of the LM309, although bypassing does improve immunity from transient responses. Input bypassing is needed, however, if the regulator is located very far from the filter capacitor of the power supply. Typical values of input bypass capacitance are 0.15 and 0.22 μF. Although designed primarily as a fixed-voltage regulator, the LM309 can be used to obtain a regulated output at voltages higher than five. This is done by returning the "ground" connection of the IC to a tap point on a voltage divider which is connected between the regulated output and a true circuit ground. An adjustable output regulator for voltages above five can be had if the "ground" pin is connected to the junction of a 300-ohm fixed resistor and one end of a 1000-ohm linear control. The opposite end of the 300-ohm resistor should be connected to the output pin, and the wiper contact and third lug of the control to a true circuit ground.

Switching Regulator

Switching regulators are used when it is necessary or desired to minimize power losses which would otherwise occur in the series pass transistor (or transistors) with large variations in input or output voltages. The basic operation of the switching regulator, known as the flyback type, may be understood by referring to Fig. 5-26A. Assume that the switch is closed and the circuit has been in operation long enough to stabilize. The voltage across the load, R_L, is zero, and the current through L is limited only by R_I, the internal resistance of the inductor. At the instant the switch is opened, the voltage across the load goes to a value higher than the source voltage, E, because of the series-aiding or "flyback" effect of the inductor. When the magnetic lines of flux about the inductor collapse completely, the voltage across R_L will be equal to that of the source (minus the small voltage drop across R_I). Each time the switch is closed and then opened, the process is repeater. By opening and closing the switch rapidly, voltage pulses may be applied across R_L which are higher than the dc input voltage. A capacitor may be connected across R_L to produce a dc output voltage. To keep the capacitor from discharging when the switch is closed, a diode can be connected in series with the load and its parallel-connected capacitor.

In a practical switching-regulator circuit the switching is performed by a transistor, as shown at B of Fig. 5-26. The transistor may be driven by any number of circuits. In the practical circuit shown later (Fig. 5-27) four sections make up the driving circuit, as shown in block diagram form in Fig. 5-26B. The oscillator triggers the monostable multivibrator and determines the frequency of operation. The sensor measures the output voltage and controls the pulse width of the multivibrator accordingly. The monostable multivibrator combines the signals from the oscillator and sensor to produce the correct pulse width. The driver receives the multivibrator output and drives the power transistor, Q1.

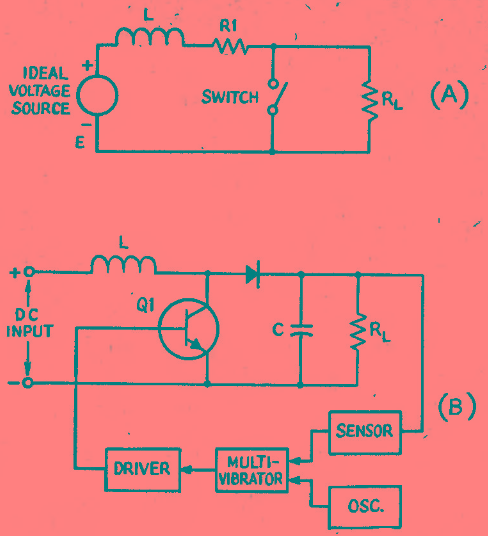
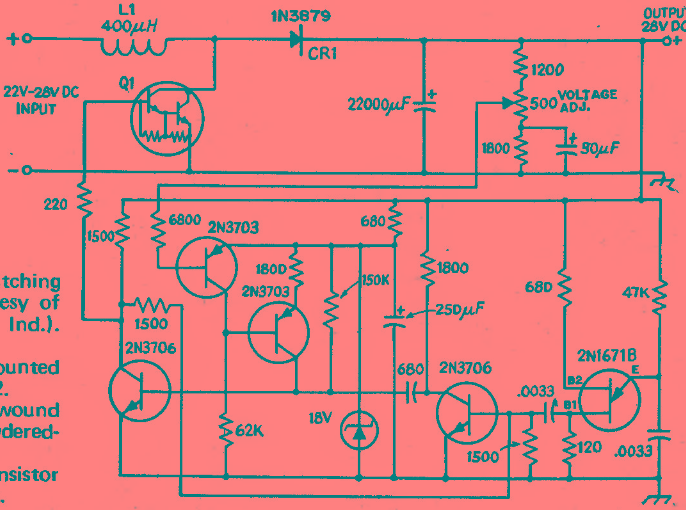


Fig. 5-26 — At A, the fundamental circuit of a flyback switching regulator, and at B, the elements of a practical circuit.

