Use this on-again, off-again regulator to power those solid-state projects from 6V to 16V at 7.5A.

A 150 WATT SWITCH-MODE REGULATOR

BY ROLLIE J. WALKER,* W2ICG

To be complete, evey ham shack should have a variable, low voltage power supply. With today's abundance of mobile equipment, designed to operate from a 12 volt battery, a solid source of 12 volt d.c. power is particularly useful, whether it be used to charge a battery or power the rig.

The switch-mode power supply has been around for a good while now, but only recently have switching transistors and integrated circuits appeared to make the use of switchers popular. Today's improved semiconductors can be used to construct an efficient, compact, and stable power regulator capable of furnishing well over 100 watts of d.c. power. This article describes such a regulator and, hopefully, will give you enough insight as to the operation of a switching regulator, so that you can do-it-yourself.

The Basic Regulator

A simple switch-mode regulator is shown in the block diagram of fig. 1. An unregulated d.c. voltage is supplied to a switch, which chops the voltage so that a rectangular wave of voltage is applied to the filter. The average voltage applied to the filter is a function of the time the switch is on, as compared to the time it is off, and the input voltage. This can be stated mathematically as follows:

$$E_o = \frac{E_i\, t_{on}}{t_{on} + t_{off}}$$

where E_i = input voltage
E_o = average output voltage
t_{on} = time on
t_{off} = time off

If we assume that there is no average voltage drop across the filter, then the average output voltage is the same as that applied to the input of the filter.

From this it can be seen that the average output voltage can be varied simply by varying the duty cycle, that is, the ratio of time on (t_{on}) to the total period ($t_{on} + t_{off}$). Therefore, we can vary the output voltage from zero to E_{in} by varying the duty cycle from zero percent to 100%. That, quite simply, is

*Application Engineer
Semiconductor Products Dept.
General Electric Company
Auburn, NY 13021

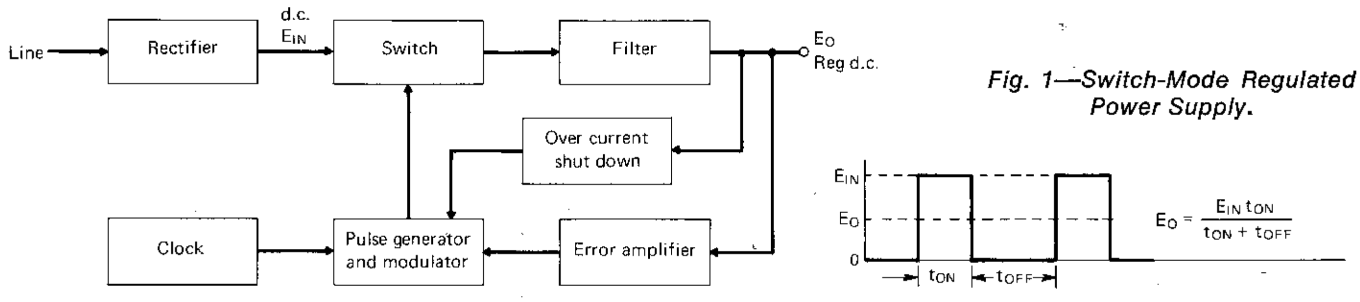

Fig. 1—Switch-Mode Regulated Power Supply.

how a switch-mode power supply works.

The Filter

The output from the switch is not very useful for power supply purposes, even though the average voltage may be just right, because it appears in the form of positive voltage pulses. All of the high-frequency components must be removed from the output by smoothing it in a filter. The best choice for our purposes is a simple RLC filter, as shown in fig. 2a. The inductor, which, in conjunction with the capacitor C, effectively limits ripple, serves a more fundamental purpose in that it limits the current through the switch. If the inductor were absent, the turn-on current of the switch would be limited only by the effective series resistance (e.s.r.) of the capacitor. This e.s.r. is about 0.2 ohms in a good capacitor, and, for good filtering, it is desirable to have as low an e.s.r. as possible.

If a constant voltage is applied to an inductor, the current will increase linearly (until the inductor saturates) as long as the voltage remains. When the voltage is removed, as when the switch is turned off, the inductor will attempt to maintain the current which was flowing at the instant of turn-off. If a path is not provided for the current to flow after turn-off the voltage across the inductor will increase to a very high value, and with reversed polarity, until the energy stored in the field of the inductor is dissipated—usually with an arc or breakdown of the switching device. That stored energy can be recovered and furnished to the load, or the storage capacitor by the use of the fly-back diode, D, of fig. 2a.

