Switching Regulator Power Supplies

A switching regulator is used to maintain the output voltage Vo constant during variations in loading. Essentially, the regulator is an inductance-capacitance (LC) filter in series with a switch and a power source. By variation in the length of time the switch is on during each cycle, the amount of energy delivered to the filter can be controlled. The output voltage Vo is a function of this energy.

BASIC REGULATOR OPERATION

As shown in Fig. 112, Q1 is used in the switching mode; therefore, large power levels may be controlled with low loss. Because the output voltage of a switching regulator is not perfectly regulated, this circuit is often used as a preregulator.

Typical operating waveforms for a switching regulator are shown in Fig. 113. The period T is constant; the transistor "on" time t, however, is variable. A differential amplifier compares the output voltage to a reference voltage, and that difference determines the "on" time t. The output voltage Vo is proportional to t for a given load. When Q1 is on, current increases linearly in the L part of the LC filter. When Q1 is off, the energy in L is transferred to C and the load. The commutating diode limits the voltage across Q1 to the supply voltage. When Q1 again turns on, the capacitance of the diode must be discharged. This discharge causes an initial spike in the collector current of Q1.

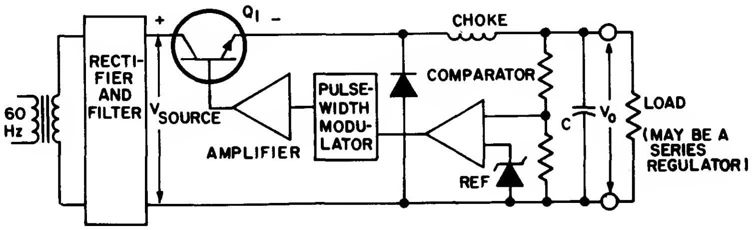

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Fig. 112 - Switching regulator.

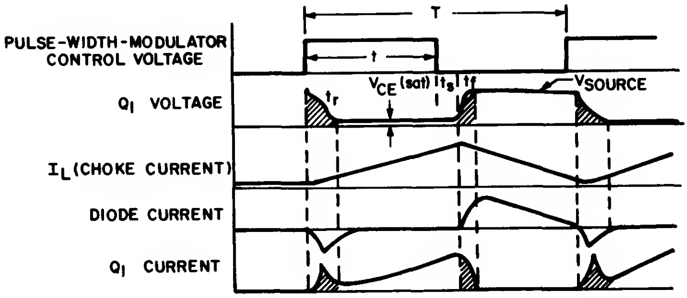

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Fig. 113 - Typical operating waveforms for a switching regulator.

Some important characteristics of the switching-regulator performance are as follows:

1. The maximum operating frequency may be limited by the switching time of the transistor Q1.
2. The collector-to-emitter saturation voltage $V_{CE}(sat)$ and switching-time losses cause device dissipation and power loss. The power dissipation P_t in Q1 is determined as follows:

$$P_t = V_{CE}(sat)\ I_C \frac{t}{T} + \frac{E_{SW}\text{ (rise and fall)}}{T}$$

   where t is the transistor "on" time. T is the period, I_C is the collector current in amperes, and E_{SW} is the energy absorbed by the output transistor during switching. The collector-to-emitter saturation voltage $V_{CE}(sat)$ and the transistor rise and fall times should be small to ensure low device dissipation.
3. The maximum output voltage is limited by the amount of voltage that Q1 can withstand without breaking down. Because the full source voltage appears across Q1 when it is off and the diode is on, the collector-to-emitter breakdown voltage V_{CEX} should be greater than the source voltage.

DESIGN OF A PRACTICAL SWITCHING—REGULATOR POWER SUPPLY

Power supplies that use switching regulation usually are smaller and lighter and operate more efficiently than conventional supplies. These improvements result from elimination of the need for a 60-Hz power transformer and heat sinks for the transistors.

A complete switching-regulator power supply is described in detail in the sections below (see Fig. 114). A block diagram of this circuit showing voltage waveforms at various points is given in Fig. 115. This supply produces 250 watts at 5 volts with an efficiency of 70 per cent. It uses two switching transistors in a push-pull arrangement with variable pulse width; the switching rate is 20 kHz. The complete supply weighs only 10 pounds and occupies only 470 cubic inches.

Power-Supply Elements

The switching-regulator power supply includes the six major elements shown in the schematic diagram of Fig. 114: (1) the main

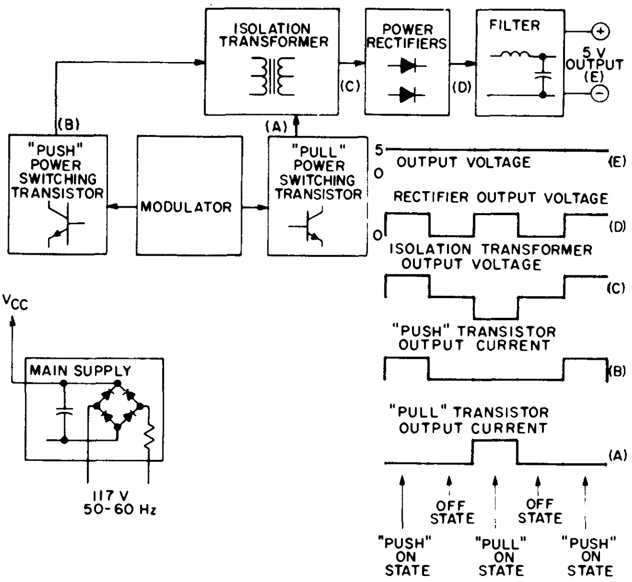

Fig. 115 - Block diagram of switching-regulator power supply, showing voltage waveforms at various points.

