Linear Regulators for DC Power Supplies

All linear voltage regulators can be classified as either **series** or **shunt** types, as determined by the arrangement of the pass element with respect to the load. In a series regulator, as the name implies, the pass transistor is connected in series with the load. Regulation is accomplished by variation of the current through the series pass transistor in response to a change in the line voltage or circuit loading. In this way, the voltage drop across the pass transistor is varied and that delivered to the load circuit is maintained essentially constant. In the shunt regulator, the pass transistor is connected in parallel with the load circuit, and a voltage-dropping resistor is connected in series with this parallel network. If the load current tends to fluctuate, the current through the pass transistor is increased or decreased as required to maintain an essentially constant current through the dropping resistor.

BASIC POWER-SUPPLY ELEMENTS

A dc power supply converts the power from the ac line into a direct current and steady voltage of a desired value. The ac input voltage is first rectified to provide a pulsating dc and is then filtered to produce a smooth voltage. Finally, the voltage may be regulated to assure that a constant output level is maintained despite fluctuations in the power-line voltage or circuit loading. The rectification, filtering, and regulation steps in a dc power supply are illustrated in Fig. 69.

Rectifier Circuits

The optimum type of rectifier circuit for a particular application depends upon the dc voltage and current requirements, the maximum amount of ripple (undesirable fluctuations in the dc output caused by an ac component) that can be tolerated in the circuit, and the type of power available. Single-phase circuits are used to provide the relatively low dc power required for radio and television receivers, public-address systems, and similar types of electronic equipment. Polyphase rectifier circuits are used to provide the dc power in high-power industrial applications.

Polyphase circuits more fully take advantage of the capabilities of the rectifier and power transformer and, in addition, provide a dc output with a small percentage of ripple. Polyphase rectifiers circuits, therefore, require

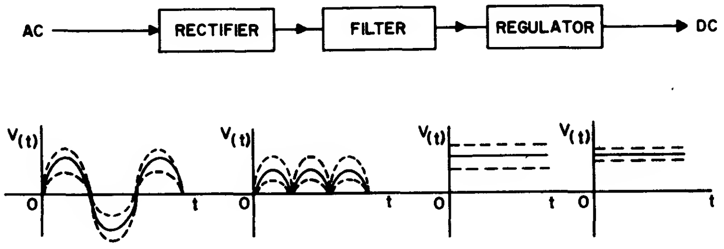


Fig. 69 - Block diagram of a regulated dc power supply. The waveforms show the effects of rectification, filtering, and regulation. (Dashed lines indicate voltage fluctuations as a result of input variations)

less filtering of the dc output voltage than is required for the dc output from single-phase rectifier circuits.

Rectifier Voltage and Current Ratios

Table IV lists voltage and current ratios for the basic rectifier circuits shown in Figs. 70 through 72 and in Figs. 78 through 81. For most effective use of the rectifiers and power transformers, operation of the rectifier circuits into inductive loads, except for the single-phase half-wave type, is generally recommended. Current ratios given for inductive loads are applicable only when a filter choke (inductance) is used between the output of the rectifier and any capacitor in the filter circuit. The values shown neglect the voltage drops in the power transformer, the silicon rectifiers, and the filter components that occur when load current is drawn. When a specific type of rectifier has been selected for a specific circuit, the information given in Table IV can be used to determine the parameters and characteristics of the circuit.

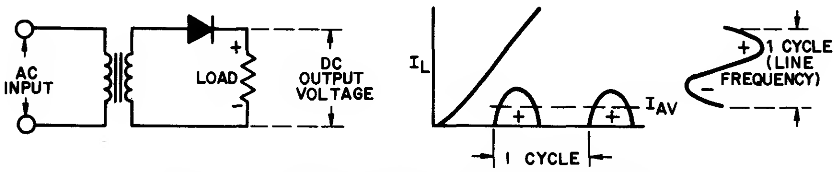


Fig. 70 - Single-phase half-wave rectifier and load-current waveform.

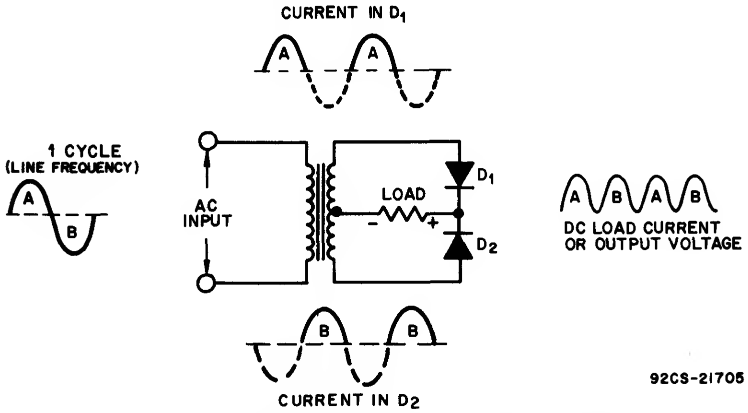


Fig. 71 - Single-phase full-wave rectifier circuit with center-tapped transformer.

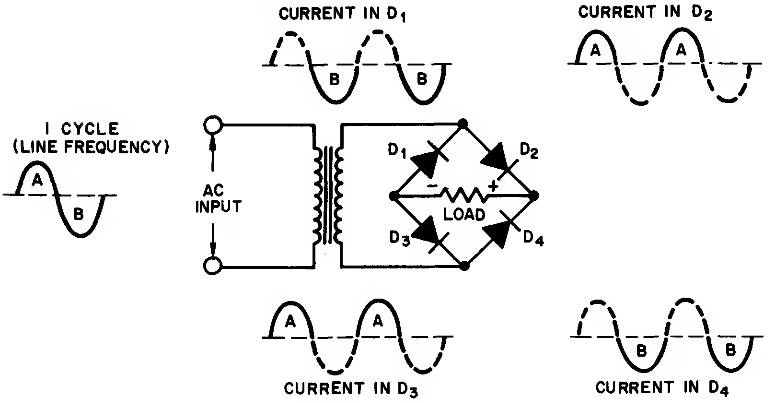


Fig. 72 - Full-wave bridge rectifier without center-tapped power transformer.

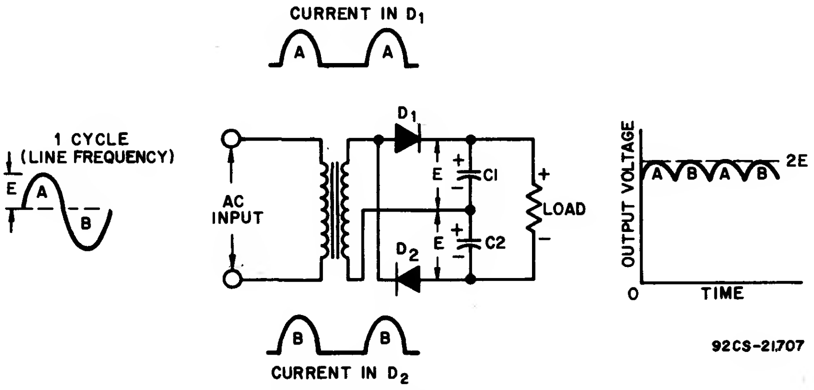


Fig. 73 - Full-wave voltage-doubler circuit.

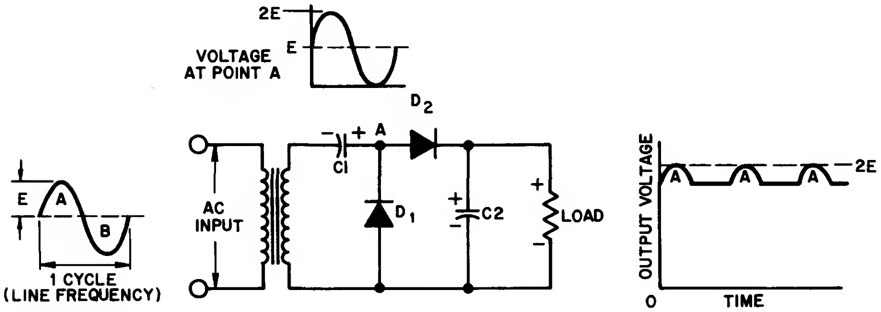


Fig. 74 - Half-wave voltage-doubler circuit.

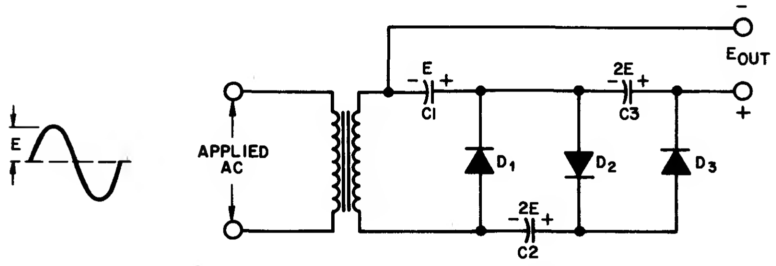


Fig. 75 - Half-wave voltage-tripler circuit.

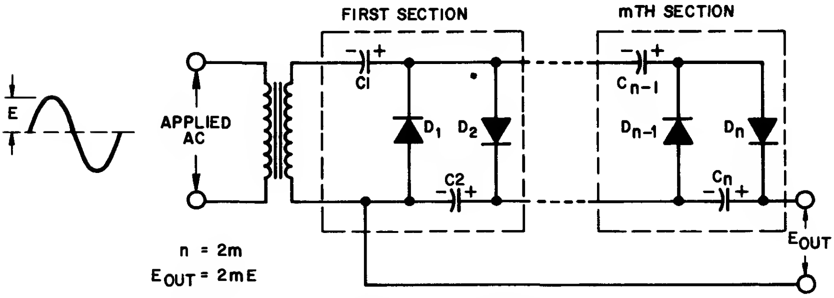
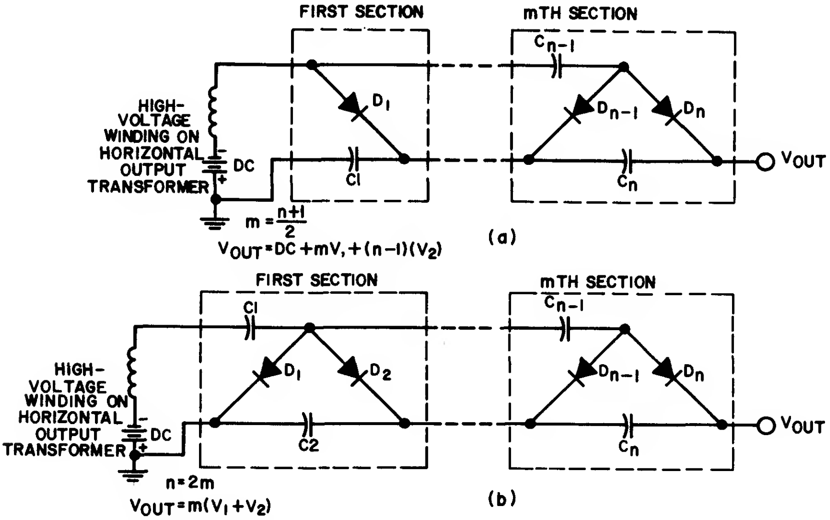


Fig. 76 - Half-wave "n" multiplier rectifier circuit.