The time relationships of the steady-state voltages and currents in the circuit are shown in fig. 2b. The first waveform shows the voltage across the diode, D. Notice that the diode is blocking a voltage equal to V_{in} while the switch is closed; but, when the switch is opened, the voltage across the inductor reverses, as shown in the waveform for V_D, allowing current to flow through the diode. While the switch is on, the inductor current increases linearly to a maximum value determined by the value of the inductance, the on time, and the difference between the input voltage and the output voltage. When the swich is opened, the inductor current will continue to flow, but now it flows through the diode, D, still in the same direction as before, but will decrease until it reaches zero or the switch is closed again. In the figure, the shaded area represents current which is in excess of that required by the load, so that it flows into the capacitor for storage until the load calls for it. The unshaded current flows into the load. When the inductor current is less than that required by the load, the additional load current is delivered by the capacitor, as shown by the shaded portion of the waveform for I_C.

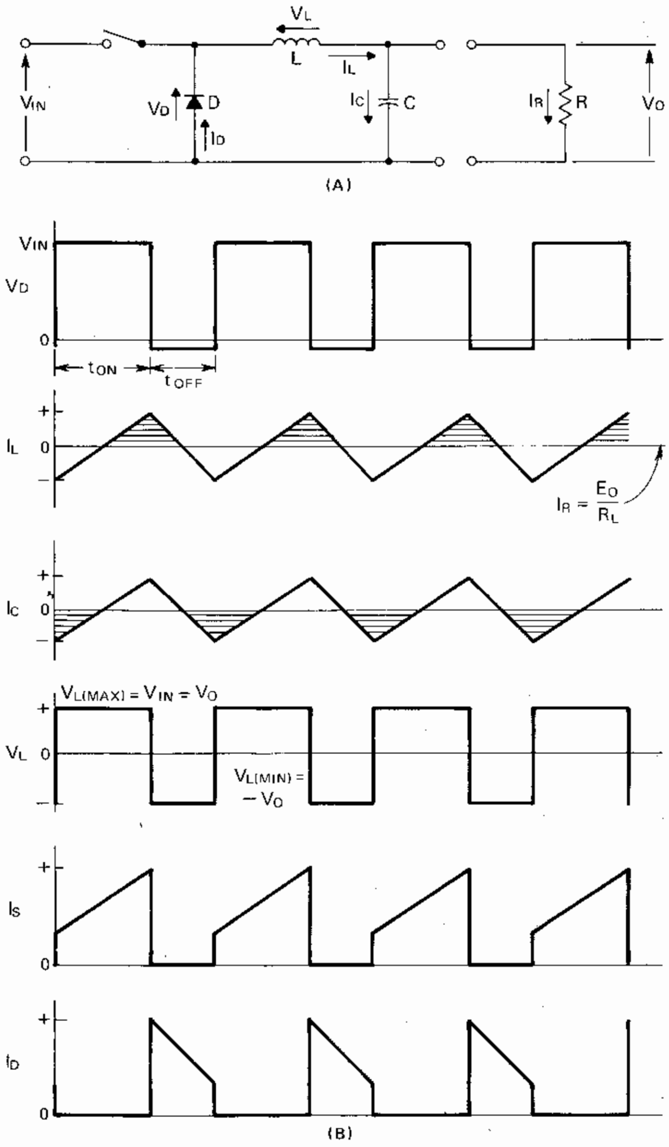

Fig. 2—(a) Basic filter network. (b) Filter circuit waveforms.

Of particular interest is the current through the switch (I_S) and that flowing through the diode (I_D). Each of these devices must be capable of conducting the peak inductor current and, since the current must be rapidly passed from one to the other, they must be fast switching devices to prevent excessive power loss. The diode, in particular, must be able to recover rapidly from a conducting state to a blocking state to prevent current through the switch from being shunted uselessly to ground. This recovery current may, if large enough, damage or even destroy the switch in the case of a semiconductor switch.