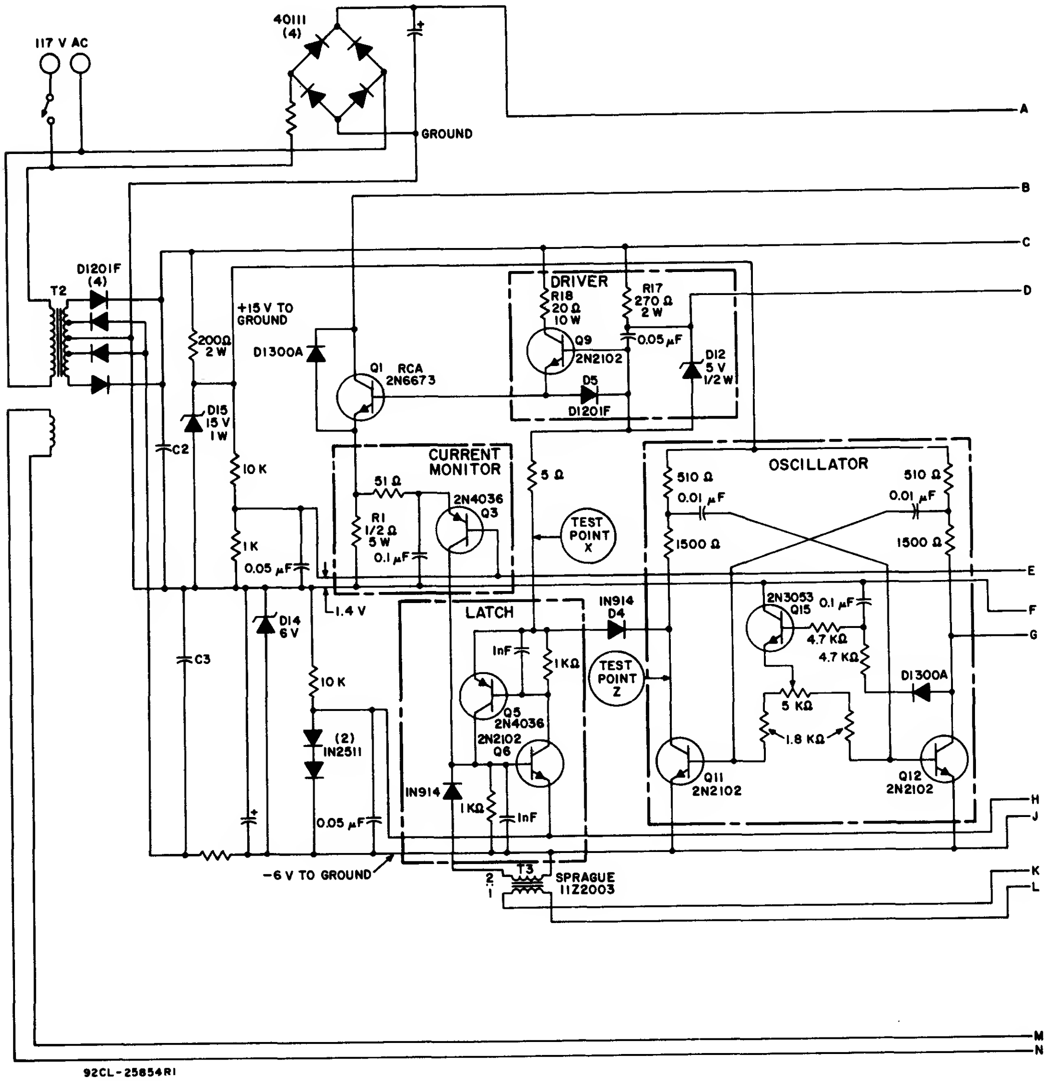

Fig. 114 - Diagram of switching-regulator power supply.

power supply, (2) the power-switching transistors, (3) the isolation transformer, (4) the modulator circuits, (5) the power rectifiers, and (6) the filter. The important parameters of these elements are discussed below.

Main Power Supply

The **main power supply** provides the power that ultimately becomes the output power. It rectifies and filters the line voltage without use of a 60-Hz transformer. For a switching-regulator type of power supply, the main supply may be designed for high ripple without increased regulator losses (such as would occur in a conventional series regulator). Therefore, smaller capacitors and lower-cost rectifiers can be used. Some resistance must be added in series with the power line to prevent damage to the rectifiers during turn-on. The voltage delivered by the main power supply varies with line-voltage and load variations. The peak output voltage of the main supply at the maximum line conditions (with transients) determines both the collector-voltage rating required for the power-switching transistors and the turns ratio of the isolation transformer.

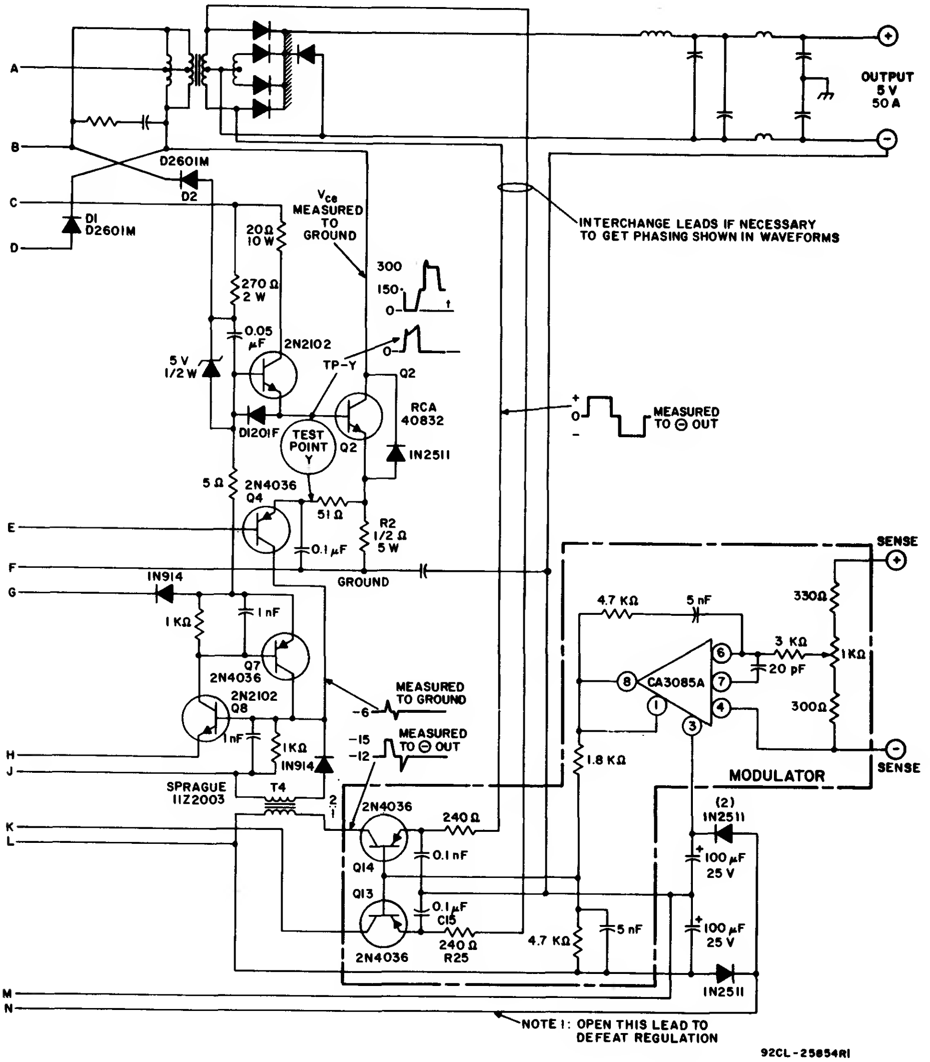

Fig. 114 - Diagram of switching-regulator power supply (cont'd).

Power-Switching Transistors

The performance capabilities of the power supply are determined by **the switching transistors**, because they are the parts least able to withstand overloads such as those caused by load faults or misuse. Therefore, the switching transistors must have the following characteristics (see Table VI for typical examples). Listed in order of importance:

1. High forward-bias second-breakdown capability. The transistor must carry high currents at high voltages shown in the switching load line of Fig. 116.
2. Ability to withstand the required collector voltage specified in Table V while in the cut-off condition. A leakage current specification I_{CEV} establishes this capability.
3. Short rise and fall times (t_r and t_f) for low power dissipation in the transistors and thus high efficiency of the power supply.
4. Reasonably low V_{CE}(sat) for low dissipation and economical transistor heat sinks.

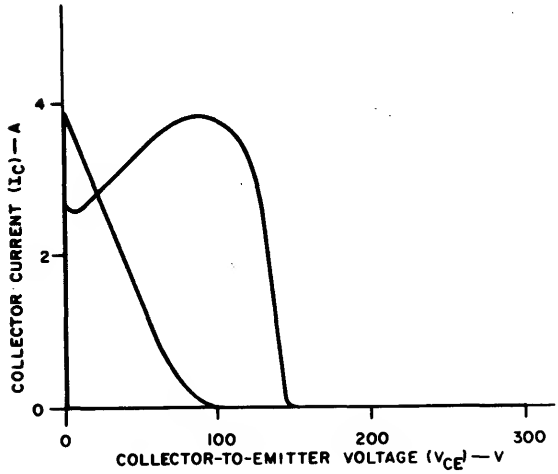

Fig. 116 - Typical load line for a switching transistor in the pulse-width modulated switching-regulator type power supply of Fig. 114.