V_1 = POSITIVE PORTION OF PULSE VOLTAGE ACROSS HIGH-VOLTAGE WINDING

V_2 = NEGATIVE PORTION OF PULSE VOLTAGE ACROSS HIGH-VOLTAGE WINDING

Fig. 77 - Basic multiplier circuits: (a) with odd number of diodes; (b) with even number of diodes.

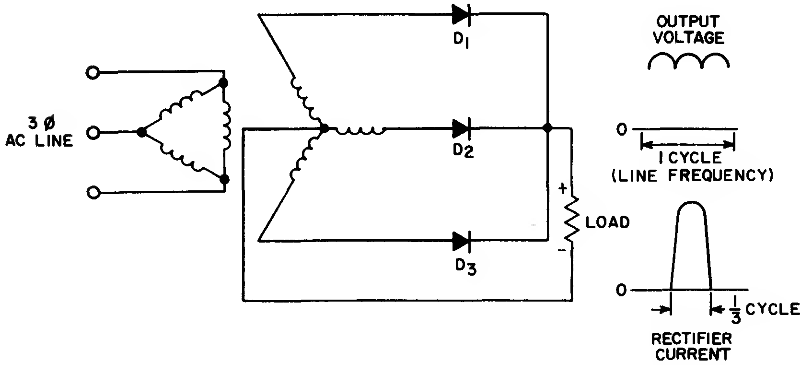


Fig. 78 - Three-phase half-wave delta-wye circuit.

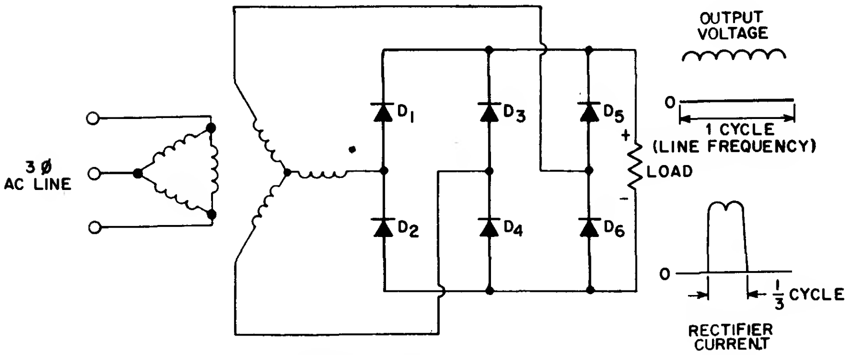


Fig. 79 - Three-phase, full-wave, delta-wye bridge rectifier.

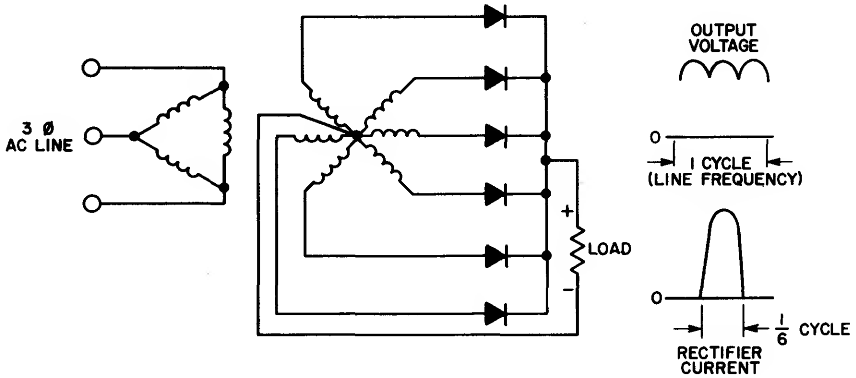


Fig. 80 - Three-phase, delta-star (six-phase), half-wave rectifier.

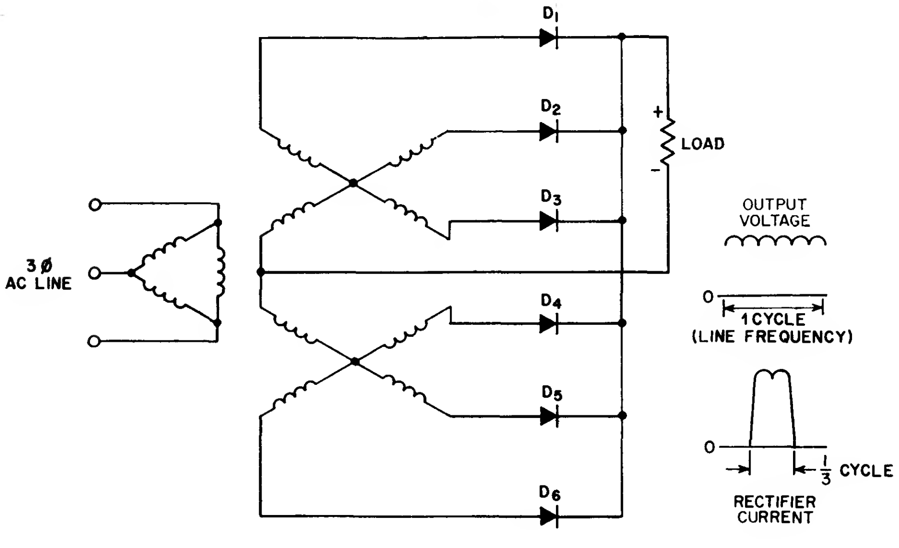


Fig. 81 - Three-phase, half-wave, double-wye and interphase transformer circuit.

Filter Networks

In general, the output-voltage waveform of a dc power supply should be as flat as possible (i.e., should approach a pure dc). The objective, therefore, is a voltage waveform that has a peak-to-average ratio of unity. The output of a basic rectifier circuit, however, is a series of positive or negative pulses rather than a pure dc voltage. The rectifier output may be considered as a steady dc voltage with an alternating voltage superimposed on it. For most applications, this alternating voltage (ripple) must be removed (filtered out), or the equipment in which the power supply is used will not operate properly.

Figs. 82 through 86 illustrate the various types of filter networks and the resulting degree of ripple content appearing at the output.

Table IV—Normalized Characteristics for Rectifier Circuits With Resistance and Choke-Input-Filtered Loads•

E = Transformer Secondary Voltage (rms)
E_{av} = Average DC Output Voltage
E_m = Peak Transformer Secondary Voltage
E_{bmi} = Peak Inverse Anode Voltage
E_r = Major Ripple Voltage (rms)
F = Supply Frequency
t_r = Major Ripple Frequency
I_{av} = Average DC Output Current
I_b = Average Anode Current
I_p = Anode Current (rms)
I_{pm} = Peak Anode Current
P_{ap} = Transformer Primary Volt-Amperes
P_{as} = Transformer Secondary Volt-Amperes
P_{dc} = DC Power = ($E_{av} \times I_{av}$)

Item	1-Phase Half-Wave (Fig. 70)	1-Phase Full-Wave (Fig. 71)	1-Phase Full-Wave Bridge (Fig. 72)	3-Phase Half-Wave Delta-Wye (Fig. 78)	3-Phase Full-Wave Delta-Wye (Fig. 79)	3-Phase Half-Wave Delta-Star (Fig. 80)	3-Phase Half-Wave Double-Wye with Bal. Coil (Fig. 81)
Voltage Ratios							
E_m/E_{av}	3.14	1.57	1.57	1.21	1.05	1.05	1.05
E/E_{av}	2.22	1.11	1.11	0.854	0.74	—	0.854
E_{bmi}/E	1.41	2.83	1.41	2.45	2.83	2.83	2.45
E_{bmi}/E_{av}	3.14	3.14	1.57	2.09	2.09	2.42	2.09
E_r/E_{av}	1.11	0.471	0.471	0.177	0.040	—	0.04
Frequency Ratio ■f_r/f	1	2	2	3	6	6	6
Current Ratios ■I_b/I_{av}	1	0.5	0.5	0.333	0.167	0.167	0.167
Resistive Load							
I_p/I_{av}	1.57	0.785	0.785	0.587	0.409	0.409	0.294
I_{pm}/I_{av}	3.14	1.57	1.57	1.21	1.05	1.05	0.525
I_{pm}/I_b	3.14	3.14	3.14	3.63	6.3	6.30	3.14
Inductive Load°							
I_p/I_{av}	*	0.707	0.707	0.577	0.408	0.408	0.289
I_{pm}/I_{av}	*	1.00	1.00	1.00	1.00	1.00	0.5

Notes:

•Conditions assume sine-wave voltage supply; zero voltage drop across rectifiers when conducting; no losses in transformer or choke; output load is a pure resistance.

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

* Single-phase, half-wave, choke-input-filtered load has no practical significance; only a minute pulsating dc current will flow.

■These ratios also apply for the case of capacitor-input filtered load.

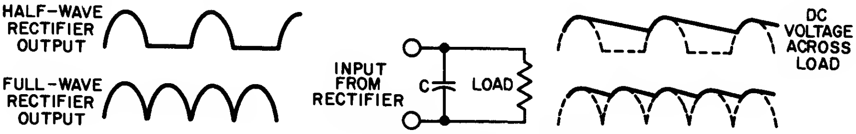


Fig. 82 - Single capacitor filter.

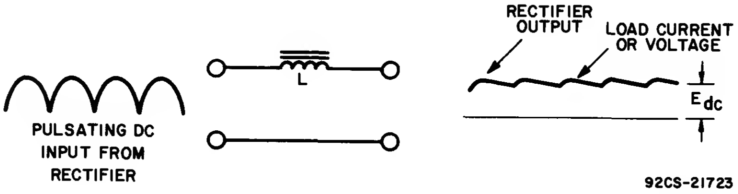


Fig. 83 - Simple inductance filter.

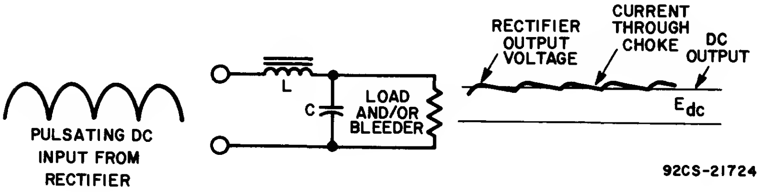


Fig. 84 - Choke-input filter.

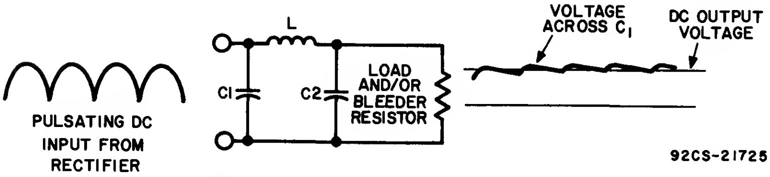


Fig. 85 - Capacitor-input LC filter.