The voltage step-up capability of the inductor has been mentioned briefly. However, in choosing the value of the inductor, energy is an important consideration. During the time the transistor is turned on, the inductor stores energy. This energy is added to the supply and delivered to the load when the transistor turns off. The total energy must be enough to supply the load and maintain output voltage. As the load is increased, the transistor must remain on longer in order to store more energy in the inductor. The required value of inductance depends on frequency of operation, duty cycle, and load. A linear change in current through the inductor is a desirable condition and indicates operation is over a small segment of the inductor's charging and discharging curve. A powdered-iron-core inductor is normally used to prevent a large inductance change with increased current.

Efficiency of the circuit depends mainly upon the switching and saturation losses of the power transistor. The peak current through the transistor is considerably greater than the input current. The flyback diode must have a fast reverse recovery time and low forward drop. There will be a large current spike through the transistor if the diode is slow.

The complete circuit of a switching regulator is given in Fig. 5-27. This regulator will handle 100 watts of power efficiently, at output voltages as much as 6 volts above the input voltage. The switching rate of the regulator is 9 kHz, and it operates with an input of 22 to 28 volts. Regula-



EXCEPT AS INDICATED, DECIMAL VALUES OF CAPACITANCE ARE IN MICROFARADS (µF) ; OTHERS ARE IN PICOFARADS (pF OR µµF); RESISTANCES ARE IN OHMS ; k = 1000, M = 1000 000.

Fig. 5-27 — A 100-W 28-V switching regulator (circuit design courtesy of Delco Electronics, Kokomo, Ind.). All resistors are 1/2 W.

CR1 — Motorola rectifier mounted on Delco heat sink 7281352.

L1 — 124 turns No. 18 wire wound on Arnold BO79024-3 powdered-iron core.

Q1 — Darlington power transistor (Delco DTS 1020 or equiv.).

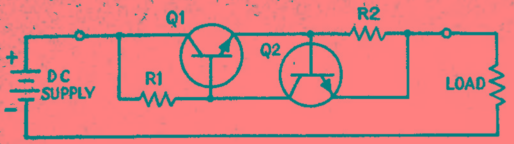


Fig. 5-28 — Two-terminal current limiter. See text for discussion of component values and types.

tion and ripple are less than 1 percent at full output. The switching device, Q1, is a commercially available Darlington transistor.

The efficiency of the circuit drops off at low power levels. This is because the losses of the circuit are not proportional to the output power. Maximum efficiency occurs at about 80 watts because the duty cycle of the transistor is an optimum for the chosen value of the inductor. Whenever the input voltage increases above 28 volts, the output voltage tracks the input. The difference between the two voltages is the drop in the flyback diode.

Output voltage variations resulting from changes in ambient temperature are caused by two major factors; positive temperature coefficient of the Zener diode, and the negative temperature coefficient of the emitter-base junctions of the transistors. One way to compensate partially for temperature is to connect diodes that have negative temperature coefficients in series with the Zener diode.

Two-Terminal Current Limiter

The simple circuit of Fig. 5-28 performs the current limiting function of fuses or circuit breakers with greater speed, accuracy, reliability and automatic resetting. Fuses and circuit breakers are commonly used for protection of dc power supplies or experimental solid state devices under test and development, but such protective devices are not fast enough to cope with instantaneous overcurrents. The circuit uses only two transistors and two resistors. The necessary supply voltage for operation is obtained from the power source being protected, with the load functioning as the return to the power source. Q1 is a series element which allows current, up to a desired maximum, to flow to the load. R1 provides a suitable bias for Q1 to permit such current to flow. R2 is a sensing resistor interposed between the series transistor and the load, and provides bias for Q2. Normally this bias is low enough to prevent Q2 from conducting. Q2 controls the bias applied to Q1. When excess current flows through R2 as a result of a circuit malfunction or a short across the load, the voltage drop across R2 rises, biasing Q2 into conduction. When Q2 turns on, it reduces the bias on Q1 and limits the amount of current flow. The maximum amount of current flow can be varied by changing the value of R2. If an adjustable limiting level is desired, R2 may be a variable resistor. The limiting level is an inverse function of the resistance value.