Table V - Relationship Between Line Voltage and the Required Collector Voltage Rating for the Switching Transistors

Rms Line Voltage (V)	Peak Line Voltage (V)	Nominal Collector Voltage (V)	Safe (15% Added) Collector Voltage Rating (V)	
90	127.3	254.5	292	
95	134.3	268.7	309	
100	141.4	282.8	325	
105	148.5	296.9	341	↑
110	155.5	311.1	357	
115	162.6	325.2	374	Operating
120	169.7	339.4	390	Range
125	176.7	353.5	406	
130	183.8	367.6	422	
135	190.0	381.8	439	↓
140	198.0	395.9	455	
145	205.0	410.1	471	
150	212.1	424.2	487	

5. Stable leakage current (I_{CEV}). The magnitude of the leakage is not important (even 20 milliamperes at 500 volts contributes less than 5 watts to the average dissipation per transistor), but it should be stable.

Transistor Parameters

The transistor parameters affecting the performance of a switching regulator are the current gain h_{FE}, the collector-to-emitter saturation voltage V_{CE}(sat), the leakage current I_{CER}, forward-bias second-breakdown voltage, and switching times (see Table VI). The forward-current transfer ratio h_{FE} determines the amount of drive current needed. The collector-to-emitter saturation voltage V_{CE}(sat) is important because it determines part of the power loss in the circuit and the dissipation of the transistor during the ON period. The amount of leakage current is important because the transistor essentially conducts this amount of current during the OFF period and thus increases dissipation. If this leakage current is large enough, the transistor can enter into a condition of thermal runaway. Silicon transistors, with their inherently lower leakage-current value, do not often exhibit this problem.

The transistor safe-area rating determines the maximum power that can be handled by the transistor and by the supply. This parameter and its implications are explained in detail in the section on Safe-Area Ratings.

The switching times, t_r (rise time) and t_f (fall time), are of prime consideration in selection of a transistor to be used as the switch. For good regulation over a wide range of input voltage and output current, the duty cycle must be variable from at least 10 to 90 per cent (i.e., the pulse width could be a minimum of one-tenth of the period 1/10f). For low switching losses, the rise and fall times should each be less than 10 per cent of the minimum pulse width.

Table VI - Recommended Specifications for Switching Transistors

Parameter	Measurement Conditions		Value
	General	For Transistors Used in Design Example	
I_{CEV}	V_{CE} from Table V $V_{BE} \leq V_{EE}$(1)	V_{CE}=450 V V_{BE} = 1.5 V	5 mA max.
I_{EBO}	V_{EB} = V_{EE}(1)	V_{EB} = 6 V	5 mA max.
$I_{S/b}$	I_C = I_C(max.) V_{CE} = V_{CC} (max.) $t \geq 50\ \mu s$	I_C = 4 A V_{CE} = 200 V t = 100 μs	(must pass test)
V_{CE}(sat)	I_C = I_C(max.) I_B as provided by driver circuit	I_C = 4 A I_B = 0.8 A	<3 V
V_{BE}(sat)	"	"	<2 V(2)
t_r	I_C = I_C(max.) I_{B1} and I_{B2} as provided by driver circuits	conditions(3)	$<1\ \mu s$
t_f	"	"	$<1\ \mu s$

(1) V_{EE} is negative voltage source applied to the base.

(2) Importance depends upon drive-circuit design. For the design shown, V_{BE}(sat) is not critical.

(3) Because of the great variations in parameters and waveforms, some standard test condition is used for control. The manufacturers standard conditions are usually adequate control.

Switching Arrangement

The transistor switching arrangement usually takes on one of two forms as illustrated in Fig. 117. If isolated supplies appear in the drive circuits of Q1 and Q2, performance of the two circuits is basically the same. However, if no isolated supplies are used, then the circuit of Fig. 117(b) has the disadvantage that the V_{CE} of Q2 cannot be reduced below the V_{BE} of Q2. This condition results because the base of Q2 cannot be tied to a point more positive than the plus voltage of the power supply.

The circuit of Fig. 117(a) can avoid this problem if the collector of the driver unit is connected to the positive side of the supply. The disadvantage is that current in the driver does not flow through the load; the power associated with this current, therefore, is lost.

The circuit of Fig. 117(b) is usually preferred when the power that results from a high V_{CE}(sat) can be tolerated.

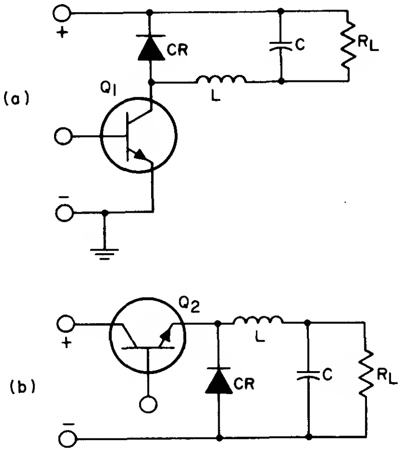

Fig. 117 - Basic transistor switching arrangements: (a) filter elements and load impedance in collector circuit of switching transistor; (b) filter elements and load impedance in emitter circuit of switching transistor.

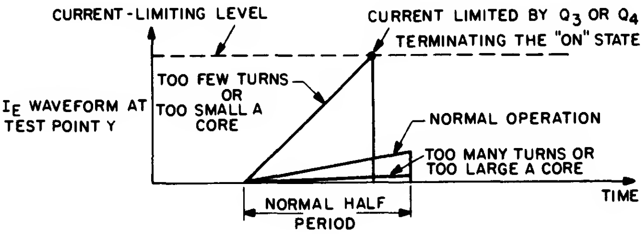

Fig. 118 - Waveform of emitter current in power-switching transistor showing effects of core size and number of primary turns, with regulation defeated (see note on Fig. 114).

Fig. 118 shows the emitter-current waveform of a power-switching transistor, monitored at point Y of Fig. 114 for different numbers of primary turns. If the emitter current is excessive, the circuit reduces the duty cycle to protect the power-switching transistor. Fig. 119 shows the waveforms for unbalanced dc drive. These unbalanced currents result from unequal duty cycles, caused by oscillator unbalance or by unbalance or faults in the modulator. Because such unbalances occur in normal operation, the protective circuits must be included in the design.

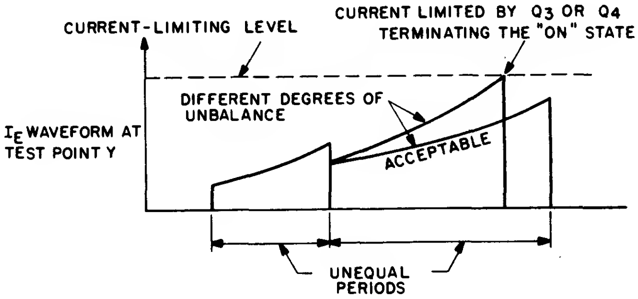

Fig. 119 - Waveform of emitter current in power-switching transistor showing effect of unbalanced direct current, with regulation defeated and load current of 25 amperes.