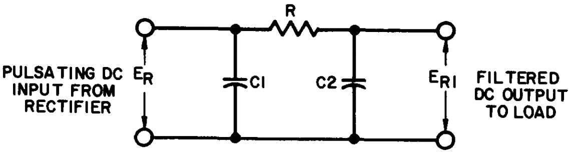


Fig. 86 - Resistance-capacitance filter.

SERIES REGULATORS

Series-regulated power supplies are classified as voltage-regulating types, voltage-regulating current-limiting types, current-regulating types, or voltage-regulating current-regulating types. Fig. 87 shows the response characteristics for each type of series-regulated power supply.

Linear series regulators provide an excellent means for prevention of large variations in power-supply load current or output voltage. Fast response time provided by the linear control circuit makes possible close control of the output voltage. However, because the series pass transistor is equivalent to a variable resistance in series with the load, the transistor must dissipate a large amount of power at low output voltages. Another disadvantage of the series regulator is that the total fault current passes through the regulating transistor if the load becomes short-circuited. As a result, overload and short-circuit protection in the form of current-limiting or drive-reduction networks that operate rapidly must be used to protect the transistor.

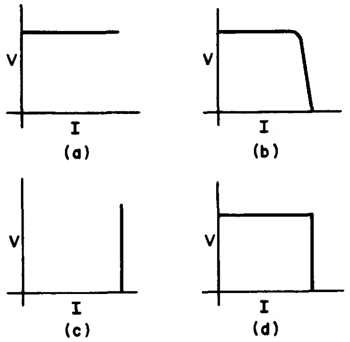


Fig. 87 - Typical response characteristics for series-regulated power supplies: (a) voltage-regulating types; (b) voltage-regulating current-limiting types; (c) current-regulating types; (d) voltage-regulating current-regulating types.

Basic Circuit Configurations

Fig. 88 shows a basic configuration for a linear series regulator which is representative of the type used in **voltage-regulating power supplies**. In this type of regulator, the series pass transistor is usually operated as an emitter-follower, and the control (error) signal used to initiate the regulating action is applied to the base. The base control is developed by a dc amplifier. This amplifier, which is included in the feedback loop from the load circuit to the pass transistor, senses any change in the output voltage by comparison of this voltage with a known reference voltage. If an error exists, the error voltage is amplified and applied to the base of the pass transistor. The conduction of the pass transistor is then increased or decreased in response to the error signal input as required to maintain the output voltage at the desired value.

Voltage-regulating power supplies are required to maintain a constant output voltage, independent of the load current, as shown in Fig. 87(a). The supply, therefore, usually has a very low output impedance. For this reason, voltage-regulating supplies must often be made current-limiting to protect the regulator from very high current drawn at the output terminal, such as may be caused by a short circuit. In **voltage-regulating current-limiting power supplies**, the load current is prevented from rising above some predetermined design value by reduction of the power-supply output voltage when this current limit is reached, as shown in Fig. 87(b).

Fig. 89 shows the basic configuration for a linear regulator circuit used in **current-regulating power supplies**. This regulator senses the voltage across a resistor in series with the load, rather than the voltage across the load circuit as in the linear voltage regulator. Because the voltage across the series resistor is directly proportional to the load current, a detected error signal can be used to cancel any tendency for a change in load current from the desired value. Ideally, the linear current regulator has an infinite output impedance and output characteristics as shown in Fig. 87(a).

The regulator circuit used with **voltage-regulating current-regulating power supplies** is essentially a combination of the other types of linear regulators. As shown in Fig. 87(d), the output response characteristics of this type of regulated supply exhibit a crossover point at which the supply switches from voltage regulation to current regulation.

Fig. 90 shows a block diagram of a voltage-regulating current-regulating power supply. The input ac power is rectified and filtered and is then applied to the regulating circuit. When preregulators are used, as is normally the case, switching types are preferred. The efficiency of the switching regulator is extremely high, and a fast response time to load or line

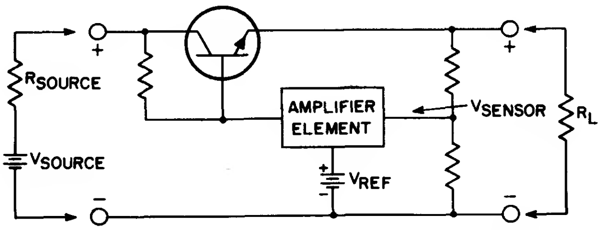


Fig. 88 - Basic series voltage regulator.

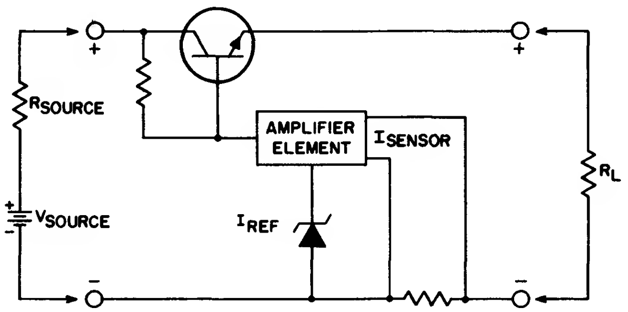


Fig. 89 - Basic series regulator modified for current sensing.

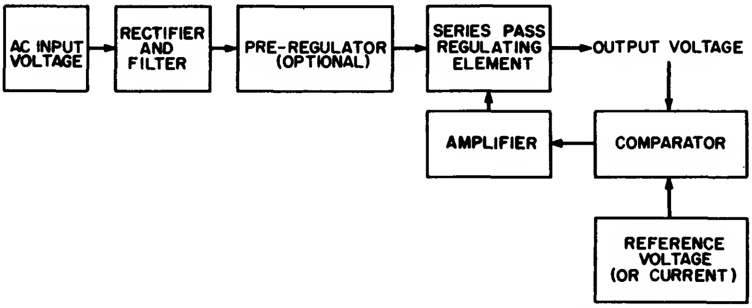


Fig. 90 - Block diagram of series voltage-regulating current-regulating dc power supply.

variations is not required at this point in the circuit. (The operation and characteristics of switching regulators are discussed later in the section on **Switching Regulators**.)

The output from the preregulator is transferred to the series pass element which provides the fast response time for the entire regulating circuit. At this point in the circuit, a sample of the output voltage is compared with a reference voltage and the resulting error signal, which is proportional to the difference between these voltages, is amplified and delivered to the base of the pass transistor to correct the output voltage.

In this type of system, the resulting output voltage is highly dependent upon the accuracy of the reference supply. Such a voltage source may be a temperature-compensated zener diode in series with a very constant source of current so that the diode incremental resistance has no effect on the output voltage. The sensitivity of the regulator is an inverse function of the gain of the drive amplifier. The smaller the variation to be sensed, the higher the required gain of the amplifier. A higher gain, however, results in less stability.

Performance Parameters

Most voltage-regulated power supplies are required to provide voltage regulation for wide variations in load current. It is important, therefore, to specify the output impedance of the supply, $\Delta V_{out}/\Delta I_{out}$, over a large band of frequencies. This parameter indicates the ability of the power supply to maintain a constant output voltage during rapid changes in load. The output impedance of a typical voltage-regulated supply is normally less than 0.1 ohm at all frequencies below 2 kHz. Above this frequency, the impedance increases and may be as much as several ohms.

A power supply must continue to supply a constant voltage (or current) regardless of variations in line voltage. An index of its ability to maintain a constant output voltage or current during input variation is called the **line regulation** of the supply, which is defined as 100 (V_o'/V_o), or as the change in output voltage ΔV_o, for a specified change in input voltage, expressed in per cent. Typical values of line regulation are less than 0.01 per cent.

Another important power-supply parameter is **load regulation**, which specifies the amount that the regulated output quantity (voltage or current) changes for a given change in the unregulated quantity. Load regulation is mainly a function of the stability of the reference source and the gain of the feedback network.

A power-supply parameter referred to as **recovery time** denotes the time required for the regulated quantity (voltage or current) to return to the specified limits when a step change in load is applied, as shown in Fig. 91.

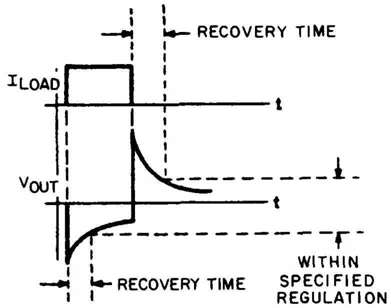


Fig. 91 - Typical recovery-time characteristics for regulated dc power supplies.

Recovery time is a function of the frequency response of the feedback network of the power supply. For voltage-regulated supplies, the "roll-off" of the feedback network increases the output impedance at high frequencies, and the impedance becomes inductive. As a result, the high-frequency harmonics of the step change in the load current induce a spike of voltage at the output.

The amount of change in the output voltage of the regulated power supply from an initial value over a specified period of time is referred to as **drift**. This parameter is measured after an initial warm-up period with a constant input voltage and load applied and the ambient temperature held constant.

Transistor Requirements

In linear series regulators, the transistor parameters that affect circuit design and performance are collector dissipation, maximum collector current I_C(max), leakage current (I_{CER} in most cases), current gains h_{FE} and h_{fe}, collector-to-emitter saturation voltage V_{CE}(sat), collector-to-emitter breakdown voltage V_{CEO}(sus), and second breakdown.

The collector-dissipation rating limits the amount of power which the series transistor can safely dissipate when the power supply is short-circuited. The maximum collector current I_C(max) limits the total current which the regulator can handle. A low value of leakage current is required to maintain the stability of the circuit and, possibly, to prevent thermal runaway. This requirement makes silicon transistors especially suitable for use as the regulator pass element because leakage current is generally much lower in silicon transistors than in germanium types. The current-gain parameters h_{FE} and h_{fe} determine the amount of drive current needed at various collector current levels. The ac forward-current transfer ratio h_{fe} also determines the output impedance of the supply. A high h_{fe} results in a low output impedance. The saturation voltage V_{CE}(sat) is one factor that determines the required input voltage to the regulator for a specified output voltage and current. The collector-to-emitter breakdown voltage V_{CEO}(sus) limits the maximum output voltage of the power supply. Second-breakdown considerations in circuit applications of transistors were discussed previously in the section on **Power Transistor Ratings and Characteristics.**

Current-Limiting Techniques

One of the problems encountered in the design of series transistor voltage regulators is protection of the series control element from excess dissipation because of current overloads and short circuits.

In some series voltage-regulator circuits, overloading results in permanent damage to the series control transistor. For example, when the output terminals of the regulator circuit shown in Fig. 92 are shorted, the full input voltage and available current are applied to the series control transistor. This power usually is many times greater than the dissipation ratings of the series transistor.

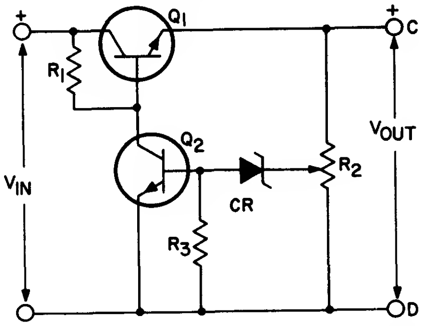


Fig. 92 - Series voltage regulator without current limiting.

