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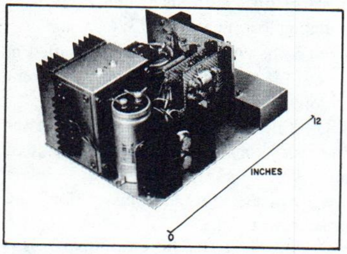

Compact 5-Volt Power Supplies Using High-Voltage Power Transistors

By R.S.Myers

This Note discusses the use of low-cost, industrial-type, high-voltage power transistors and fast-recovery rectifiers to achieve size and weight reductions and efficiency improvements in 5-volt dc power supplies with output currents of 50 amperes or more. The power supplies described, like those used in high-reliability aerospace applications, use switching rather than dissipating regulators to eliminate the need for a 60-Hz power transformer and heat sinks for the transistors. As a result, these supplies achieve three important advantages over conventional power supplies:

- Size – Volume is reduced by a factor of four. This size reduction does not cause any cooling problems, because these supplies dissipate very little power (approximately 0.33 W/in.^{3}).
- Efficiency – Power dissipation in the regulator is virtually eliminated; only the power rectifiers require cooling. The reduction of heat dissipation in a 250-watt supply can be 200 to 300 watts, which represents a substantial economic saving.
- Weight – Weight is reduced by a factor of five. Portability is improved, mounting is simplified, and chassis cost is decreased.

A complete switching-regulator power supply that uses high-voltage transistors is described in detail. This unit produces 250 watts at 5 volts with an efficiency of 70 per cent. The performance of this supply is compared with that of a conventional supply in Table I. The design can be modified for more or less power, multiple outputs, or higher output voltages.

THE POWER-SUPPLY CONCEPT

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, as shown in Fig. 1. 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.

Table I – Comparison of Power Supplies

	CONVENTIONAL SUPPLY	NEW SUPPLY	
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	%

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.

POWER-SUPPLY ELEMENTS

The design of a switching-regulator power supply involves the six major elements shown in Figs. 1 and 2: (1)

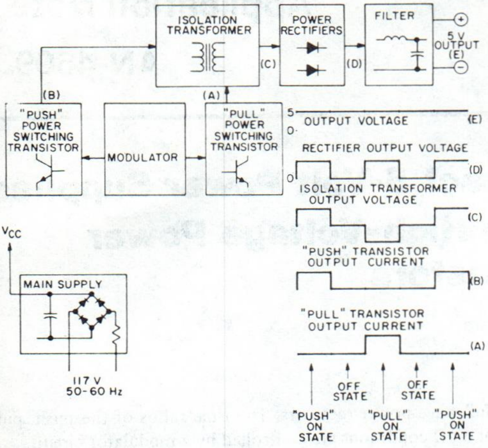

Fig. 1 - Block diagram of switching-regulator power supply, showing voltage waveforms at various points.

the main 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 supply provides the power that ultimately becomes the output power. It rectifies and filters the line voltage without use of a 60-Hz transformer. The design of such a supply is well covered in available literature[1-3]. In the case of 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.[1, 2] 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. Table II shows the relationship between line voltage and transistor collector voltage rating.

Power-Switching Transistors. The power-switching transistors are the most important components in the switching-regulator power supply. In the past, the high cost of these devices limited their use to aerospace applications; however, recent developments have made them economically competitive with other devices. 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 (listed in order of importance):

- High forward-bias second-breakdown capability. The transistors must carry high currents at high voltage, as shown in the switching load line of Fig. 3.[2]
- Ability to withstand the collector voltages specified in Table II in the cut-off condition. A leakage current (I_{CEV}) specification guarantees this capability.
- 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.
- Reasonably low V_{CE}(sat), for low dissipation and economical transistor heat sinks.
- 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.

Table III lists the recommended specifications for the switching transistors.