Modulator Circuits

The **modulator circuit (oscillator, drivers, modulators, and latches)**, which is indicated in the circuit diagram, delivers the base drive to the power-switching transistors. The forward drive must be sufficient to keep the transistors saturated under all conditions, and must have a short rise time to provide fast transistor turn-on and low dissipation. The reverse drive must have short rise time and a magnitude equal to or greater than the forward base drive.

The oscillator frequency should be stable to minimize rectifier losses, and should be greater than 20 kHz to eliminate sound. All of the circuits should be insensitive to component-value variations, component drift, and random or stray interference. The circuits also sense excessive emitter current in the power-switching transistors, and compensate by adjustment of the duty cycle, as noted above.

These circuits eliminate common-mode conduction in the power-switching transistors. This conduction occurs in a driven inverter when the transistor that has been "off" is turned "on"; the other transistor continues to conduct because of its storage time. For several microseconds both transistors conduct, and the current is not limited by the collector circuit. The transistor that has just been switched on has high current and voltage simultaneously, and therefore high dissipation perhaps 50 per cent of the rated power-supply output). This power dissipation is wasteful and may even damage the transistor.

Power Rectifiers

Most of the losses in the power supply occur in the power rectifiers. For example, in a 5-volt, 50-ampere supply utilizing four 1N3909 rectifier diodes, each of the diodes carries a nominal peak current of 25 amperes at 50-percent duty cycle. The forward power loss in the rectifier can be calculated from the current and voltage values. The voltage drop is not specified for 25-ampere operation, but the rectifier has a maximum voltage drop of 1.4 volts at a current of 30 amperes. Because this 30-ampere data is close to 25-ampere operation (and unbalance could cause the current to exceed 25 amperes), the maximum forward-drop rectifier losses can be estimated from the 30-ampere specifications: ½ x 1.4 V x 30 A x 4= 84 watts at maximum rated output.

Reverse recovery losses in the diodes add to the total dissipation; these losses, which are significant at 20 kHz, depend on the rectifiers used, the leakage inductances in the wiring and the isolation transformer, the transistor switching times, and the operating frequency. Because of the many variables (and unknowns) involved, the rectifier losses should be determined by measurement of circuit efficiency or heat-sink temperature. A total rectifier loss of 45 per cent of the rated output power of the regulator is to be expected.

Isolation Transformer

The isolation transformer is a ferrite-core transformer that operates at 20 kHz. Its design formulas are the same as those for conventional 60-Hz transformers, but the results are significantly different. The number of turns is never greater than 200, and may be as low as one. These turns always fit in the large "windows" in the ferrite core. Leakage inductance is reduced in the primary turns by sectioning the primary winding. Leakage in the secondary is less important because the secondary is loaded by a filter choke. The copper losses can easily be made negligible, and the copper wire costs are small. The size of the transformer core is determined by the need to dissipate the heat generated in the core material; the Indiana General Co.* recommends that dissipation be kept below 0.25 W/in. The 20-kHz ferrite core is much smaller than a 60-Hz core (3 in.^{3} vs. 140 in.^{3}), and is much lighter (1 lb. vs. 33 lbs.).

The design of a 20-kHz power transformer involves three basic problems: core material selection, windings to keep peak flux below saturation, and compensation for unbalanced direct currents.

If a core has too much loss, it will overheat. If it has too many turns, the flux density will be below saturation, but the copper losses will be greater than necessary. The number of turns is kept low to avoid unnecessary copper losses, but must be great enough to keep the peak flux in the core below saturation.

The core will saturate if its cross section is too small, if there are not enough turns in the primary winding, or if the primary direct current is unbalanced. Core saturation causes the power-switching transistors to draw excessive currents.

Filter Considerations

A fundamental part of every switching regulator is the filter. Fig. 120 shows the various types of filters that can be used. Selection of the optimum filter for a power supply is based on the load requirements of the particular circuit and consideration of the basic disadvantages of the various types of filters.

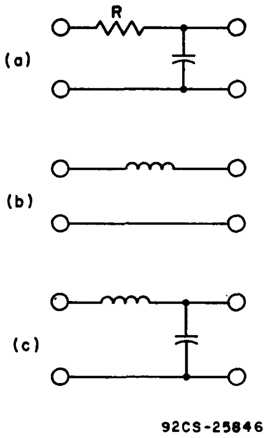

Fig. 120 - Typical filter circuits for use between pass element and load in a switching regulator: (a) capacitive filter; (b) inductive filter; (c) inductive-capacitive filter.

A capacitive filter, shown in Fig. 120(a), has two primary disadvantages: (1) because large peak currents exist, R must be made large enough to limit peak transistor current to a safe value; and (2) the resistance in this circuit introduces loss.

An inductive filter, shown in Fig. 120(b), has three disadvantages: (1) The inductance may produce a destructive voltage spike when the transistor turns off. This problem, however, can be solved effectively by the addition of a commutating diode, as shown in Fig. 121.

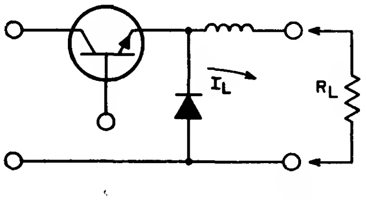

Fig. 121 - Use of inductance and commutating diode as filter network between pass transistor and load in switching voltage regulator.

This diode commutates the current flowing through the inductor I_L when the transistor switches off. (2) An abrupt change in the load resistance R_L produces an abrupt change in output voltage because the current through the load I_L cannot change instantaneously. (3) A third disadvantage of the inductive filter becomes evident during light loads. The energy stored in an inductor is given by

$$E=\frac{1}{2}LI^2$$

As a result, the capability of the inductor to store energy varies with the square of the load current. Under light load conditions, the inductor must be much larger to provide a relatively constant current flow when the transistor is off than is required for a heavy load.

Most of the problems associated with either a capacitive filter or an inductive filter can be solved by use of a combination of the two as shown in Fig. 120(c). Because the energy stored in an inductor varies directly as current squared, whereas the energy output at constant voltage varies directly with current, it is not usually practical to design the inductor for continuous current at low current outputs. The addition of a capacitor eliminates the need for a continuous flow of current through the inductor. With the addition of a commutating diode, this filter has the following advantages: (1) no "lossy" elements are required (2) The inductive element need not be oversized for light loads because the capacitance maintains the proper output voltage V_{out} if the inductive current becomes discontinuous. (3) High peak currents through the transistor are eliminated by the use of the inductive element.

In summary, the switching-regulator filter can take on various forms depending upon the load requirements. However, if a wide range of voltage and current is required, an LC filter is used in combination with a commutating diode.

A practical rule of thumb is to design the inductor to be large enough to dominate the performance during maximum-load conditions. The filter capacitor is chosen to be large enough to dominate performance at mid-range current values and the full range of output voltages.

A primary advantage of the transistor switching regulator is that the switching frequency can be made considerably higher than the line frequency. As a result, the filter can be made relatively small and light in weight.

The means by which the switching regulator removes the line-frequency ripple component is illustrated in Fig. 122. The on time increases under the valley points of the unregulated supply and decreases under the peaks. The net result is to remove the 60-Hz component of ripple and introduce only ripple at the switching frequency which is relatively high frequency and easily filtered out.

The inductor carries a current equal to the dc output. It can have small size and low

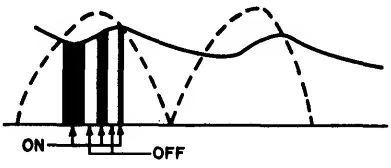

Fig. 122 - Effect of high-frequency switching of the switching regulator on power-supply ripple component.