A series fuse is sometimes used in an attempt to protect the series transistor from this excessive dissipation. A series fuse cannot usually provide the necessary protection under all overload conditions, however, because the thermal time constant of the fuse is normally much greater than that of the transistor.

Protection for all overload conditions may be accomplished by use of a circuit which limits the current to a safe value, as determined from the dissipation rating of the series regulator transistor. An effective current-limiting circuit must respond fast enough to protect the series transistor and yet permit the circuit to return to normal regulator operation as soon as the overload condition is removed. It is desirable to achieve current-overload protection with minimum degradation of regulator performance.

One method of achieving limiting is to use a resistor in series with the regulator transistor. The large resistance normally required, however, dissipates a large amount of power and degrades the regulator performance.

The current-limiting section (dashed line) of the regulator circuit shown in Fig. 93(a) is designed to appear as a large series resistance during current overload and as a negligible resistance during normal operating conditions. The value of resistance R_5 is designed so that, during normal regulator operation, transistor Q_4 operates in the saturated condition. For the overload condition, R_4 is adjusted so that the maximum allowable value of overload current through this resistor produces a voltage drop large enough to cause silicon rectifier CR_1 to conduct. Conduction of CR_1 reduces the bias to Q_4, so that the transistor appears as an increasing series resistance in the regulator circuit.

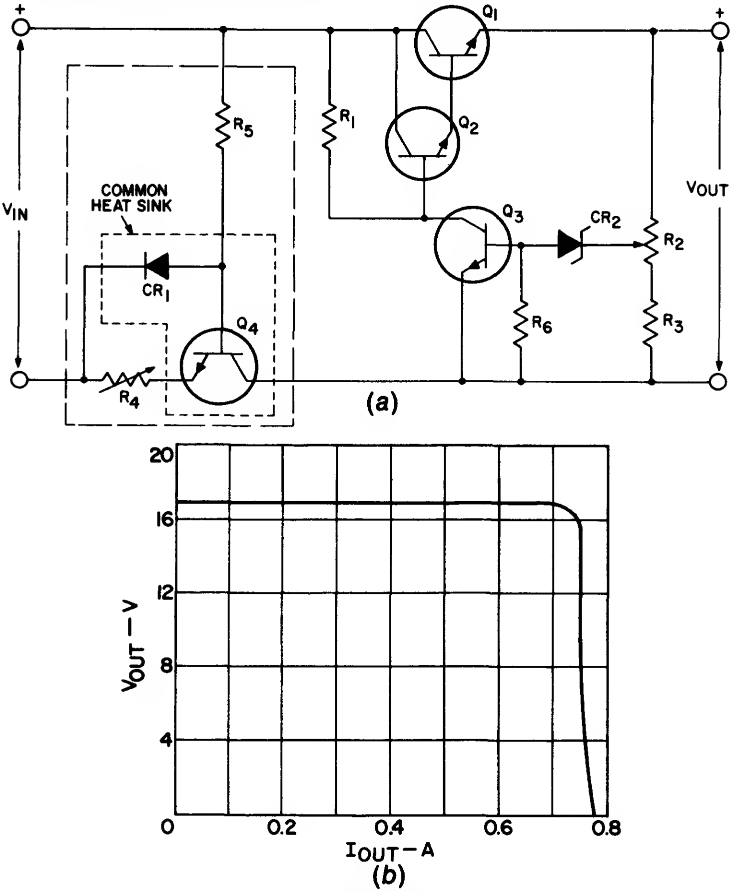
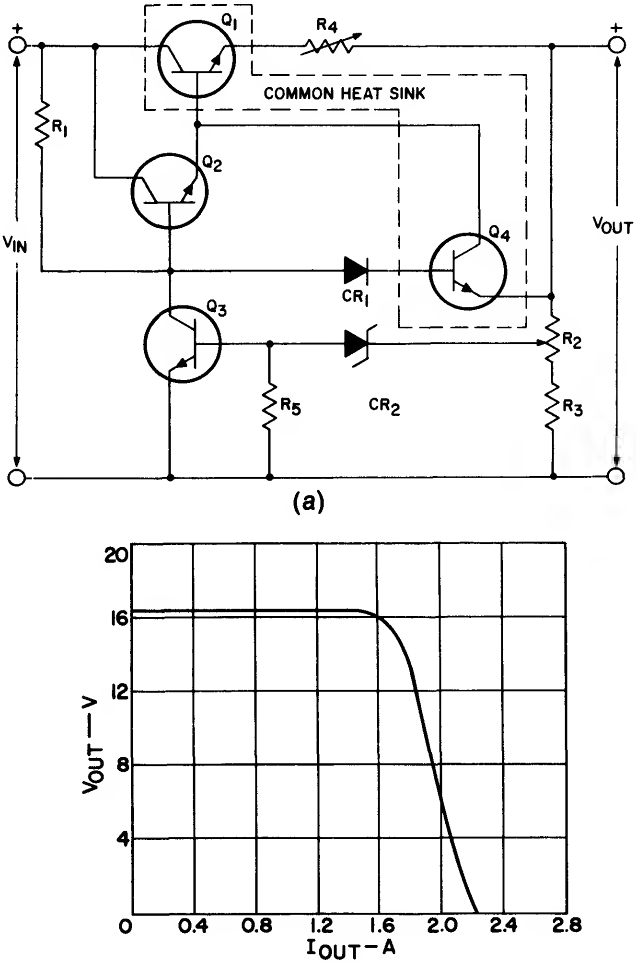


Fig. 93 - Series voltage regulator with transistor current-limiting circuit (inside dashed lines) added: (a) schematic diagram; (b) response characteristics.

Under short-circuit conditions, the entire value of input voltage V_{in} appears across Q_4 simultaneously with the limiting value of current. Transistor Q_4 must be capable of withstanding the resulting dissipation. When the current limit is reached, the junction temperature of Q_4 rises to a value considerably above the ambient temperature. This increase in junction temperature causes the value of short-circuit current to rise slightly because of the inherent variation of the base-to-emitter voltage V_{BE} with temperature in transistors. This effect is minimized by mounting silicon rectifier CR_1 and transistor Q_4 on a common heat sink so that their respective junction temperatures may reach the same value (the values of their respective V_{BE} and forward-voltage-drop temperature coefficients are comparable).

Performance characteristics for the transistor series voltage regulator of Fig. 93(a) are shown in Fig. 93(b).

Although the series-regulator circuit shown in Fig. 93(a) provides adjustable current limiting with simple circuitry and minimum power loss during normal operation, it has the disadvantage of requiring a second series transistor capable of withstanding short-circuit output current and total input voltage simultaneously.



(a)

(b)

Fig. 94 - Series voltage regulator using pass transistor as part of current-limiting circuit: (a) schematic diagram; (b) response characteristics (for R_4=0).

In many high-current high-voltage regulator circuits, it is necessary to use parallel or series connections of pass transistors so that the voltage, current, and power ratings of the series control element are not exceeded. The method shown in Fig. 93(a) may not be practical in this application because of the additional series transistor required. The circuit shown in Fig. 94(a) eliminates the need for an additional series transistor by use of the series regulator transistor as the current-limiting element. This method is very effective when a Darlington connection is used for the series control transistor. A desirable feature of this circuit in high-current regulators is that it functions well even when the value of resistor R_4 is reduced to zero.

In the circuit shown in Fig. 94(a), current limiting is achieved by the combined action of the components shown inside the dashed lines. The voltage developed across R_4 and the base-to-emitter voltages of Q_1 and Q_2 are proportional to the circuit output current. During current overload, these voltages add up to a value great enough to cause CR_1 and Q_4 to conduct. As CR_1 and Q_4 begin to conduct, Q_4 shunts a portion of the bias available to the series regulator transistor. This action, in turn, increases the series resistance of Q_1. The value of current in the circuit, under current-limiting conditions, is adjusted by varying the value of resistance R_4.

Higher current ranges may be obtained by increasing the number of rectifiers represented by CR_1. Temperature drift is minimized by mounting transistors Q_1 and Q_4 on a common heat sink. Performance characteristics for this circuit (for $R_4 = 0$) are shown in Fig. 94(b).

The circuit shown in Fig. 95(a) is a variation of that shown in Fig. 94(a). Current limiting is adjusted by varying R_4 and by changing the number of silicon rectifiers represented by CR_1. Temperature drift is minimized by mounting the series control transistor Q_1 and silicon rectifier CR_1 on a common heat sink. Performance characteristics for this circuit are shown in Fig. 95(b). The circuits shown in Figs. 94 and 95 are both applicable to high-current high-voltage regulators because additional series power transistors are not required.

Fig. 96(a) shows another current-limiting circuit in which the regulator series control transistor is used as the current-limiting element. The series element must be capable of withstanding input voltage and short-circuit current simultaneously. The value of short-

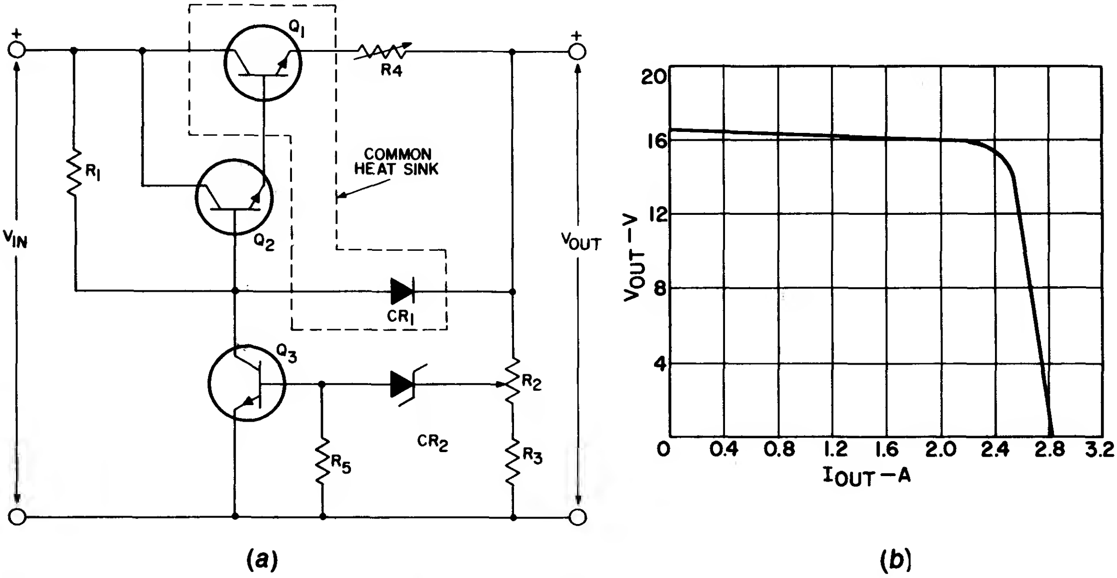


Fig. 95 - Series voltage regulator which uses additional transistor-diode network and series pass transistor to accomplish current-limiting function: (a) schematic diagram; (b) response characteristics.