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.[4] 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.^{2}.[5,6] 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 loses, 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

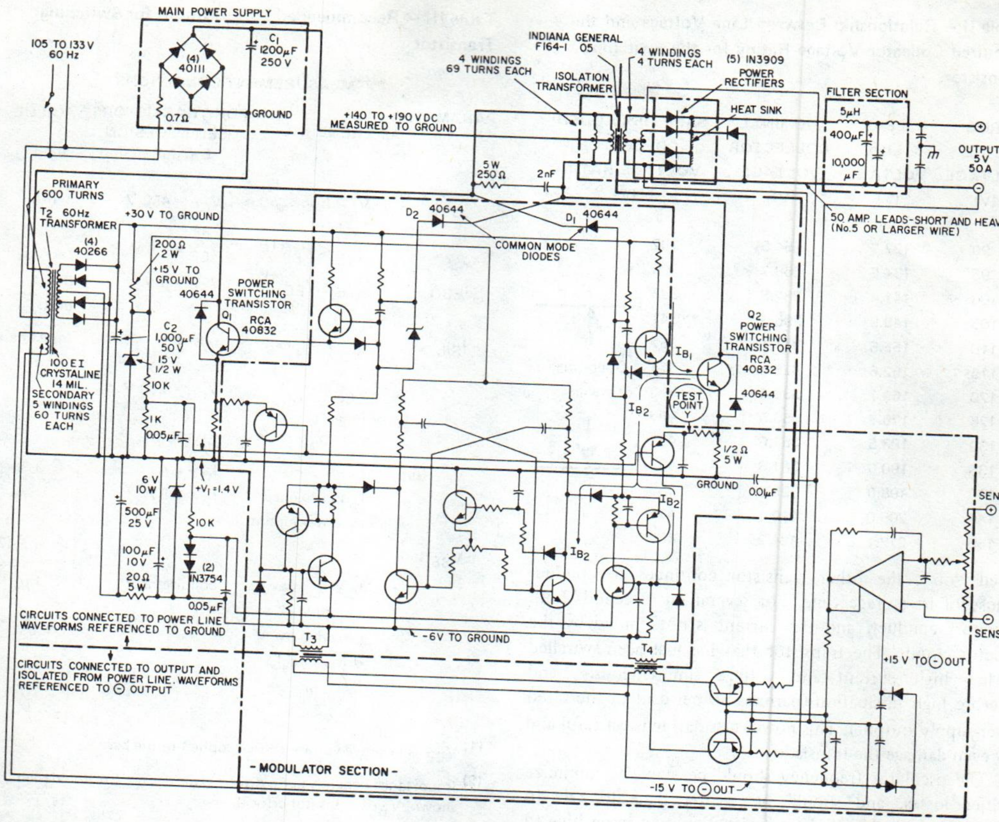

Fig. 2 - Circuit diagram of switching-regulator power supply, with major elements indicated.

that can increase collector dissipation to destructive levels. To prevent these high currents, the power supply includes a monitor circuit that cuts off the base drive to the switching transistors when emitter current reaches the maximum safe value.

Fig. 4 shows the emitter-current waveform of a power-switching transistor, monitored at point Y in Fig. 2, 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. 5 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 power supply design.

Modulator Circuit (Oscillator, drivers, modulators, and latches). These circuits, which are indicated in the circuit diagram of Fig. 6 and are described in Table IV, deliver 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 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

Table II – 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	Operating Range
110	155.5	311.1	357	
115	162.6	325.2	374	
120	169.7	339.4	390	
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	

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.

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.

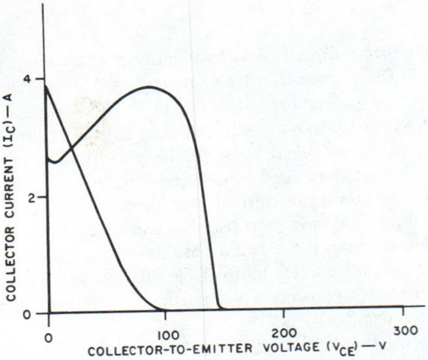

Fig. 3 - Typical load line for a switching transistor in the switching-regulator power supply.

Table III – Recommended Specifications for Switching Transistor

PARAMETER	MEASUREMENT CONDITIONS GENERAL	MEASUREMENT CONDITIONS FOR TRANSISTORS USED IN DESIGN EXAMPLE	VALUE
I_{CEV}	V_{CE} from Table II $V_{BE} \leqslant V_{EE}$(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.) $t \geqslant 50\ \mu s$	$I_C = 4$ A $V_{CE} = 200$ V $t = 100\ \mu s$	(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.