The Control Circuits

Referring again to fig. 1, we recall that the average output voltage is determined by the amplitude of the input voltage and the ratio of the on time to the length of the pulse cycle. Thus, by controlling the duty cycle, we can control the average output

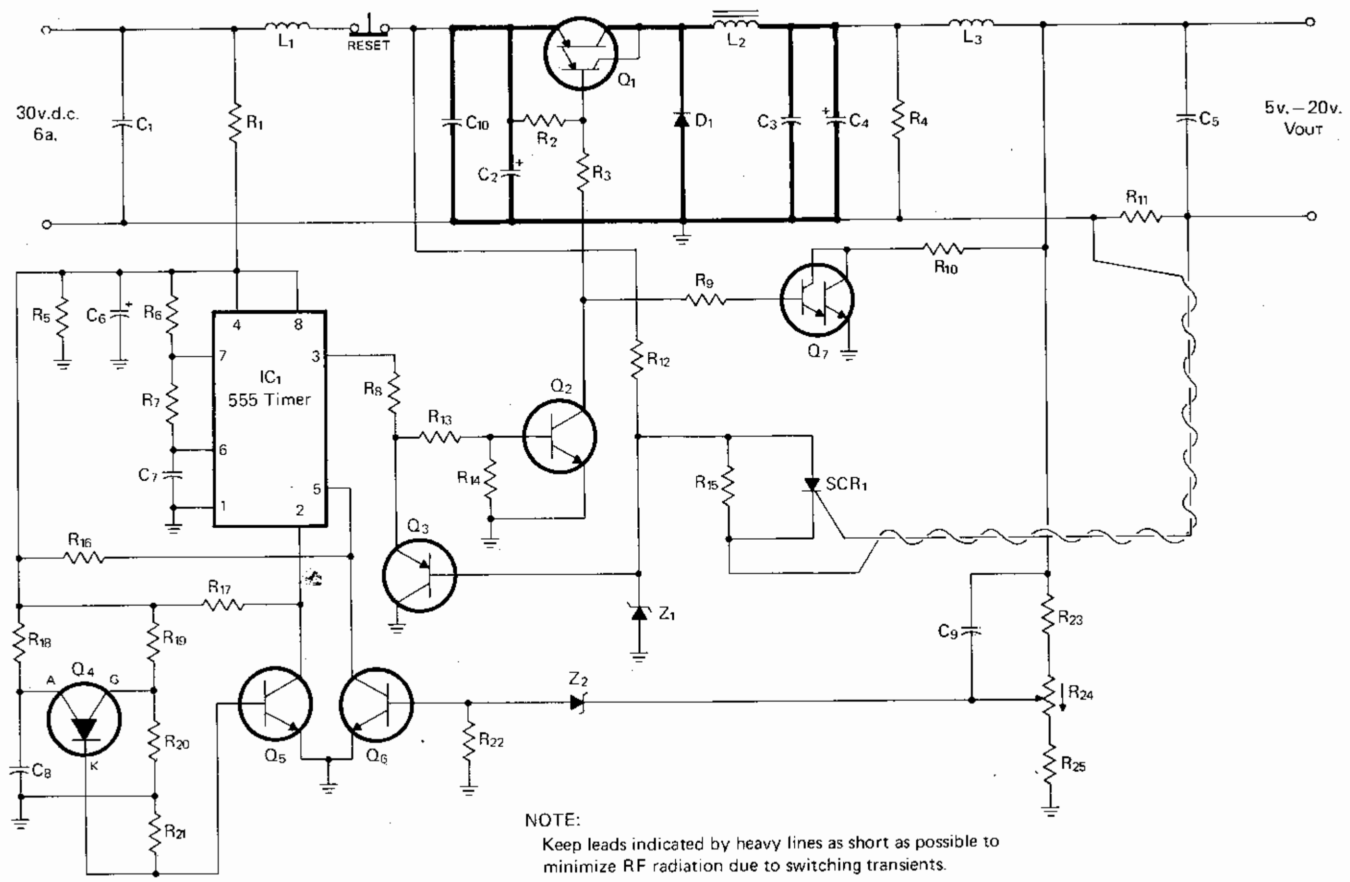

Fig. 3—Switch-Mode Regulator.

C_1, C_3, C_5, C_{10}—1.0μF, Polycarb
C_2, C_6—100μF, 50V
C_4—1000μF, 50V
C_7—0.0082μF
C_8—390pF
C_9—0.002μF
D_1—1N3890
L_1, L_3—10μhy, 10 amps
L_2—180μhy—(see text)
Q_1—D45E2 (General Electric)—
Q_2, Q_5—D33D25
Q_3—D29E25
Q_4—2N6027
Q_6—D32S4
Q_7—D40K2—Use Thermalloy 6063B heatsink, or equivalent
R_1, R_3, R_4, R_5—1.2K, ½W
R_2, R_7—110Ω, ½W
R_6—4.7K, ½W
R_8, R_{13}, R_{23}—1.2K, ½W
R_9—15K, ½W
R_{10}—20Ω, 10W
R_{11}—0.075Ω, 6 watts (see text)
R_{12}—1.5K, 1W
R_{14}—330Ω, ½W
R_{15}, R_{19}—680Ω, ½W
R_{16}—22K, ½W
R_{17}—4.7K, ½W
R_{18}—120K, ½W
R_{20}—1K, ½W
R_{21}—100Ω, ½W
R_{22}—18K, ½W
R_{24}—1K, 1W Pot.
R_{25}—390Ω, ½W
SCR-1—C103B
Z_1—1N5233B
Z_2—1N5226B
IC-1—555 Timer