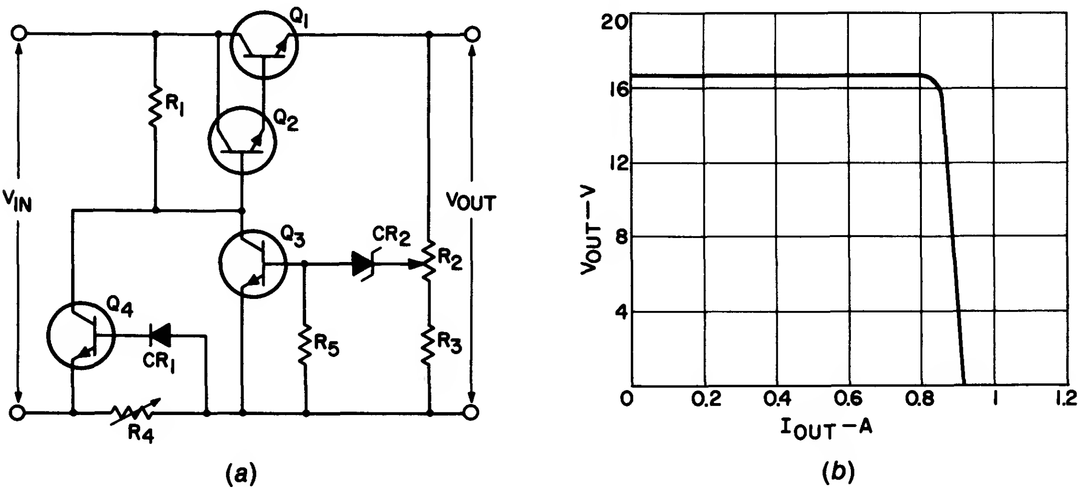


Fig. 96 - Current-limiting series voltage regulator in which series pass transistor must be capable of withstanding input voltage and short-circuit current simultaneously: (a) schematic diagram; (b) response characteristics.

circuit current is selected by adjusting the value of resistor R_4. Performance characteristics of this circuit are shown in Fig. 96(b). The circuit functions equally well with resistor R_4 located in the positive output lead.

Foldback Current Limiting

Foldback current limiting is a form of protection against excessive current. If the load impedance is reduced to a value that would draw more than the predetermined maximum current, the foldback circuit reduces output voltage and thus reduces the current. Further reduction of load impedance causes further decrease of output voltage and current; therefore a regulated power supply that includes a foldback current-limiting circuit has the voltage-current characteristic shown in Fig. 97. The foldback process is reversible; if the load impedance is increased while the circuit is in the limiting mode, the output voltage and current increase. When the current reaches the threshold level, the regulator is re-activated, and the power supply returns to normal operation.

For additional information on the Design of Current Regulated Supplies, refer to **RCA Solid State Power Circuits Handbook**, SP-52 Series.

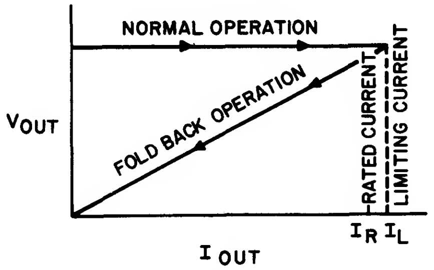


Fig. 97 - Output characteristic of a regulated power supply with foldback current-limiting protection for pass transistor.

A foldback current-limiting circuit is shown in Fig. 98. At low output current, transistor Q_5 is cut off; the value of resistor R_5 is selected so that Q_5 has zero bias when the output current reaches its rated value, I_R. When the load current I_{OUT} reaches the limiting value, I_X, Q_5 begins to conduct; current flows through resistor R_2, transistor Q_4 turns on, and the base-to-emitter voltage of transistor Q_3 is reduced. Therefore, the base-to-emitter voltage of transistor Q_2 decreases, and the output voltage of the power supply decreases. This decrease in the output voltage V_{OUT} reduces the output current, so that Q_5 continues to conduct at the same emitter current. If the load impedance is reduced further, Q_5 is

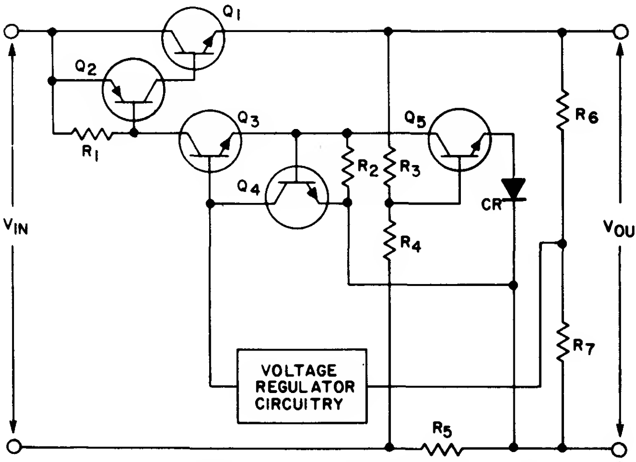


Fig. 98 - Foldback-current-limiting circuitry in a series voltage regulator

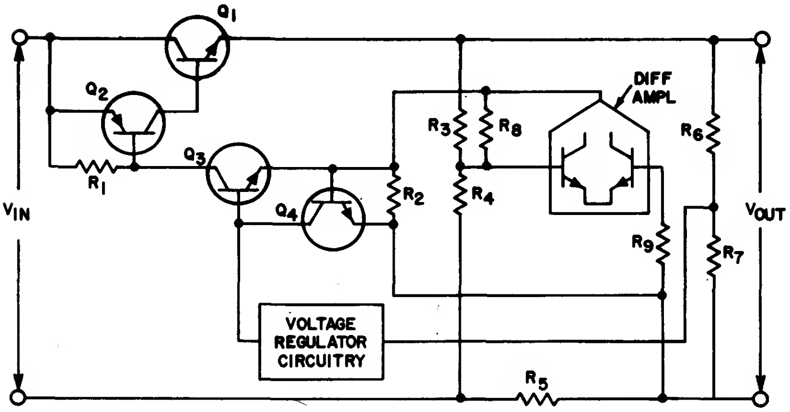


Fig. 99 - Foldback-current-limiting circuit with a differential amplifier for greater sensitivity.

driven even harder, and the output voltage and current decrease even further.

Improved foldback-circuit performance can be achieved by use of a differential amplifier instead of single-ended amplifier Q_5. With the improved circuit, illustrated in Fig. 99.

FOLDBACK—LIMITED REGULATED SUPPLY

Fig. 100 shows a series regulated power supply with foldback current limiting. This supply can deliver currents of up to 3 amperes at 20 volts. The circuit uses integrated circuits for the regulation and protection functions; the voltage regulator is an RCA-CA3085A and the foldback limiter uses an RCA-CA3030 operational amplifier as a linear differential amplifier.

Circuit Description

Specifications for the 60-watt, 20-volt supply shown in Fig. 100 are listed on page 69. The circuit uses an external pass transistor and driver to extend the current capability of the RCA-CA3085A integrated circuit voltage regulator; the overload protection provided by a foldback current-limiting circuit permits operation of the transistor at a dissipation level close to its limit. This foldback circuit achieves high efficiency by use of an RCA-CA3030 integrated circuit operational amplifier.

The over-all operation of the circuit can be understood with the aid of the schematic diagram shown in Fig. 100. Transformer T1 and its rectifiers supply the raw dc power that is regulated by pass transistor Q_1; this pass transistor is driven by driver Q_2, which is driven by the CA3085A voltage regulator. Transformer T2, with its rectifiers and shunt regulator Q_4, provides positive and negative supplies for the operational amplifier CA3030. This operational amplifier drives the current-limiting control Q_3. Output voltage is sensed at resistance string (R_6 + R_{13}), and load current is sensed by R_S.

Voltage Regulation

The power-supply output voltage is sampled by the voltage divider (R_6 + R_{13}), and a portion is fed to terminal No. 6 (the inverting input) of the CA3085A. (This portion is less than the 3.3-volt breakdown voltage of the type 1N5225 zener diode; the zener is present only to protect the integrated circuit from accidental overvoltages.) If the output voltage decreases, the base-to-emitter voltage of Q_2 increases, as explained in the next paragraph. Therefore the pass transistor Q_1 is driven harder, and as a result the output voltage increases to its original value (minus the error dictated by the system gain).

The process by which a voltage decrease at

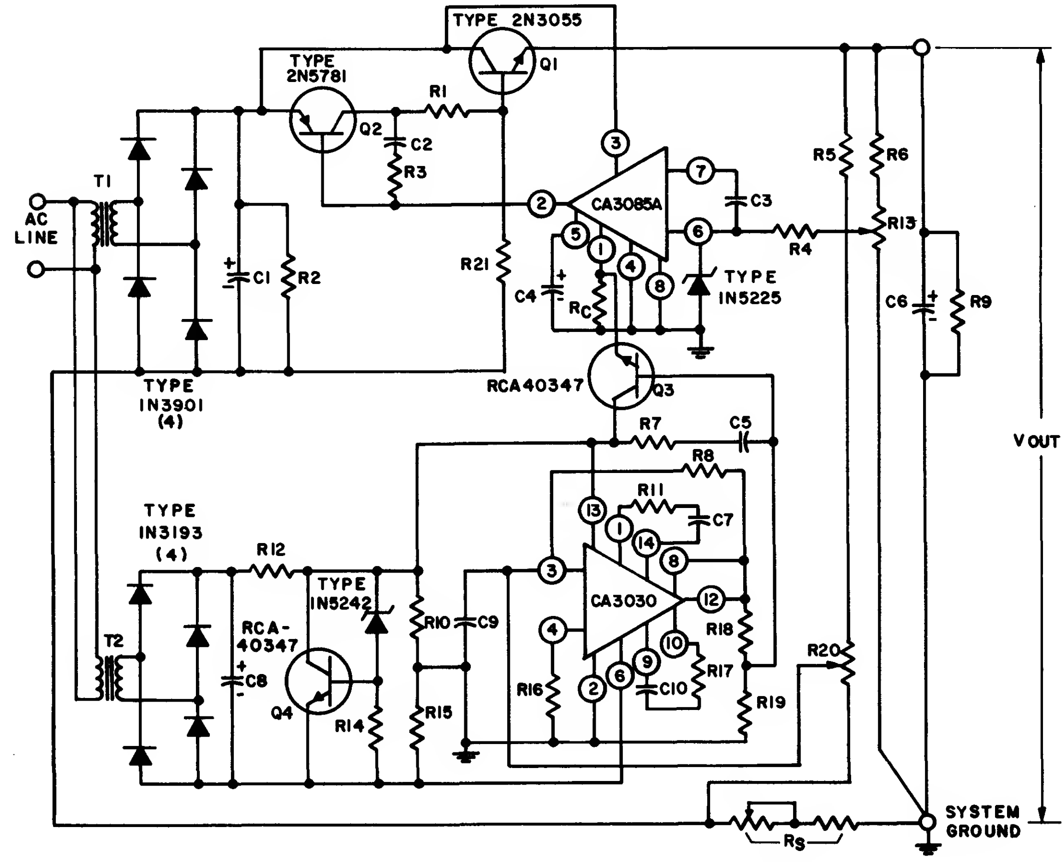


Fig. 100 - Schematic diagram of a dc power supply that uses integrated circuits in the voltage regulator and foldback-current-limiting circuitry.