Power Recifiers. Most of the losses in the power supply occur in the power rectifiers. In a 5-volt, 50-ampere supply, for example, each of the four 1N3909 rectifier diodes carries a nominal peak current of 25 amperes at 50-per-cent duty cycle. The forward power loss in the rectifier can be calculated from the current and voltage values. The voltage

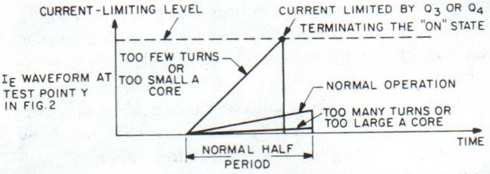

Fig. 4 - Waveform of emitter current in power-switching transistor showing effects of core-size and number of primary turns, with regulation defeated (see note on Fig. 6).

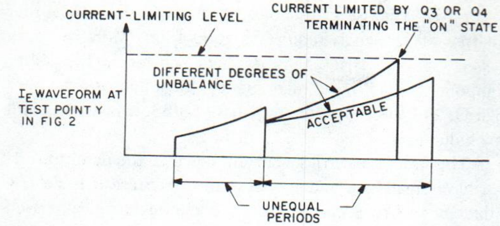

Fig. 5 - Waveform of emitter current in power-switching transistor showing effect of unbalanced direct current, with regulation defeated and load current of 25 amperes.

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: 1/2 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

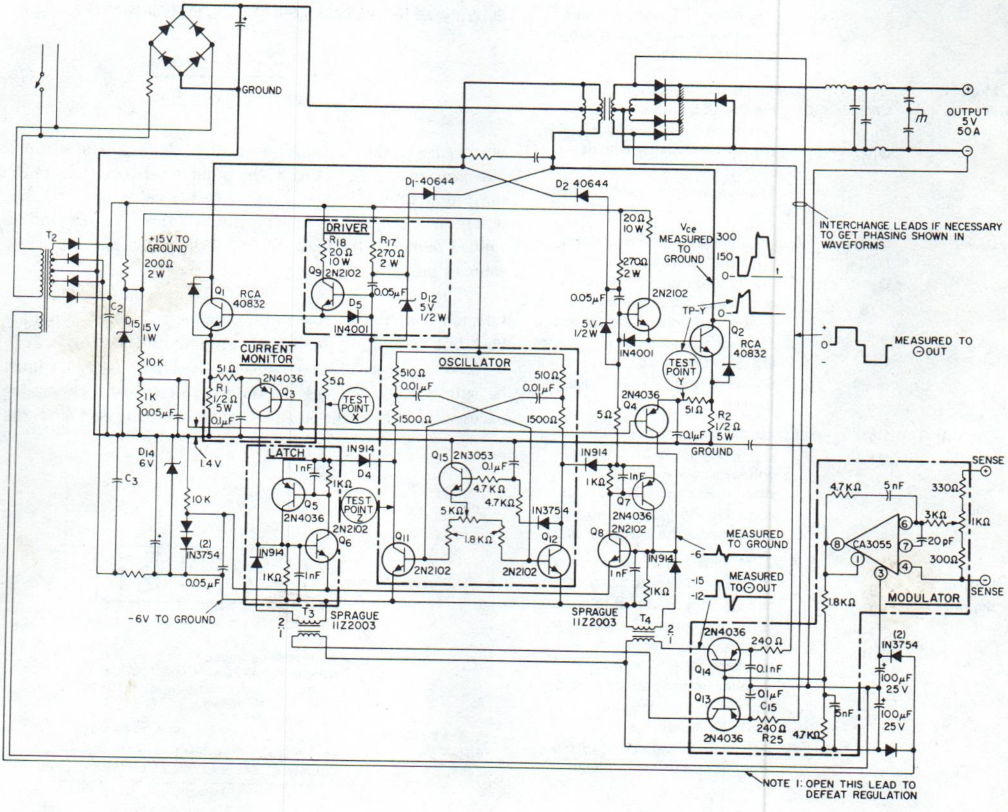

Fig. 6 - Diagram of switching-regulator power supply, with modulator circuits emphasized.