The current limiter works equally well with germanium or silicon, or npn or pnp types of semiconductors (so long as proper polarities are observed). The circuit values are not critical but one must not exceed the maximum voltage rating or the dissipation rating of the components used, as in any other circuit. The voltage and dissipation ratings are the only actual limiting factors in using this circuit; the device ratings may be scaled up or down depending on their utilization. For protecting micro-circuitry (low current protection), for example, Q1 and Q2 may be 2N4401 silicon npn 310-mW audio transistors. If R1 is 10,000 ohms and R2 is 350 ohms, the current will be limited to approximately 2 mA with a 9-V supply. If R1 is changed to 820 ohms and R2 changed to 24 ohms, the current will be limited to approximately 30 mA. With fixed resistance values and with a fixed voltage input, the limited current value will be somewhat dependent upon the beta of the transistors. If regulation is of concern, germanium transistors will exhibit less voltage drop, and R2 may be made only about 1/3 the value for equivalent limiting with silicon transistors.

BIAS SUPPLIES

Bias supplies are used to provide grid voltage to the PA and modulator stages of amateur transmitters, to supply grid voltage to linear amplifiers, and to provide control voltage for cutting off receiver and transmitter output. Negative bias voltage is also used for grid-block keying in most modern amateur exciters.

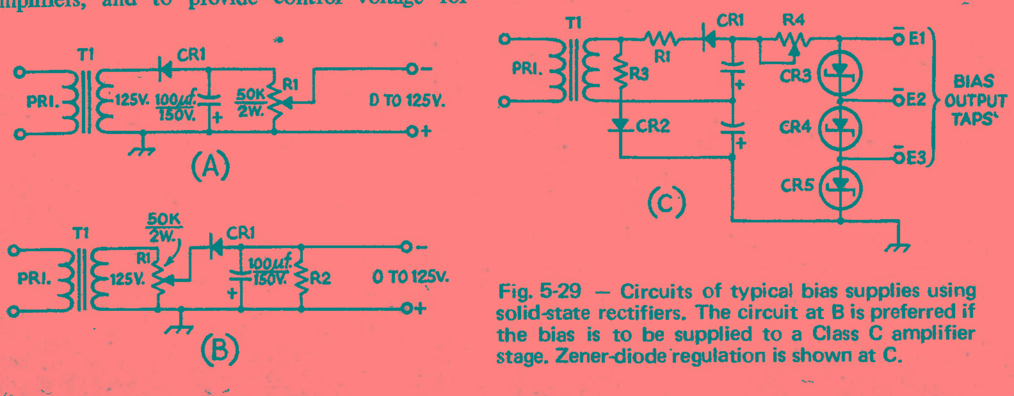


Fig. 5-29 — Circuits of typical bias supplies using solid-state rectifiers. The circuit at B is preferred if the bias is to be supplied to a Class C amplifier stage. Zener-diode regulation is shown at C.

Typical circuits for bias supplies are shown in Fig. 5-29. At A, a simple half-wave rectifier (CR1) provides dc voltage to R1, which is adjusted for the desired output. If the bias is being fed to a Class C amplifier, the circuit at B is preferred. R1 is used to set the bias voltage at the desired level and R2 is the value that would ordinarily be used as a grid-leak resistor for the Class C stage. No other grid resistor should be used.

A voltage-doubler bias supply is shown at C. T1 is chosen to provide the desired output voltage, when doubled, while allowing for the voltage drop across R4. Zener diodes are connected in series (CR3 through CR5, incl.) to offer regulation and to enable the user to obtain three different bias voltages. The Zener diodes are selected for the operating voltages required. Fewer, or more, Zener diodes can be connected in the string, or a single Zener diode can be used. R4 is adjusted to provide the proper Zener-diode current for the string, and its wattage must be sufficient to handle the current flowing through it. R2 and R3 are current-limiting resistors to protect CR1 and CR2.