Parts List for Schematic Diagram of Fig. 100

T_1=Signal Transformer Co., Part No. 24-4 or equivalent
T_2=Signal Transformer Co., Part No. 12.8-0.25 or equivalent
C_1=5900 μF, 75 V, Sprague Type 36D592F075BC or equivalent
C_2=0.005 μF, ceramic disc, Sprague TGD50 or equivalent
C_3, C_7, C_{10}=50 pF, ceramic disc, Sprague 30GA-Q50 or equivalent
C_4=2 μF, 25 V, electrolytic, Sprague 500D G025BA7 or equivalent
C_5=0.01 μF, ceramic disc, Sprague TG510 or equivalent
C_6=500 μF, 50 V, Cornell-Dubilier No. BR500-50 or equivalent
C_8=250 μF, 25 V, Cornell-Dubilier BR 250-25 or equivalent
C_9=0.47 μF, film type, Sprague Type 220P or equivalent
R_1=5 ohms, 1 watt, IRC type BWH or equivalent
R_2=1000 ohms, 5 watts, Ohmite type 200-5 ¼ or equivalent
R_3=1200 ohms, ½ watt, carbon, IRC Type RC ½ or equivalent
R_4=100 ohms, ½ watt, carbon, IRC Type RC ½ or equivalent
R_5=430 ohms, 2 watt, wire wound IRC Type BWH or equivalent
R_6=9100 ohms, 2 watts, wire wound, IRC Type BWH or equivalent
R_7=470 ohms, ½ watt, carbon, IRC type ½ or equivalent
R_8=5100 ohms, ½ watt, carbon, IRC type RC ½ or equivalent
R_9,R_{14}=1000 ohms 2 watts, wire wound, IRC type BWH or equivalent
R_{10},R_{15}=250 ohms, 2 watts, 1% wire wound, IRC type AS-2 or equivalent
R_{11},R_{17}=1000 ohms, ½ watt, carbon, IRC type RC ½ or equivalent
R_{12}=82 ohms, 2 watts, IRC type BWH or equivalent
R_{13}=1000 ohms, potentiometer, Clarostat Series U39 or equivalent
R_{16}=1200 ohms, 2 watts, wire wound, IRC type BWH or equivalent
R_{36}=510 ohms, ½ watt, carbon, IRC type RC ½ or equivalent
R_{19}=10,000 ohms, ½ watt, carbon, IRC type RC ½ or equivalent
R_{20}=300 ohms, potentiometer, Clarostat Series U39 or equivalent
R_{21}=510 ohms, 3 watts, wire wound, Ohmite type 200-3 or equivalent
R_C=240 ohms, 1%, wire wound, IRC type AS-2 or equivalent
R_S=(See text for fixed portion); 1 ohm, 25 watts, Ohmite type H or equivalent

Miscellaneous

(1 Req'd)—Heat Sink, Delta Division Wakefield Engineering NC-423 or equivalent
(3 Req'd)—Heat Sink, Thermalloy #2207 PR-10 or equivalent
(1 Req'd)—8-pin socket Cinch #8-1CS or equivalent
(1 Req'd)—14-pin DIL socket, T.I., #ICO14ST-7528 or equivalent
(2 Req'd)—TO-5 socket ELCO #05-3304 or equivalent
Vector Board #838AWE-1 or equivalent
Vector Receptacle R644 or equivalent
Chassis—As required
Cabinet—As required
Dow Corning DC340 filled grease

60-Watt, 20-Volt Power-Supply Specifications

V_{input}	105-130 V, Single Phase, 55-420 cps	Transients: No load to full load: Full load to no load:	 100 mV, recovery within 50 μs 100 mV, recovery within 50 μs
V_{output}	20 V ±0.5 V		
I_{load}(max)	3 A		
Ambient Temperature	0 to +55°C	Drift	20 mV in 8 hours of operation at constant ambient temperature
Voltage spikes	None at turn-on or turn-off		
Regulation	Line: ±0.25% Load: ±0.25%	Short Circuit and Overcurrent Protection	Foldback technique
Ripple	33 mV pp; 9.5 mV rms		

terminal No. 6 of the CA3085A produces an increase of Q_2 base-to-emitter voltage can be understood with the aid of Fig. 101, which shows some of the internal circuitry of the CA3085A. The drop of voltage at terminal No. 6 causes a higher base-to-emitter voltage at the Darlington combination Q_{13}-Q_{14}. Therefore the collector current of Q_{14} increases, and thus increases the voltage drop across the 500-ohm resistor, which is the base-to-emitter voltage of Q_2.

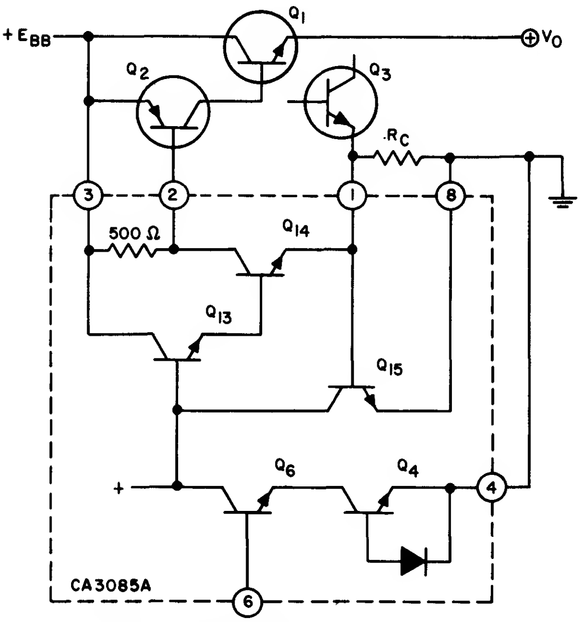


Fig. 101 - CA3085A control of the power transistors.

Foldback Current-Limiting Circuit

The purpose of the current-limiting circuit is to prevent the power supply from passing a load current that could damage the pass transistor if a very low impedance (or a short circuit) is placed across the output terminals. Fig. 102 shows the effect of this circuit. The supply voltage remains constant until the load current reaches the threshold for activation of the limiting circuit; any further decrease of load impedance causes output voltage V_O and load current I_O to decrease, so that the V_O-I_O characteristic folds back to limit the power dissipation in the pass transistor. Activation of the foldback limiting circuit disables the voltage-regulation circuit.

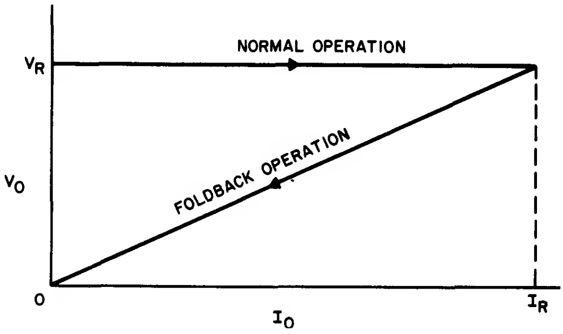


Fig. 102 - Foldback current-limiting characteristic.

The foldback current-limiting circuit shown in Fig. 103 uses the CA3030 integrated circuit as a differential amplifier. A signal from the voltage divider R_{R1} and R_{R2}*, which is across V_O and the E_{BB} return, is applied to the inverting input (terminal No. 3) of the CA3030. The non-inverting input is tied to system ground through R_{16}. Thus the base-to-base signal that actuates the CA3030 is the difference between $V_{RS}(=I_OR_S)$ and V_{RR2}. The CA3030 output, which is the voltage at terminal No. 12, varies linearly with the actuating voltage, as shown in Fig. 104. When the load current is zero*, V_{RS} is zero; therefore $(V_{RS}-V_{RR2})$ is negative, terminal 12 is negative with respect to ground, and Q_3 is back-biased (i.e., cut off). Therefore Q_3 does not interfere with the normal voltage-regulated operation of the supply. As the load current increases, V_{RS} increases and the voltage at terminal 12 increases.

The value of resistor R_S is adjusted so that when the load current reaches the foldback-activation value (about 3 amperes in the power supply shown), the voltage at terminal No. 12 of the CA3030 becomes positive. At about 0.7 volt, transistor Q_3 begins to conduct; current flows through the current-limiting resistor R_C, with the result that terminal No. 1 of the CA3085A control circuit is driven positive. Q_{15} of Fig. 101 turns on, and the base-to-emitter voltage of Q_{13}-Q_{14} is therefore reduced; the base-to-emitter voltage of Q_2 is reduced, and the output voltage of the power supply decreases. This decrease of V_O tends to reduce the load current; however, V_{RR2} also

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*R_{R1} actually consists of R_5 and the upper portion of R_{20} in the schematic diagram of Fig. 100. R_{R2} is the lower portion of R_{20}.

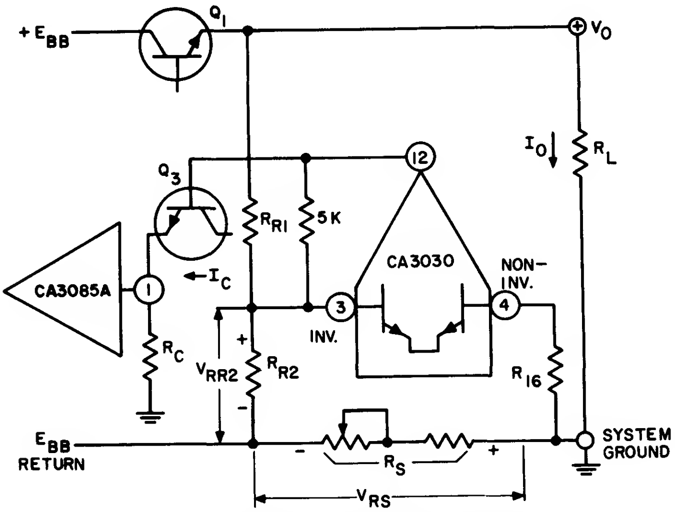

Fig. 103 - Foldback current-limiting circuit.

decreases with V_O, so that $(V_{RS}-V_{RR2})$ remains fixed and Q_3 continues to conduct at the same emitter current. If the load impedance is reduced, Q_3 will be driven even harder, and therefore the output voltage and the load current will decrease even further. Fig. 102 shows the foldback as R_L decreases.

This process is reversible. If the load impedance R_L is increased, I_O and V_O will increase. When I_O reaches the foldback-activation level, Q_3 will cut off again and the power supply will return to regulated operation.

The CA3030 must be operated as a linear voltage amplifier in the foldback circuit, so that the gain is as shown in Fig. 104. If the CA3030 is misadjusted, a Schmitt trigger action can occur. Such operation may be desirable in latching-type current protection, e.g., in circuits that switch off at overload. Such circuits, however, introduce other problems such as lack of automatic turn-on, hysteresis effects on varying loads during the shutdown process, and capacitive and nonlinear loads.