voltage. There are several ways to accomplish this change in duty cycle, including fixing the on time to a constant value and varying the period of the cycle, (called pulse-position modulation), or by pulse-width modulation where the cycle time is held constant (constant frequency) and the width of the on time is varied. Pulse-width modulation will be considered here.

In the block diagram the control functions consist of the pulse generator and modulator and the clock. Output voltage regulation is achieved by sampling the output voltage, amplifying the deviation from a preset value and adjusting the pulse width of the driver circuit to compensate for the error. We can

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look at one way to put all these things together by referring to the circuit diagram of a practical switch-mode regulator as shown in fig. 3.

This regulator is designed to deliver any voltage from 7 volts to 20 volts at any load current up to 7 amps. The circuit is optimized at 12 volts output with respect to regulation, but does a nice job over the range indicated. At 12 volts output, the output voltage changes only 0.5 volt as the load current is changed from zero to 7 amps, indicating a source impedance of only 0.07 ohms. The low voltage end of the range may be extended to about 4 volts, at the expense of the upper voltage limit, by decreasing the input voltage to 20 volts. The supply is protected from short circuit damage by an overcurrent cut-out circuit which must be manually reset after it is activated.

This circuit closely follows the block diagram of fig. 1. A power darlington was chosen for the switching transistor, Q_1, to simplify the drive circuitry. Some sacrifice is made in switching and saturation losses with a darlington, but the D45E2 darlington has exceptionally low saturation voltage (less than 1.2 Volts at 10 Amps) and fast switching times. The D45E2 could be driven directly from the 555 IC, but an inverter (Q_2) is required to provide the 180° phase shift necessary for regulation.

The Regulator

The 555 timer provides the functions of pulse generator and pulse-width modulator. A varying voltage applied to pin 5 will modulate the pulse width linearly with respect to the applied voltage. Unfortunately, if the 555 is connected to operate in the astable mode some frequency modulation also occurs. Since it is desirable to operate at a fixed frequency the timer is connected to operate in the monostable mode, and a clock circuit is provided to trigger the timer.

In the monostable mode, the output (pin 3) of the timer is low until a negative going trigger pulse is applied to pin 2. At that time, the ouput is driven high and the timing capacitor, C_7, begins to charge. When the voltage on C_7 reaches a value determined by the volage on the control pin, pin 5, the output switches low and C_7 is discharged through R_7 and pin 7, and remains in that state until another trigger pulse occurs. Thus, the period between pulses is determined by the clocked trigger pulses and the pulse width, i.e. the time during which the output is high, is determined by the charge rate of C_7 and the voltage on pin 5. With a fixed charge rate the pulse width increases as the voltage on pin 5 is made more positive, thus keeping Q_2 and Q_1 on longer, raising the output voltage of the power

(Continued on page 74)

150 Watt Switch-Mode Reg. *(from page 43)*

supply. As the output voltage increases, the voltage on the arm of the control potentiometer, R_{24}, increases, causing transistor Q_6 to conduct more current, thus lowering the voltage at pin 5. That results in a shorter pulse width at the base of Q_1, shortening the on time and reducing the output voltage.

Since the entire system is designed to maintain a constant voltage at the arm of the control potentiometer, the output voltage of the regulator can be set by moving the position of the arm along R_{24}. This system will always stabilize so that the voltage at the arm of the potentiometer is about 3.6 volts, that is the sum of the B-E voltage of Q_6 and the zener voltage of Z_2. If the arm of the pot is set near R_{23}, the output voltage must drop to maintain the 3.6 volts at the arm and, if the arm is set near R_{25}, the output voltage must rise to develop 3.6 V at that point.