Of course, full-wave center-tapped and full-wave bridge rectifiers can be used in place of the half-wave examples shown in Fig. 5-29. Similarly, voltage triplers can be used in bias supplies. The full-wave rectifiers are easier to filter and may be preferred for some applications.

CONSTRUCTION OF POWER SUPPLIES

The length of most leads in a power supply is unimportant, so the arrangement of components from this consideration is not a factor. More important are the points of good high-voltage insulation, adequate conductor size for filament wiring – and most important of all – safety to the operator. Exposed high-voltage terminals or wiring which might be bumped into accidentally should not be permitted to exist. They should be covered with adequate insulation or made inaccessible to contact during normal operation and adjustment of the transmitter. Power-supply units should be fused individually. All negative terminals of plate supplies and positive terminals of bias supplies should be securely grounded to the chassis, and the chassis connected to a waterpipe or radiator ground. All transformer, choke, and capacitor cases should also be grounded to the chassis. Ac power cords and chassis connectors should be arranged so that exposed contacts are never "live." Starting at the conventional ac wall outlet which is female, one end of the cord should be fitted with a male plug. The other end of the cord should have a female receptacle. The input connector of the power supply should have a male receptacle to fit the female receptacle of the cord. The power-output connector on the power supply should be a female socket, never a male type. A male plug to fit this socket should be connected to the cable going to the equipment. The opposite end of the cable should be fitted with a female connector, and the series should terminate with a male connector on the equipment. There should be no "live" exposed contacts at any point, regardless of where a disconnection may be made.

Rectifier filament leads should be kept short to assure proper voltage at the rectifier socket. Through a metal chassis, grommet-lined clearance holes will serve for voltages up to 500 or 750, but ceramic feedthrough insulators should be used for higher voltages. Bleeder and voltage-dropping resistors should be placed where they are open to air circulation. Placing them in a confined space reduces the rating. Other precautions are given earlier in this chapter, in the section on power-line considerations.