Table IV – Functional Description of Modulator Circuits

MODULATOR CIRCUIT SECTIONS	MAIN PARTS IN SECTION	FUNCTION OF SECTION
Oscillator	Q_{11}	Provides basic operating frequency. Holds off driver Q_9 through D_4 to keep Q_1 off for half the period. Provides reverse base drive for Q_1 at 100% duty cycle through D_4 and D_5. Resets the latch circuits.
	Q_{15}	Insures oscillator starts, by removing base drive if Q_{12} saturates too long.
Latch	Q_5	Terminates power-on cycle by latching and causing reverse base to Q_1.
	Q_6	Is triggered on by either the current monitor Q_3 or the modulator Q_{13} through T_3, and is held on by regenerative action. Is turned off by the oscillator.
Modulator	Q_{13} CA3055 R_{25} C_{15}	Compares the voltage developed by the CA3055 with a triangular waveform developed by R_{25} C_{15}. When the triangular voltage exceeds the other, Q_{13} conducts and triggers on the latch through T_3.
Driver	Q_9 D_{12} D_5 D_1 D_4 R_{18}	Supplies the forward base drive to Q_1, which is set by R_{18}. Prevents common-mode conduction. Diode D_1 senses V_{CE} of Q_2 and prevents base drive to Q_9 and thus to Q_1. Zener D_{12} causes Q_1 to be held off until V_{CE} of Q_2 exceeds the zener voltage (5V).
Current Monitor	Q_3 R_1	Limits the emitter current through Q_1. That current produces a voltage across R_1 which is filtered; if it exceeds 2.0 V, Q_3 conducts and triggers the latch to terminate the power-on cycle.
Low-Voltage Supplies	T_2 C_2 C_3 D_{14} D_{15}	A 30-volt unregulated supply is used to supply the base drive for Q_1 and Q_2. It is regulated to 15 volts by D_{15} to supply the oscillator. A -12-volt unregulated supply is regulated to -6 V by D_{14}. It supplies reverse base drive to Q_1 and Q_2, and operates the oscillator circuit. An isolated supply operating from T_2 supplies bias to the modulator circuit.

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.

Filter. The use of ac power to generate dc outputs that are free of ac signals requires a good filter. Moreover, in a power supply that delivers high current, the filter components must be of high quality: the inductor must have high Q, and the capacitor must have both low resistance and low inductance.

The inductor carries a current equal to the dc output. It can have small size and low 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. Fig. 7 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. 8, 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.

The filter capacitors for this application must be selected for 20-kHz operation. Ceramic and paper types are best, 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

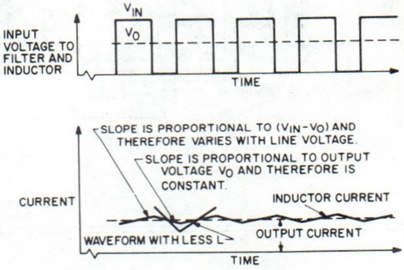

Fig. 7 - Waveforms for filter inductor under steady-state operation at 60-per-cent duty cycle.

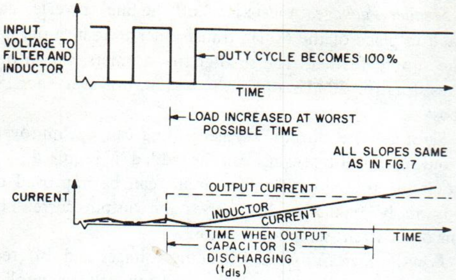

Fig. 8 - Waveforms for filter inductor under sudden increase of load current.

inductor supplies less than the load current. The minimum capacitance is given by

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

where

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

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

A SPECIFIC DESIGN EXAMPLE

A power supply that uses the circuits shown in Figs. 1, 2, and 6 can deliver a load current of 50 amperes at 5 volts. 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 more 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 (see Fig. 6 and Table IV), either from pulse transformers T3 and T4 to regulate the output voltage, or from transistors Q3 and Q4 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 (T1), the 60-Hz transformer (T2), and the pulse transformers (T3 and T4). This circuit isolation is indicated in Fig. 2.

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 Q5 and Q6 or Q7 and Q8, or by the oscillator transistors (Q11 and Q12) 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 Q15 insures that the oscillator does not "hang up."

Common-mode conduction is reduced by cross-coupled diodes D1 and D2. These diodes conduct when 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; this operation is illustrated in the waveforms of Fig. 9. 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. 6, 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 overcurrent 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.