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*Indiana General Ferramic Components, Indiana General Corp. Keasbey, N.J.

resistance because it has a low inductance (3 to 8 microhenries). The inductance value used is a compromise between the need for a high value to limit peak currents and thus permit good transistor utilization, and the need for a low value to permit fast response to sudden current demands. The minimum value of inductance is determined by the peak collector current allowed, as follows:

$$L_{min} = \frac{t_{off}(max)\ E_{out}}{n_T I_c(peak) - I_{load}}$$

where n_T is the turns ratio of the isolation transformer.

The filter capacitors for this application must be selected for 20-kHz operation. Ceramic and paper types are recommended, but tantalum or high-quality aluminum electrolytics can be used for large values of capacitance. The capacitance must be sufficient to prevent the output voltage from decreasing excessively when the load is suddenly increased and the inductor supplies less than the load current. The minimum capacitance is given by

$$C_{min} = \frac{I_{load}[t_{dis} + 2t_{off}(max)]}{2(\Delta V)\ allowed}$$

where

$$t_{dis} = \frac{L\ I_{load}}{\dfrac{V_{CC}(min)}{n_T} - V_o - 1.0}$$

and $t_{off}(max)$ is 12.5 microseconds for this design.

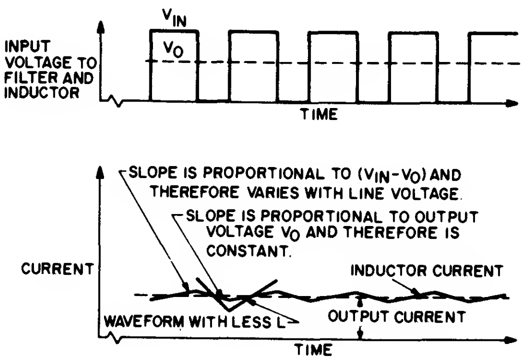

Fig. 123 - Waveforms for filter inductor under steady-state operation at 60-per-cent duty cycle.

Fig. 123 shows how the inductor controls the ratio of peak collector current to average collector current in the power-switching transistors under steady-state operation. Smaller inductors cause higher peak currents, which require larger transistors and result in poor utilization of the transistor capabilities. The minimum value of inductance is determined by the peak collector current allowed, as follows:

$$L_{min} = \frac{t_{off}(max)\ E_{out}}{n_T\ I_c(peak)\ -\ I_{load}}$$

where n_T is the turns ratio of the isolation transformer. However, as shown in Fig. 124, the inductor also establishes the maximum rate of rise of current to the capacitor, and thus determines the ability of the power supply to respond to sudden demands for load current. For quick response, a low value of inductance is desirable.

Power-Supply Performance

The power supply shown in Fig. 114 can deliver a load curent of 50 amperes at 5 volts.

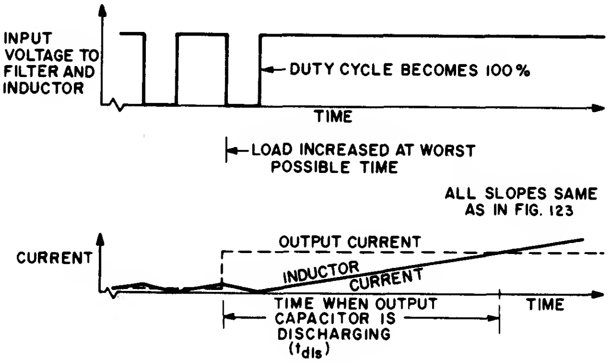

Fig. 124 - Waveforms for filter inductor under sudden increase of load current.

All of the pulse-width modulation circuits, drivers, and latches are duplicated for each power-switching transistor. This duplication uses more than the minimum number of components, but it provides wide design margins and reliable operation.

Voltage regulation and overload regulation are accomplished by reducing the duty cycle of the power-switching transistors. The duty cycle is reduced by triggering the latches on, either from pulse transformers T_3 and T_4 to regulate the output voltage, or from transistors Q_3 and Q_4 to prevent excessive emitter currents in the power-switching transistors. The excessive currents could be caused by overloads at the output or by transformer core saturation resulting from unbalanced duty cycles.

Input-to-output isolation is maintained through the main isolation transformer (T_1), the 60-Hz transformer (T_2), and the pulse transformers (T_3 and T_4). This circuit isolation is indicated in Fig. 114.

This power supply is capable of operating into any load impedance, including short circuits, without damage. It can operate at duty cycles from less than 10 per cent to 100 per cent. With a duty cycle of 100 per cent, the supply operates as a straight inverter at the full capacity of the transistors, transformers, and rectifiers.

The base drive for the power-switching transistors is direct-coupled, and is supplied by an unregulated low-voltage power supply that operates from a 60-Hz transformer. Direct coupling of the base drive provides positive control over transistor bias. The reverse base drive is supplied by the two-transistor latch circuits Q_5 and Q_6 or Q_7 and Q_8, or by the oscillator transistors (Q_{11} and Q_{12}) if the duty cycle is 100 per cent. The reverse base voltage is obtained from a 6-volt regulated supply.

The frequency is controlled by the astable transistor oscillator that operates from 15-volt and -6-volt regulated sources. A potentiometer for equalization of the duty cycle is shown, but is not normally required. Transistor Q_{15} insures that the oscillator does not "hang up."

Common-mode conduction is reduced by cross-coupled diodes D_1 and D_2. These diodes conduct when the V_{CE} of the power-switching transistor is less than 5 volts (breakdown of the zener diode), and prevent conduction of the opposite power-switching transistor. These diodes are of critical importance because the storage time of the power-switching transistors is several microseconds at light load conditions ($I_{B_1} > 0.5$ amperes and $I_C < 0.5$ amperes).

A major consideration in the design of this power supply is the protection of the switching transistors and the load circuit from damage caused by transients or faults in the modulator. The faults most likely to occur are lock-up in the oscillator, transient turn-on of the latching transistors caused by dv/dt at point X in Fig. 114, and magnetic pickup in the pulse transformers. The circuit is designed so that any of these faults will cause the power-switching transistors to turn off; this design protects the transistors and keeps the output voltage low. The over-current protection circuit is made independent of the proper functioning of the output regulator or its associated circuits, and is dc-coupled to minimize the possibility of failure. Finally, if the low-voltage supplies fail, the output voltage merely falls to zero without any harmful surges.

STEP-DOWN SWITCHING REGULATOR

A transistor switching regulator can be used as a dc step-down transformer. This circuit is a very efficient means of obtaining a low dc voltage directly from a high-voltage ac line without the need for a step-down transformer. Fig. 125 shows a typical step-down transistor switching regulator. This regulator utilizes the dc voltage obtained from a rectified 117-volt line to provide a constant 60-volt supply. Fig. 126 shows the performance characteristics for this circuit.

20-KHZ SWITCHING-REGULATOR CIRCUIT

The following paragraphs describe a 20-kHz switching-regulator circuit that operates from a 28-volt supply and has a regulated output between 4 and 16 volts dc. The circuit features overload protection which limits the current to about 11 amperes.

The control element of the switching regulator is a 2N6650, a p-n-p Darlington power transistor used as a switch and driven directly from a CA3085A integrated-circuit positive voltage regulator shown in Fig. 127. The regulator does not operate at a fixed clock frequency, but is free running.