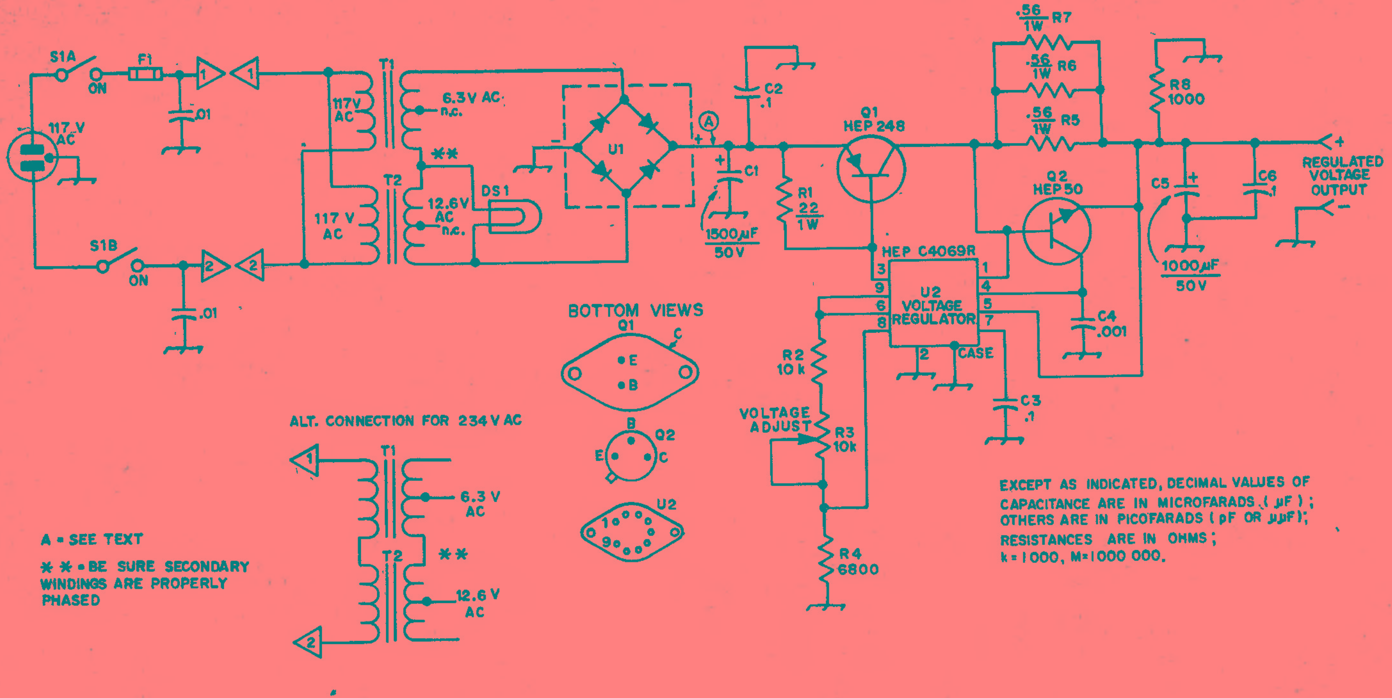
A REGULATED POWER SUPPLY

This regulated power supply is suitable for use as a "battery eliminator" for transceivers of the 10-watt output variety, or for general purpose workbench duty. This supply is designed to provide up to 2 amperes continuously at 12 volts, although the output voltage may be adjusted with an externally mounted control within the range of 9 to 13 volts with the circuit constants shown in Fig. 1. Current limiting at a predetermined level is included to eliminate the possibility of damaging the supply in the event of a short circuit across the output terminals.

Circuit Description

Up to point A in Fig. 1, the circuit is a fairly conventional step-down transformer, full-wave bridge rectifier, and capacitor-input filter. The use of two transformers, rather than one, allows a certain degree of flexibility of operation, in that the supply may be used on either 117 or 235 volts ac with only minor differences in wiring. The dc voltage at point A is approximately 30. Q1 is used as a series pass transistor. Its function is to drop the voltage at point A of Fig. 1 to the desired 12-volt-output value, and maintain that voltage over wide variations in the output load current. U2 is an integrated-circuit voltage regulator which, with the aid of a few external components, is

capable of handling up to 600 mA of output current. Since an output current of 2 A is desired, however, U2 is used here to properly bias Q1, which has a much higher current rating. The inner circuitry of U2 can be divided into four basic elements: a fixed voltage reference, a variable voltage reference derived from the fixed reference, an error amplifier, and an output regulator. An internal Zener diode is used as the fixed reference. This reference voltage is applied to one input of a differential amplifier (a differential amplifier responds to the difference between two applied voltage levels), while the other input is connected to the junction of R3 and R4 (pin 8 of U2). R3 (in



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A - SEE TEXT

** - BE SURE SECONDARY WINDINGS ARE PROPERLY PHASED

Fig. 1 — Circuit diagram for the power supply. Unless otherwise noted, all resistors are 1/2-watt composition. Component designations not listed below are for text reference and circuit-board layout purposes. Capacitors are disk ceramic except those with polarity marked, which are electrolytic.

C1 — 1500 µF electrolytic, 50 volts dc (Sprague TVA 1318).
C5 — 1000 µF electrolytic, 50 volts dc (Sprague TVA 1316).
DS1 — 12-volt pilot lamp.
F1 — 1.5 A, type 3AG fuse.
Q1 — Motorola HEP248 or equiv.
Q2 — Motorola HEP50, 2N706A, or equiv.
R3 — 10-kΩ printed-circuit-mounting pot (Radio Shack 271-218).
R5, R6, R7 — 0.56Ω 1-watt wirewound resistor (Radio Shack 271-072).
S1 — Miniature dpst toggle.
T1 — 117-volt pri., 6.3-volt ct sec. (ct unused), 3 amperes (Radio Shack 273-1510).
T2 — 117-volt pri., 12.6-volt at sec. (ct unused), 3 amperes (Radio Shack 273-1511).
U1 — Full-wave bridge rectifier assembly, 50 volts, 10 amperes (Radio Shack 276-1156).
U2 — Motorola HEP C4069R, MC1469R, or MC1569R.