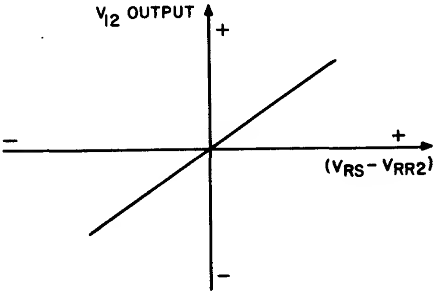

Fig. 104 - Output voltage from the CA3030 operational amplifier as a function of actuating voltage.

FOLDBACK-LIMITED SUPPLY

Hybrid-Circuit Regulator

The RCA line of power hybrid circuits includes a series voltage regulator, shown in Fig. 105, designed for use as the regulating element in foldback-current-limited, regulated dc power supplies. The hybrid-circuit regulator includes an RCA-CA3085A integrated-circuit voltage-regulator chip for voltage regulation, stability, and temperature compensation. This integrated circuit supplies a regulated signal to a two-stage high-current booster circuit that consists of a p-n-p driver chip Q_2 and an n-p-n hometaxial-base transistor chip Q_4 (RCA-2N3055 type) used as the series pass transistor. This two-stage output circuit makes possible a load-current capability of 4 amperes without the use of external booster devices. With the use of two external booster transistors, the hybrid circuit can provide regulation at load currents up to 12 amperes. For load currents greater than 12 amperes, the regulator circuit is used as a Darlington driver.

The internal circuitry of the hybrid regulator also includes a foldback-current-limiting circuit, a crowbar trigger circuit, and three

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*The currents in the 1-kilohm bleeder resistor and the 10-kilohm sensing string are neglected in this discussion.

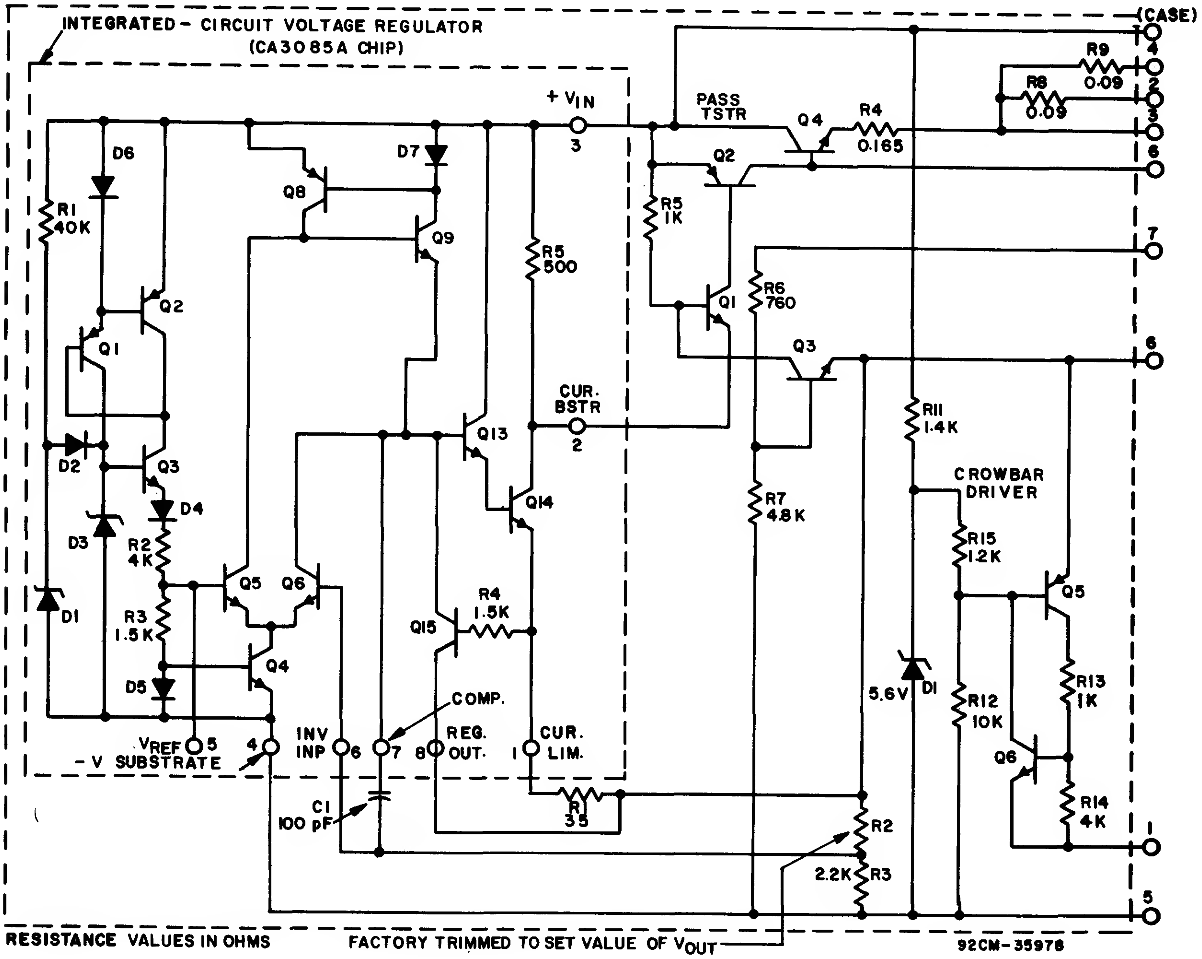


Fig. 105 - RCA high-current hybrid-circuit series voltage regulator.

ballast resistors. The ballast resistors are provided to assure current sharing between the internal pass transistor and two external pass transistors when regulation is required at current levels between 4 and 12 amperes.

Because the CA3085A chip is rated for a maximum supply voltage of 40 volts and a feedback voltage to the inverting input (terminal 6) of 1.8 volts, the output-voltage capability of the hybrid-circuit regulator is limited to a range from 2 to 32 volts. Standard-design regulator circuits that provide a regulated output of 5, 8, or 12 volts are available. For each type, the output voltage is regulated to within ±1 per cent for typical line-voltage, load-current, and temperature variations.

The values of the voltage-divider resistors R_2 and R_3 establish the level of the output voltage. The junction of these resistors is directly coupled to the inverting input of the CA3085A voltage-regulator chip. The values of the resistors are selected to divide the output voltage so that, for the rated output, the voltage applied to the CA3085A inverting input is approximately 1.6 volts. Any change in output voltage produces a corresponding change at the inverting input of the CA3085A and this circuit then develops an output to cancel the change in output voltage. For example, an increase in load resistance causes the output voltage to rise. The resultant increase in the voltage at the inverting input of the CA3085A is applied to the base of transistor Q_6 on the CA3085A chip, and the collector current of this transistor increases. The base current of transistor Q_{13} then decreases because it is derived from a constant-current source. This action, in turn, causes the base and collector currents of transistor Q_{14} to decrease so that the drive for the p-n-p driver transistor Q_2 and the n-p-n pass transistor Q_4 is reduced. The load current then decreases to return the output voltage to its original value.

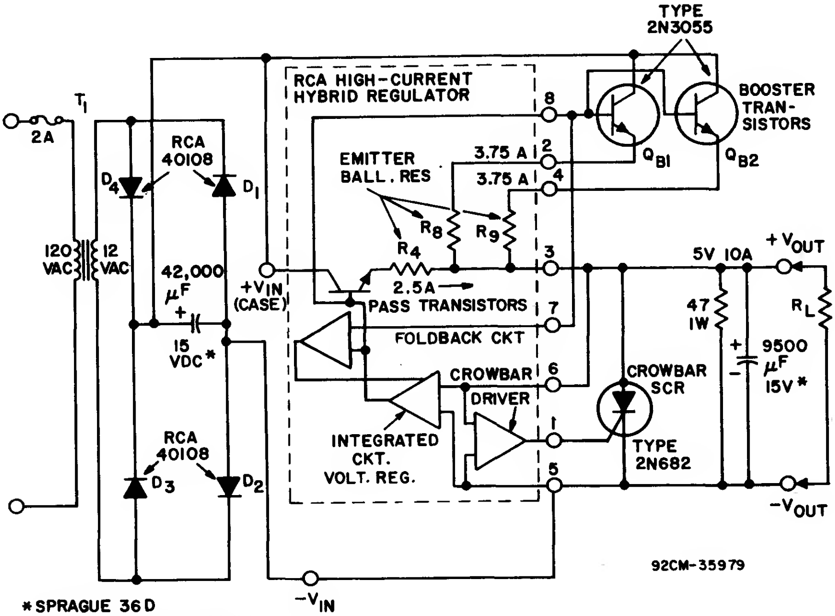
HIGH-OUTPUT-CURRENT VOLTAGE REGULATOR WITH FOLDBACK CURRENT LIMITING

Fig. 106 illustrates the use of the hybrid-circuit series voltage regulator in a foldback-current-limited, regulated dc power supply. This supply provides an output of 5 volts regulated to within ±1 per cent. The two external 2N3055 hometaxial-base transistors Q_{B1} and Q_{B2} are used as booster pass transistors to increase the load-current capability of the basic regulator circuit to 10 amperes.

The values of the three ballast resistors (R_4, R_8, and R_9) in the hybrid circuit are selected so that (1) the voltage drop across each resistor at the rated current is approximately 450 millivolts and (2) the current through each external pass transistor is 1.5 times that through the internal pass transistor. These resistors, therefore, force the required current sharing between the internal and external pass transistors.

The foldback-current-limiting circuit consists of transistors Q_1 and Q_3 and resistors R_1, R_5, R_6, and R_7 in the hybrid circuit (shown in Fig. 105). Transistor Q_3 senses the voltages across the branches of the bridge circuit formed by resistors R_6 and R_7 on one side and the base-emitter junction of the series pass transistor Q_4, resistor R_4, and the load resistance on the other side. Because the base-to-emitter voltage of transistor Q_4 increases with the collector current, inclusion of the base-emitter junction of this transistor in the bridge increases circuit sensitivity.

During normal operation, transistor Q_1 is operated in the saturation region, and transistor Q_3 is cut off. When an overload occurs, transistor Q_3 is driven into conduction, and the collector current of this transistor flows through resistor R_5 to decrease the base-to-emitter voltage of transistor Q_1. This effect reduces the base drive to the p-n-p driver



*SPRAGUE 36D
CORNELL FAH, OR EQUIV.
T_1=SIGNAL TRANSFORMER CO.
No. 36-6, OR EQUIV.

Fig. 106 - Foldback-current-limited regulated dc power supply that uses an RCA high-current power hybrid circuit as the series voltage regulator.

transistor Q_2 and subsequently the voltage drop across the load resistor. The voltage-feedback condition reaches a stable point on the load-resistance characteristic because the loop gain is less than unity. Transistor Q_1 effectively protects transistors Q_2 and Q_4 and the main pass transistor Q_{14} on the CA3055 integrated-circuit chip (shown in Fig. 105), but it does not protect transistor Q_{13}. Protection of this latter transistor is provided by transistor Q_{15}, which turns on when the current through resistor R_1 reaches 20 milliamperes.