The regulator circuit is basically a step-down switching regulator. When the pass unit, Q3 (2N6650) is switched on, current is charged into L1; when Q3 switches off, the

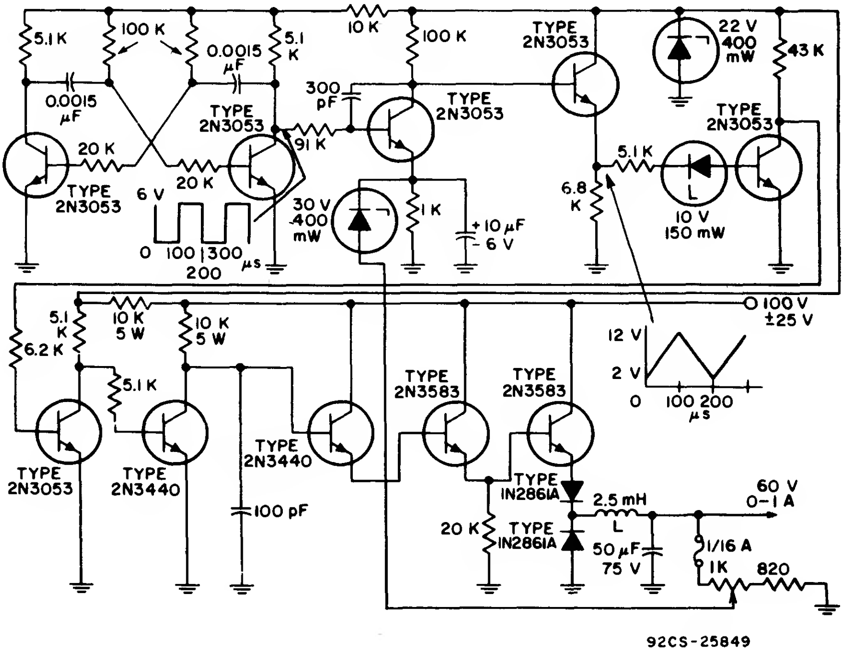

Fig. 125 - Typical step-down transistor switching regulator.

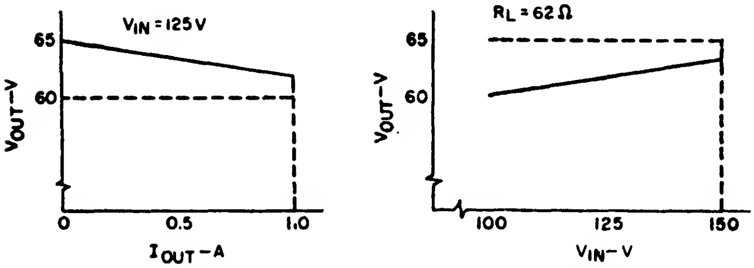

Fig. 126 - Performance characteristics of step-down switching regulator shown in Fig. 125.

current through L1 continues to flow by way of the commutating diode, D1.

The dc output voltage is determined by the ratio of R10 to R11, just as in a linear series regulator. Switching action is accomplished by comparing a ripple voltage to a hysteresis voltage. The circuit switches on and off, triggered by the ripple of the output voltage. The voltage at pin 6 of the CA3085A (Fig. 128) is determined by R10 and R11 of Fig. 127, and is proportional to the output voltage plus the ripple voltage at point A, V_A, fed in by capacitor C5. This voltage is compared with the voltage at pin 5. The voltage at pin 5 consists of the built-in reference voltage of the CA3085A plus a variable component proportional to the voltage at point, B, V_B, fed through R8.

The impedance of C5 at the operating frequency (10-kHz minimum) must be low compared to the input impedance at pin 6. As shown in Fig. 129, the Darlington, Q3, is switched on when the output voltage becomes too low, i.e., when the voltage at pin 6 becomes less than the voltage at pin 5; when this condition is reversed Q3 is switched off.

Diodes D2 and D3 are added for the protection of the very sensitive input at pin 6. Resistors R7 and R12 and capacitor C3 control the drive current and improve the

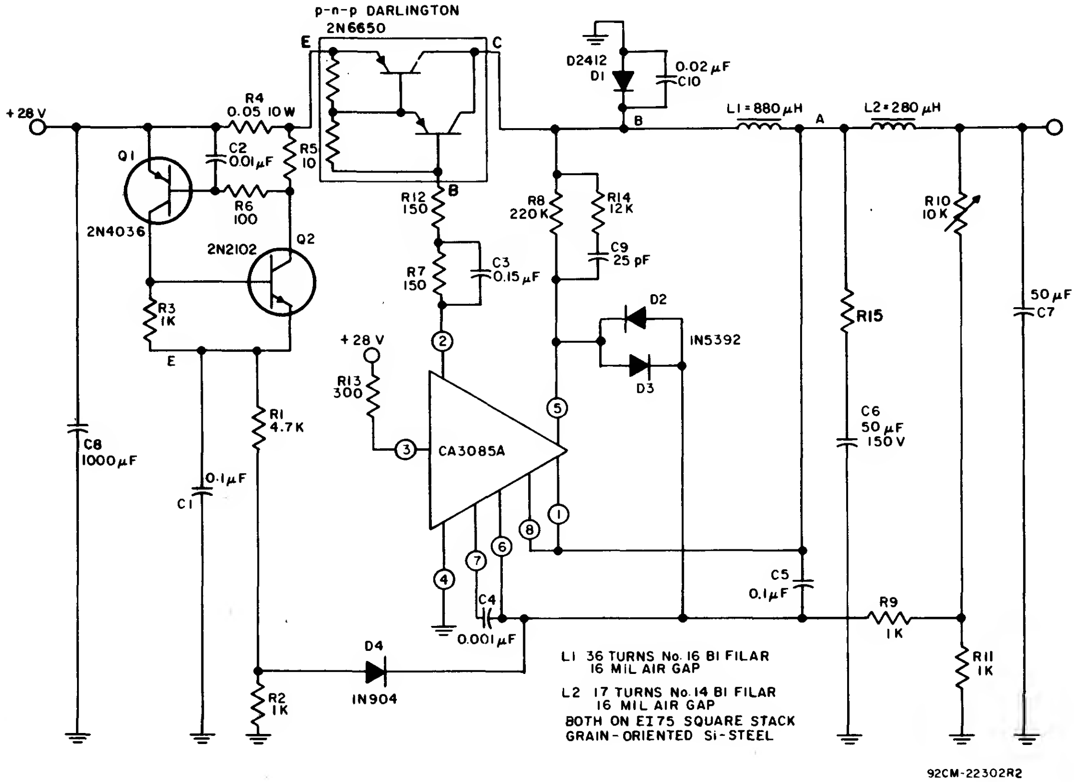

Fig. 127 - The switching-regulator circuit.

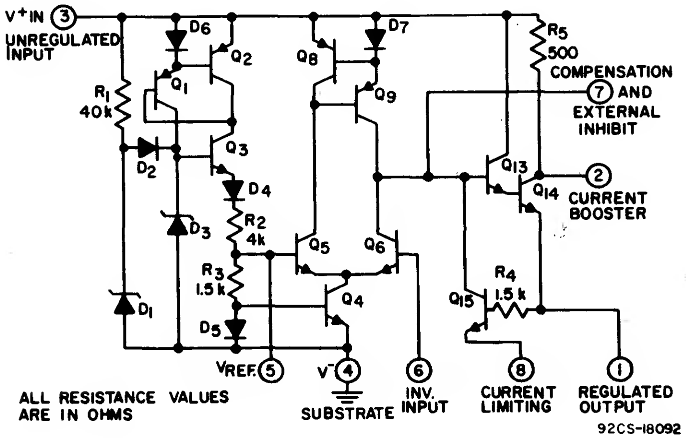

Fig. 128 - The CA3085A.

switching performance of the Darlington, Q3.