The Clock

The clock and trigger circuit is comprised of Q_4, Q_5, and the associated components. Q_4 is a PUT, that is, a programmable unijunction transistor. As the timing capacitor, C_8, charges, the anode voltage rises until it reaches a point about 0.7 Volts above the voltage at the gate. The PUT then turns on, discharging the capacitor through the cathode resistor, R_{21}. The PUT will discharge the capacitor almost completely in about 5 microseconds, producing a positive pulse at the base of Q_5 and triggering the timer. Immediately after discharging, the PUT turns off allowing C_8 to begin charging again to the trigger point. In this fashion, the PUT produces a very stable clock pulse at the rate of 20 KHz, thus setting the period of the timer to a value of 50 microseconds. The high frequency allows the use of a small value of filter inductor and minimizes ripple at the output by making the filtering easier. The frequency is also high enough that it is not audible to the human ear.

Overcurrent Protection

Semiconductors are very unforgiving if they are submitted to excessive current or voltage. For that reason, any solid-state power supply must be protected against dangerous current surges. Fusing will not protect the semiconductors because even the fast-blow variety is much too slow to prevent a catastrophic failure. Protection for this circuit is provided by the sensing resistor R_{11}, the SCR and Q_3. The value of R_{11} given here (0.075 Ohm) is that necessary to cause the SCR to turn on when 7.5 amperes flows through it. Since turn-on voltage (V_{gt}) may vary a few millivolts from one device to another, this value should be adjusted so that the shut-down circuit will operate around 8 amperes. The sensing resistor, R_{11}, may be made up of four 0.3 Ω, 2 w resistors in parallel to get the 0.075 ohms specified. At 7.5 amps, 4.2 watts will be dissipated in R_{11}.

When SCR-1 turns on the emitter of Q_3 is pulled down to about 1 volt, causing Q_2 to turn off, thus shutting down the regulator. The regulator will remain shut down until the voltage supplied to the anode of SCR-1 is removed (by operating the reset switch). This circuit is fast enough to prevent regulator damage even should a direct short circuit be applied to the output. Incidentally, the zener diode, Z_1, functions to prevent the E-B junction of Q_3 from avalanching when the output of the timer is low. Such avalanching is detrimental to the beta of a transistor and, should Q_3 fail to operate, the regulator would not be protected.

Low Load Currents

A switch-mode regulator regulates poorly, and may even oscillate, with light load currents. This is usually prevented by building in some pre-loading if the load current is expected to be low. Preloading in this circuit is provided by Q_7 and R_{10}. This method of preloading is advantageous because the preload is applied only when the regulator switch is off. Since the off time is shorter at heavy loads or higher voltage, the preloading is applied when it is needed most—at low output voltage and light loads.

Construction Hints

Construction of this regulator should be straight forward. All of the parts, except the inductor, L_2, should be available from your distributor. The regulator should be constructed in such a way that all of the heavy current components are well shielded to prevent r.f. radiation from escaping. Since relatively heavy currents are being switched at a very rapid rate, any stray inductances will tend to support high frequency oscillations, possibly resulting in QRM you don't need. L_1 C_1 and L_3 C_5 are provided to reduce conducted radiation from traveling along the input and output leads. Capacitors C_{10} and C_3 are intended to shunt the high frequency currents to ground near the point where they are generated. For that reason, their leads, and all of the leads in heavy black in the diagram, should be kept as short as possible. With proper attention to these details, the r.f. radiation will be negligible.

L_2, as noted in the parts list, is 180 microHenries of inductance. It should be able to handle up to 15 Amperes without saturating. The inductor can be formed by winding 16 turns of #18 wire on a Ferroxcube 1F10 "U" core of 3C8 ferrite material. The core is "U" shaped with the open end closed by a straight bar of the same material, using a gap of about 0.005" at each end of the "U". The cross section of the core is 0.56 inches square. The outside dimension of the assembled core is 1.5" × 2.5". Make the windings tight and well taped to prevent coil movement with varying current.

The D44E2 transistor should be provided with an adequate heat sink. The tab temperature of the transistor should not exceed 80°C for reliable operation. A 4½" length of Wakefield #4666 heat sink, or other material rated at 1.7°C/watt or better, is sufficient for this circuit. Remember that the collector is not at ground potential. It should be insulated from the heat sink with a thermally conductive insulator or, better still, mounted directly to the heat sink and the heat sink electrically insulated from the chassis.

The unregulated d.c. input can be supplied from any rough power supply. The regulator will hold a constant output voltage of 12 V, even when the input voltage is varied from 24 volts to 35 volts, so the input voltage is not critical. A 30V, 5A input supply will furnish an output of 6A at 20V, or up to 7.5 amps at any output between 6 volts and 16 volts. ■