The crowbar trigger circuit in the hybrid circuit provides a trigger input to the external 2N682 crowbar SCR in response to an overvoltage that ranges from 105 to 125 per cent of the rated output value. This overvoltage may result from short-duration transient currents generated by either the load, the supply, or a pass transistor that becomes short-circuited. Resistor R_{11} and zener diode D_1 provide a stable reference voltage that is reduced in value by the voltage divider formed by resistors R_{12} and R_{15}. The voltage at the junction of these resistors is compared to the output voltage by transistor Q_5. When an overvoltage occurs, transistor Q_5 turns on and provides the base drive to turn on the transistor Q_6. This action is regenerative, and the collector currents of transistors Q_5 and Q_6 are limited only by resistor R_{13}, which limits the base current of transistor Q_6. Resistor R_{14} provides a leakage path for the collector-base junction of transistor Q_6. The output of the trigger circuit is connected to the gate of the SCR. The SCR is triggered on by the gate current supplied by this circuit to provide a low-impedance path to shunt excessive currents generated by the overvoltage condition away from the load circuit.

In high-current voltage regulators employing constant-current limiting, it is possible to develop excessive dissipation in the series-pass transistor when a short-circuit develops across the output terminals. This situation can be avoided by the use of the "foldback" current-limiting circuitry as shown in Fig. 107. In this circuit, terminal 8 of the RCA CA3085A senses the output voltage, and terminal 1 is tied to a tap on a voltage-divider network connected between the emitter of the pass-transistor (Q_3) and ground. The current-foldback trip-point is established by the value of resistor R_{SC}.

The protective tripping action is accomplished by forward-biasing Q_{15} in the CA-3085A. Conditions for tripping-circuit operation are defined by the following expressions:

$$V_{BE}(Q_{15}) = \text{(voltage at terminal 1)} - \text{(output voltage)}$$

$$= \left[(V_O + I_L R_{SC}) \frac{R_1}{R_1 + R_2} \right] - V_O$$

$$\text{If } \frac{R_1}{R_1 + R_2} = K, \text{ then}$$

$$V_{BE}(Q_{15}) = (V_O + I_L R_{SC})K - V_O = KV_O + KI_L R_{SC} - V_O$$

and therefore

$$R_{SC} = \frac{V_O + V_{BE}(Q_{15}) - KV_O}{KI_L}$$

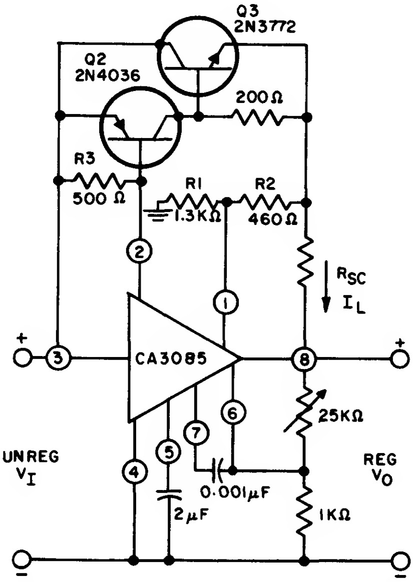


Fig. 107 - High-output-current voltage regulator with "foldback" current limiting.

Under load short-circuit conditions, terminal 8 is forced to ground potential and current flows from the emitter of Q_{14} in the CA3085A establishing terminal 1 at one V_{BE}-drop [$\cong 0.7$ V] above ground and Q_{15} in a partially conducting state. The current through Q_{14} necessary to establish this one-V_{BE} condition is the sum of currents flowing to ground through R_1 and [$R_2 + R_{SC}$]. Normally R_{SC} is much smaller than R_2 and can be ignored: therefore, the equivalent resistance R_{eq} to ground is the parallel combination of R_1 and

R_2. The Q_{14} current is then given by:

$$I_{Q_{14}} = \frac{V_{BE(Q_{15})}}{R_{eq}} = \frac{V_{BE(Q_{15})}}{\frac{R_1 R_2}{R_1 + R_2}} = \frac{0.7\,[1.3+0.46]}{1.3 \times 0.46} = 2.06 \text{ milliamperes}$$

This current provides a voltage between terminals 2 and 3 as follows:

$$V_{2\text{-}3} = I_{Q_{14}} \times 250 \text{ ohms} = 2.06 \times 10^{-3} \times 250 = 0.515 \text{ volt.}$$

The effective resistance between terminals 2 and 3 is 250 ohms because the external 500-ohm resistor R_3 is in parallel with the internal 500-ohm resistor R_5. It should be understood that the $V_{2\text{-}3}$ potential of 0.515 volt is insufficient to maintain the external p-n-p transistor Q_2 in conduction, and, therefore, Q_3 has no base drive. Thus the output current is reduced to zero by the protective circuitry. Fig. 108 shows the foldback characteristic typical of the circuit of Fig. 107.

An alternative method of providing "foldback" current-limiting is shown in Fig. 109. The operation of this circuit is similar to that of Fig. 107, except that the foldback-control transistor Q_2 is external to the CA3085A to permit added flexibility in protection-circuit design.

Under low load conditions Q_2 is effectively reverse-biased by a small amount, depending upon the values of R_3 and R_4. As the load current increases the voltage drop across R_{trip} increases, thereby raising the voltage at the base of Q_1 and Q_2 starts to conduct. As Q_2

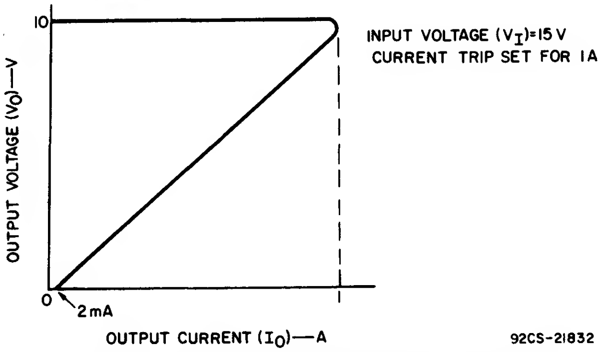


Fig. 108 - Typical "foldback" current-limiting characteristic for circuit of Fig. 107.

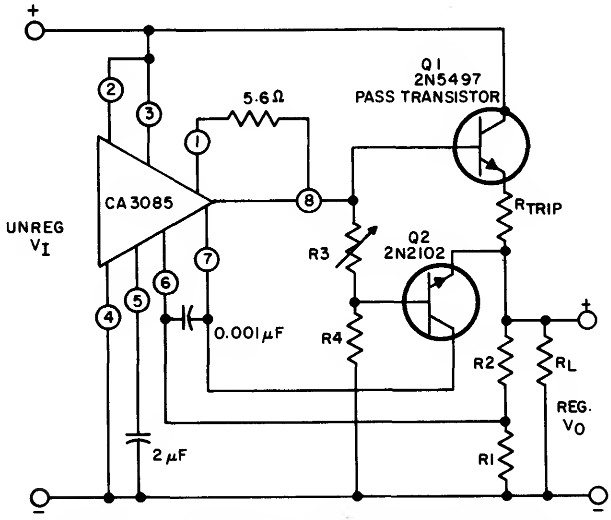


Fig. 109 - High-output-current voltage regulator using auxiliary transistor to provide "foldback" current limiting.

becomes increasingly conductive it diverts base current from transistors Q_{13} and Q_{14} in the CA3085, and thus reduces base drive to the external pass-transistor Q_1 with a consequent reduction in the output voltage. The point at which current-limiting occurs, I_{trip}, is calculated as follows:

$V_{BE}(Q_1)$=voltage at terminal 8 $-V_O$(assuming a low value for R_{trip})

$V_{BE}(Q_2)$=voltage at terminal $8\left(\frac{R_4}{R_3+R_4}\right)-V_O$

$$=\left[V_O+I_LR_{trip}+V_{BE}(Q_1)\right]\left[\frac{R_4}{R_3+R_4}\right]-V_O$$

if $K=\frac{R_4}{R_3+R_4}$, then the trip current is given by:

$$I_{trip}=\frac{V_{BE}(Q_2)-K[V_O+V_{BE}(Q_1)]+V_O}{KR_{trip}}$$

In the circuit in Fig. 107 the load current goes to zero when a short circuit occurs. In the circuit of Fig. 109 the load current is significantly reduced but does not go to zero. The value for I_{SC} is computed as follows:

$$V_{BE}(Q_2)+\left[\frac{V_{BE}(Q_2)}{R_2}+I_B(Q_2)\right]R_1=V_{BE}(Q_1)+I_{SC}R_{trip}$$

$$I_{SC}=\frac{V_{BE}(Q_2)+\left[\frac{V_{BE}(Q_2)}{R_2}+I_B(Q_2)\right]R_1-V_{BE}(Q_1)}{R_{trip}}$$

Fig. 110 shows that the transfer characteristic of the load current is essentially linear between the "trip-point" and the "short-circuit" point.

SHUNT REGULATORS

Although shunt regulators are not as efficient as series regulators for most applications, they have the advantage of greater simplicity. The shunt regulator includes a shunt element and a reference-voltage element.

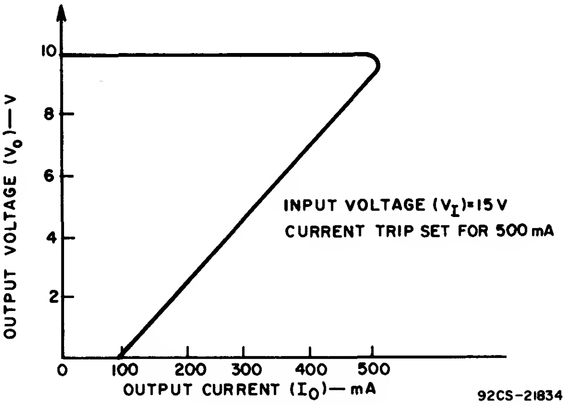


Fig. 110 - Typical foldback current-limiting characteristic for circuit of Fig. 109.

The output voltage remains constant because the shunt-element current changes as the load current or input voltage changes. This current change is reflected in a change of voltage across the resistance R_1 in series with the load. A typical shunt regulator is shown in Fig. 111.

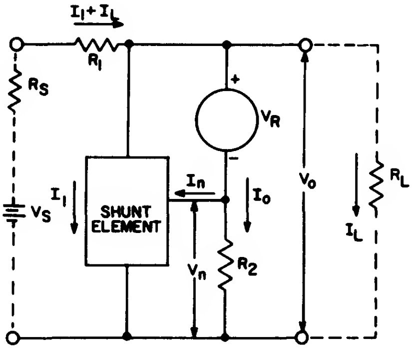


Fig. 111 - Basic configuration for a typical shunt regulator.

The shunt element contains one or more transistors connected in the common-emitter configuration in parallel with the load.

For a detailed discussion of the Design and Equations for Shunt Regulators, refer to **RCA Solid State Circuits Handbook**, SP52-Series