L2 and C7 provide additional filtering and isolate point A from the load. Isolation is necessary from loads, capacitive loads, for example, which could drastically affect the ripple voltage at point A. Therefore, at the frequencies involved, L2 must have an impedance which is high compared to R15. L2, together with C7, serves also as a filter to reduce the output ripple.

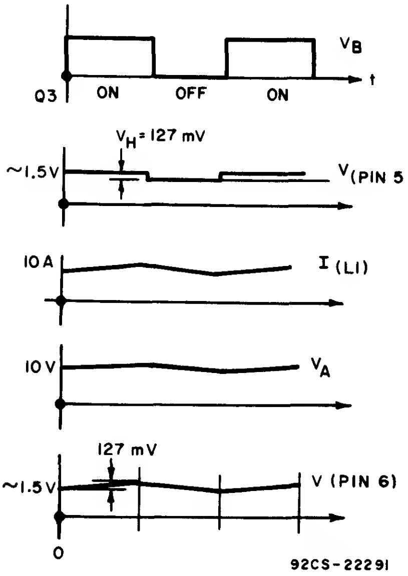

Fig. 129 - Waveforms for normal operation of the Darlington, Q3.

C10 is a small capacitor placed in parallel with D1 to buffer the surge voltage at point B when Q3 is switched on. C10 reduced the high-frequency ringing (approximate 3 MHz) at point A caused by L1 and its distributed winding capacitance. The combination of C9 and R14 speeds the switching of the CA3085A without changing the hysteresis voltage, V_H.

Transistors Q1 and Q2 and their associated circuitry provide overload protection. Normally, Q1 and Q2 are off, C1 is discharged, and the voltage at point E, V_E, is zero. In case of overload, the current through R4 produces a voltage sufficient to turn Q1 on. As a result, Q2 turns on, and C1 charges mainly through Q2 and R5. A voltage proportional to that at point E is fed through diode D4 into pin 6 of the CA3085A; this results in Q3 being turned off, even while C1 is still charging. The voltage drop across R5 caused by this charging current holds Q1 on, however, until C1 is fully charged. When C1 becomes fully charged, Q1 and Q2 are turned off, and C1 discharges slowly through R1 and R2. When V_E becomes low enough, Q3 is switched on again. Since the basic frequency-determining mechanism of the switching regulator is not disturbed (an overload or short circuit is separated or insulated from the inner circuit by the impedance of L2), a few cycles of normal operation occur until the current through R4 has built up again. Fig. 130 shows the voltage at point E, V_E, the current through inductance L1, I_{L1}, and the voltage at point B, V_B, under overload conditions.

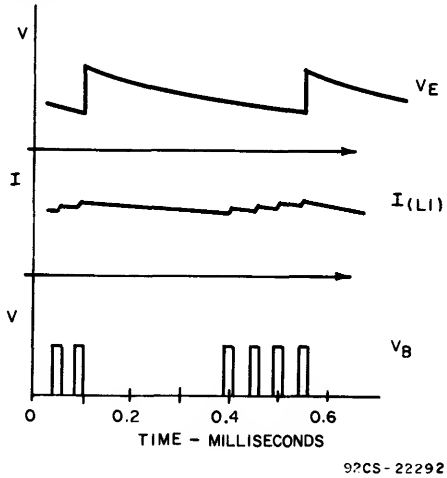

Fig. 130 - Circuit waveforms under overload conditions.

Performance

The regulator was designed mainly for use in equipment requiring supply voltages of 5 and 12 volts (computers, battery chargers, etc.). With the values of R10 and R11 shown, the voltage can be regulated between 4 and 16 volts. With other values of R10 and R11, the output voltage can be varied over a wider range, approximately 2 to 22 volts. The output voltage varies less than 0.11 volt between 10 per cent and full load. After one hour of operation, it dropped 30 millivolts.

The efficiency varies with output voltage as shown in Fig. 131. At 5-volts output efficiency is 66 to 72 per cent and at 12 volts output, 76 to 83 per cent between 20 per cent and full load.

As shown in Fig. 132, the operating frequency varies from 12 to 28 kHz for outputs between 5 and 12 volts; at outputs above 30 watts the frequency is above the audible range.

The circuit is relatively insensitive to input voltage ripple. For an input voltage ripple of 4 volts (60-Hz bridge rectified), the output ripple is 0.1-volt peak-to-peak (60 millivolts, 120 Hz, plus 40 millivolts, at approximately 20 kHz). As shown in Fig. 133, the efficiency is not affected by variations of the input voltage. The frequency changes considerably and peaks

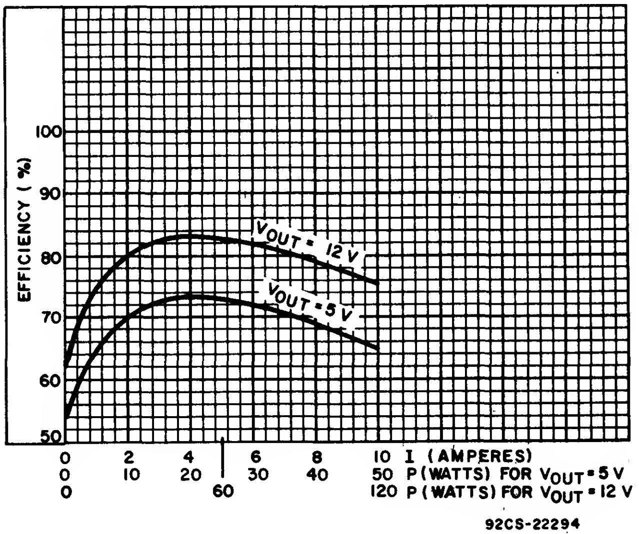

Fig. 131 - Efficiency as a function of output.

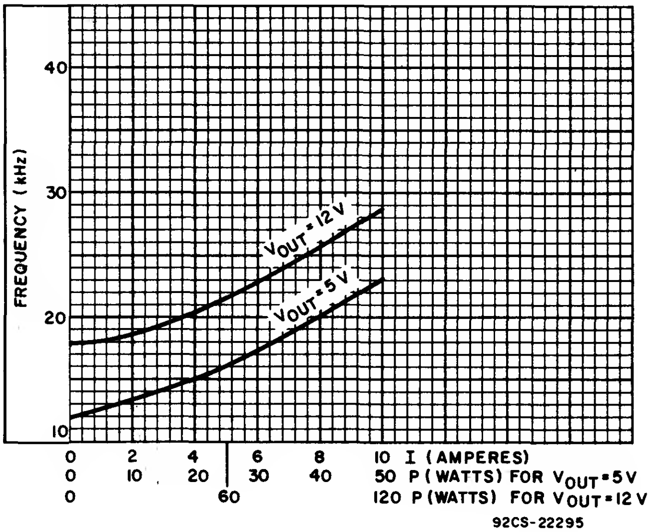

Fig. 132 - Operating frequency as a function of output.