Table IV gives a full description of the modulator circuits. For simplicity, the discussion is limited to the components on the left side of the symmetrical circuit layout shown in Fig. 6.

VARIATIONS ON THE DESIGN

The design discussed above and shown in Figs. 2 and 6 can be modified for different performance.

More Output. Larger transistors, such as the 2N5805, can be used as the power switches to increase the output by as much as 100 per cent. These transistors would require more base drive, which can be supplied by the circuit shown

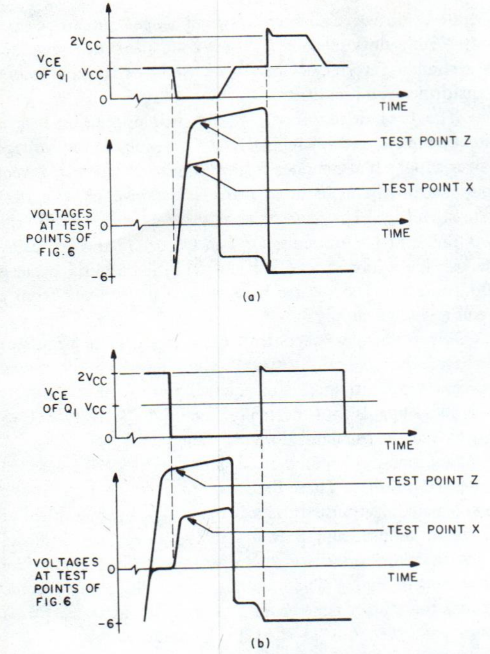

Fig. 9 - Suppression of common-mode conduction: (a) 50-per-cent duty cycle; (b) 100-per-cent duty cycle.

in Fig. 10 if the capacity of the 30-volt supply is increased.

Simpler Construction. Custom integrated circuits can reduce the number of parts in this unit.

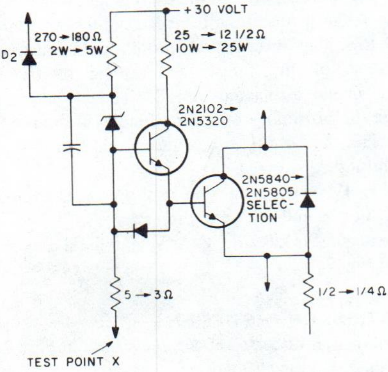

Fig. 10 - Changes in power-switching transistor drive circuit to produce increased output from larger power-switching transistors.

Smaller Package. A 20-kHz "off-the-line" inverter can be used in place of the 60-Hz transformer to reduce the size of the supply further. The smaller transformers, capacitors, and resistors for 20-kHz operation would, however, increase the cost.

Sensing. The output-voltage sensing can be improved, and output-current sensing can be added if required. The short-circuit protection in the circuit can be improved by adding an IC regulator that senses the output current by means of a current-sampling resistor.

Low-Voltage Supplies. Different voltages and different types of regulation can be used in the low-voltage supplies. One alternative, shown in Fig. 11, is the use of an extra winding on the isolation transformer to supply the base-drive transistors. This circuit reduces the cost of smoothing capacitor C2 in Fig. 2, and reduces the size of the 60-Hz transformer.

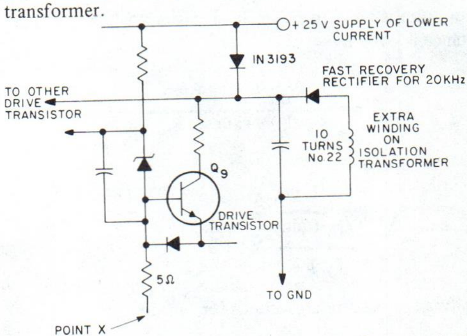

Fig. 11 - Use of a separate isolation-transformer winding to supply the base-drive transistors.

DESIGN NOTES

The switching-regulator type of power supply is more complex than a conventional dc series regulator. Because tests must be made with regard to waveforms, an oscilloscope is a required diagnostic tool. A special problem is that most of the components in these supplies are not isolated from the power line. Although the test equipment can be used "floating", the safest practice is to use an isolation transformer during tests of the power supply.

Finally, the design and construction of the filter are important to reduce spikes on the output. The filter unit should be sealed to prevent radiation.

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