Power Supply Construction

Inside view of the regulated power supply. The use of the 4-inch squera pc board (visible at upper right) simplifies the interconnection of most of the parts. The full-wave bridge rectifier assembly (U1) and the heat sink for Q1 are bolted to the chassis floor. A single transformer has been used here in place of T1 end T2 as described in *QST* for January, 1975.

series with R2) and R4 form an externally adjustable voltage divider, from the differential amplifier output (pin 9 of U2) to ground. Thus, the output of the differential amplifier will swing to the level that results in the voltage at pin 8 of U2 being identical to the fixed reference voltage. A second differential amplifier serves as the error amplifier. One input (pin 6 of U2) is tied directly to pin 9, while the other input (pin 5 of U2) is connected to the power supply output bus. The error-amplifier output controls the internal output-regulator bias of the IC, which in turn controls the bias applied to Q1. When connected in this manner, the error amplifier responds to any difference between the power supply ouput level and the (previously adjusted) voltage reference level. The output regulator acts on Q1 to correct the discrepancy. C3 and C4 are used in the interest of maintaining amplifier stability. R5, R6, R7, and Q2 are included in the circuit to protect the power supply and regulator in the event of an inadvertent short circuit between the output terminals or if the current demanded by the load is too heavy for safe operation. The operation of the current-limiting feature is as follows: When the current flowing through the parallel combination of R5, R6, and R7 (equivalent parallel resistance of about 0.18 ohm) is large enough to produce a 0.6-volt drop across the resistors, Q2 is biased into conduction. The action of Q2 on the IC internal output regulator results in the reduction of the current through Q1. The short-circuit output current in this case will be limited to 3.3 amperes (0.6/0.18 = 3.3), which is within the safe regulator/pass-transistor limits. The value of the current-sensing resistance required for short-circuit currents of other than 3.3 amperes is calculated as follows by Ohm's Law: $R_{SC} = 0.6/I_{SC}$ where R_{SC} is the current-sensing resistance and I_{SC} is the maximum allowable short-circuit current. If a long run of cable is used between the power supply and the load, the voltage drop in the cable may be large enough to be of concern. If this is the case, a separate remote voltage-sensing wire may be run from the load to pin 5 of U2, rather than connecting pin 5 to the output at the power supply. The regulator will compensate for the voltage drop in the cable. This wire may be of a small gauge, as little current will be drawn through it.

Construction Details

Most of the components were mounted on an etched circuit board (see Fig. 2), although point-to-point wiring on a perf board would have sufficed. As the transistors inside the IC are capable of operation at vhf, it is good practice to use short leads for interconnecting the regulator components to prevent unwanted oscillations from occurring. The manufacturer recommends a low-inductance connection between the case of the HEP C4069R and ground. No evidence of instability was noted with this circuit.

All parts are housed in an 8 × 6 × 3-1/2-inch Minibox (Bud CU-2109-A). Two standoff insulators support the pc board, while the power transformers, T1 and T2, are bolted directly to the Minibox. As Q1 dissipates several watts when maximum load current is being drawn, a heat sink is required. The Motorola HEP500, consisting of an MS-10 predrilled heat sink and an MK-15 power-transistor mounting kit, is ideal for this application. In accordance with the instructions supplied with the HEP500, the MK-15 should be coated on both sides with a thin layer of silicone thermal compound (Radio Shack 276-1372), with the bottom of Q1 and the center area of the heat sink treated similarly. After the Q1 emitter and base pins are inserted through the proper holes in the washer, the transistor is mounted in the socket. The mica washer insulates the case of Q1 (which is connected internally to the collector) electrically from the heat sink and chassis, while the silicone compound increases the thermal conductivity between Q1 and the heat sink. Care should be taken to prevent contact between the case of Q1 and any grounded object, as the full supply voltage appears on the transistor case. The current-limiting feature will not protect the device from destruction in event of an accidental short from Q1 to ground, since the current sensing resistors (R5, R6, and R7) are connected between Q1 and the power supply output terminals. The heat-sink assembly is bolted to the rear panel of the Minibox with No. 6 hardware. The MS-10 is 3 inches high and 4-1/2 inches wide, so it must be located off center in order to accomodate the fuse holder and the line cord on the rear panel. A 1-inch-diameter hole was punched in the rear panel prior to the heat sink installation to allow access to the transistor socket pins. Short lengths of hookup wire are used between the pc board and the transistor socket. U1 is coated with silicone compound and then bolted to one of the inside walls of the Minibox, which serves as a heat sink for the diodes. Ventilation of the Minibox is desirable. Large holes punched or cut in the sides and bottom of the box and covered with perforated metal stock can be used, or ventilation holes can be drilled individually in the