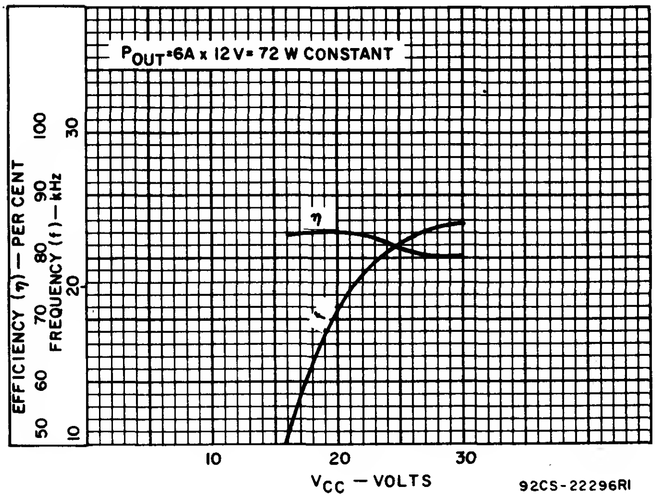

Fig. 133 - Efficiency and operating frequency as a function of input voltage.

when V_{CC} is approximately $2V_{out}$.

At 25° C ambient, the operating temperature of Q3 and D1 was 78° C at maximum load; Q3 and D1 were mounted on a common heat sink rated at 2.3° C/W. Under short-circuit operation, the diode, D1, reached 88° C, while Q3 ran cooler, 58° C. As mentioned earlier, under short-circuit or overload conditions, the circuit is self-protecting.

Fig. 134 shows efficiency and frequency versus output voltage; Fig. 135 shows the regulation characteristic for a V_{out} of 12 volts.

The free-running switching regulator described in the previous paragraphs provides a simple circuit which combines good regulation with high efficiency and relatively low output ripple. The equations for designing the regulator are straightforward, and the design procedure, although approximate, works exceedingly well.

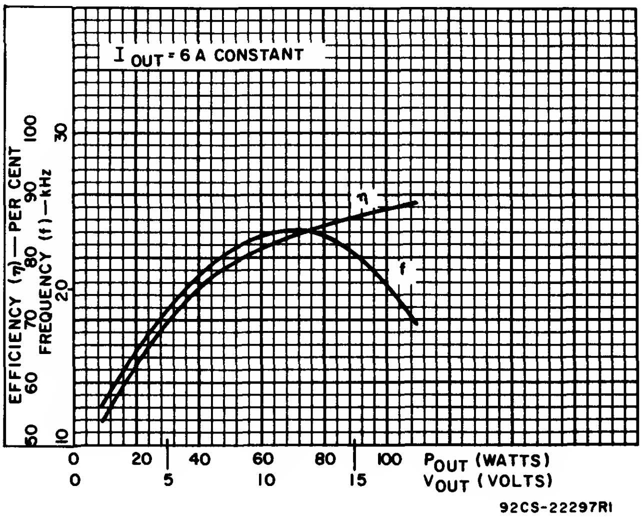

Fig. 134 - Efficiency and operating frequency as a function of output voltage.

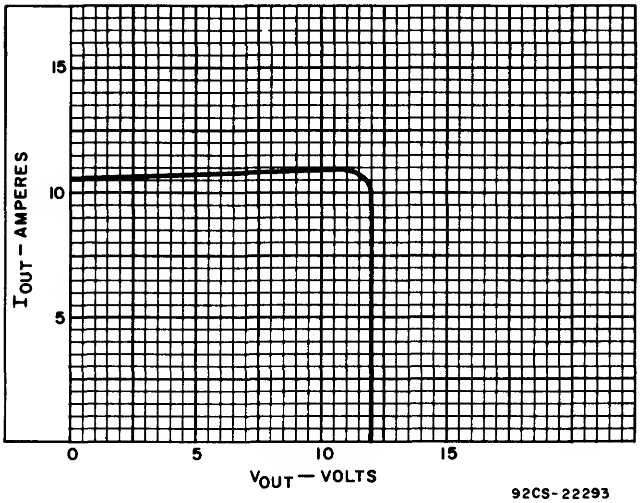

Fig. 135 - Regulation characteristic for an output voltage of 12 volts.

Table VII - Comparison of Power Supplies

	Conventional Series-Regulated Supply	**Pulse-Width Modulated Regulator**	**Units**
Output Current at 5 volts	25	50	A
Power Losses (Max.)	300	100	W
Size	1600	470	in.^{3}
Weight	50	10	lb.
Recovery Time	50	500	μs
Regulation (Half load to full load)	> 0.25	0.5	%
Line Regulation	> 0.25	0.5	%

PULSE-WIDTH MODULATED (SWITCHING-REGULATOR) SUPPLIES

In a switching-regulator type of power supply, the output voltage is regulated by a technique referred to as "pulse-width modulation", in which pulses of variable duty cycle are averaged with an inductor-capacitor filter. Regulation is accomplished by the variation of the duty cycle. The pulses constitute a two-state signal (power on and power off) that is supplied to the filter. However, to permit use of a smaller isolation transformer, the "power-on" state is operated in a push-pull mode that is then rectified by full-wave power rectifiers. The time ratios of the push, pull, and off conditions are controlled by a modulator circuit.

The on-state voltage is unregulated and is always greater than the required output voltage from the filter. It is supplied by a low-impedance source that consists of a transformer with closely coupled windings, the main supply, and a saturated transistor. The on-state voltage is decreased to the specified output value by an inductor that forms part of the filter. Thus the filter, which converts the ac signals to a dc output, is a "choke-input" type.

The switching-regulator supply operates at a frequency above the audio range to permit use of a small isolation transformer, and also to prevent sound generation.

The pulse-width-modulated converter, see chapter on Power Conversion, is finding increasingly widespread use in high-current low-voltage regulated power supplies. Such supplies use switching regulators, rather than the more common dissipating regulators, to eliminate the need for a 60-Hz power transformer and heat sinks for the transistors. As a result, pulse-width-modulated (i.e., switching-regulator) supplies offer the following important advantages over conventional power supplies:

1. Smaller size - volume is reduced by a factor of four. This size reduction does not cause any cooling problems because pulse-width-modulated supplies dissipate very little power.

2. Higher efficiency - power dissipation in the regulator is virtually eliminated; only the power rectifiers require cooling. The reduction in heat dissipation for a 250-watt supply can be 200 to 300 watts, which represents a substantial economic saving.

3. Reduced weight - weight is reduced by a factor of five. Portability is improved, mounting is simpler, and chassis cost is decreased.

Table VII compares the basic features of a conventional (series-regulated) power supply and a pulse-width-modulated (switching-regulator) power supply.

A switching-regulator circuit using the CA3085A is shown in Fig. 136. The values of L and C (1.5 millihenries and 50 microfarads, respectively) are commercially available components having values approximately equal to the computed values in the previous design example.

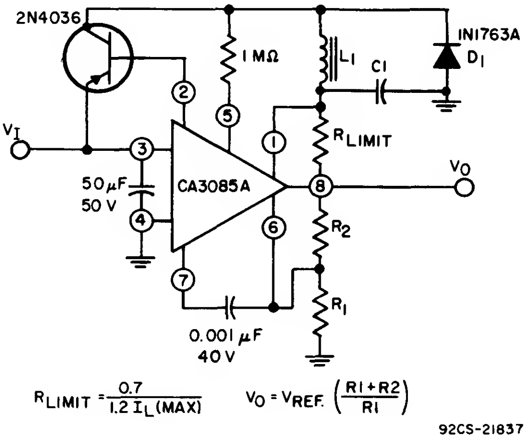

Fig. 136 - Typical switching regulator circuit.