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TWO PREVIOUS ARTICLES ON SWITCHING Power Supplies (June and July 1979 issues of **Radio-Electronics**) dealt with the basics of switching regulator theory and presented several typical circuits using IC's for basic DC-to-DC conversion. This article will present a universal regulator that can be programmed with simple jumper wires for step up, step down, or an inverting output. It is much more than the simple DC-to-DC converters discussed earlier. This approach to switching regulator design incorporates all the essential protection and control circuitry needed to maintain high efficiencies and a fully protected system.

The heart of the design is a new Switched Mode Power Supply Control circuit, the Signetics NE5560N. Unlike the simple DC-to-DC circuits on the market, this IC was developed as a "Power Supply System Controller." The following description will bare this out in detail while providing insight into the operation of the regulator.

Figure 1 shows a block diagram of the NE5560. A quick glance tells you it's much more than a DC-to-DC circuit. The oscillator consists of a highly stable sawtooth generator. The frequency is determined by an external resistor and external capacitor connected to ground from pins 7 and 8. The operating frequency range is specified from 50 Hz to 100 kHz although most NE5560N's will operate up to 150-kHz. The regulator described here uses a 20K resistor and .003 μF capacitor to achieve an approximate 30 kHz oscillator frequency, well above the audio range.

The capability of high-frequency operation is important for several reasons. First, the threshold for new technology for high-speed switching transistors has been reached. VMOS devices are now

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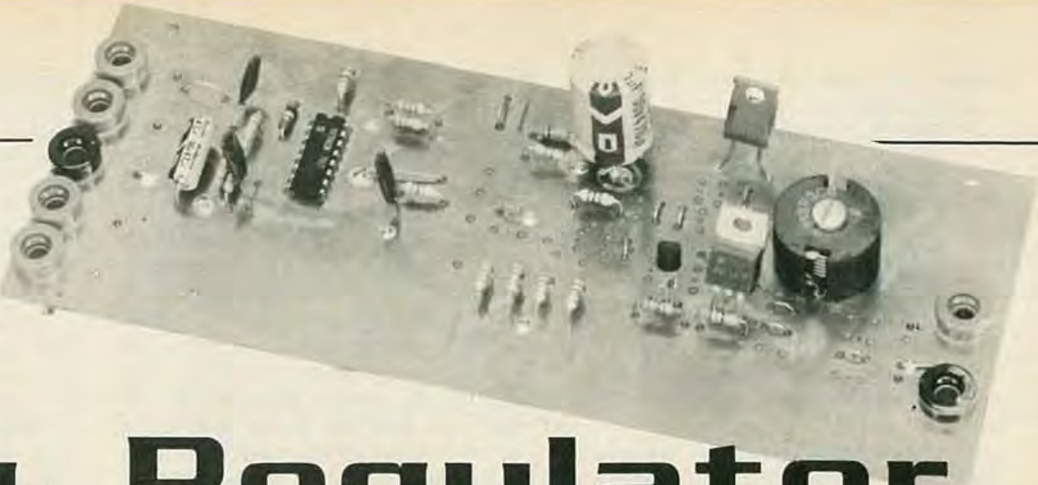
ching Regulator



The switching-type voltage regulator offers much greater efficiency than conventional regulated supplies. This design lets you invert the output polarity or program the output for step-up or step-down.

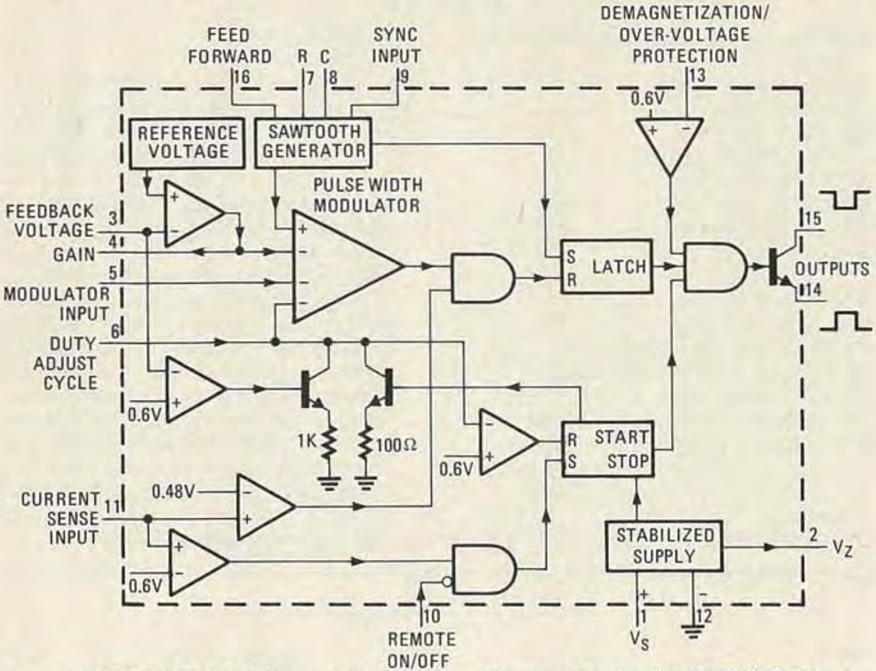


FIG. 1—BLOCK DIAGRAM of the control circuit shows the array of protective circuit features.

commercially available along with fast-recovery diodes making extremely high power switching regulators smaller, lighter, and less expensive than ever before. High-frequency operation also means small energy storage elements i.e. greatly reduced magnetics (transformers and chokes) resulting in further size, weight and cost reductions.

The ability to synchronize the oscillator to an external TTL signal is important in switching power supply design. Although it is not necessarily applicable in this project, the pin is available and brought out on the board for experimentation purposes. The oscillator can be synchronized to a frequency lower than the free-running frequency as determined by the external resistor and capacitor connected to pins 7 and 8. For example, in a video display system it is desirable to sync the switcher to the horizontal deflection signal to minimize noise and beat signal problems.

There are two basic techniques to vary output pulses to the switching elements. Many DC-to-DC converters use a frequency-modulation technique that is easy to achieve but hard to control. The system described here uses a pulse-width modulation scheme that allows precise cycle-by-cycle control of the output. The duty cycle range of the NE5560 is 0 to 98%.

With pins 5 and 6 not connected and a low feedback voltage on pin 3, the output pulse will have approximately a 98% duty cycle. In switched-mode power supplies, large output duty cycles can cause problems, especially in forward converters (see box) where duty cycles in excess of 50% can cause the magnetics to saturate. For this reason it is important to be able to control the maximum duty cycle. Applying a DC voltage to pin 6 of the NE5560 controls the duty cycle maximum limit. This relationship is illustrated in Fig. 2.

Establishing a maximum duty cycle is best done with a resistor divider from V_z (pin 2) to pin 6 and pin 6 to ground. This technique takes advantage of another pair of resistors internal to the NE5560 that then form a bridge with the two external resistors and biases pin 6 with a stable DC voltage. This configuration allows pin 6 to also be used to set a minimum duty cycle when a loop fault occurs. Resistors R1 and R2 have been selected at 10K. These may be modified to experiment with dif-

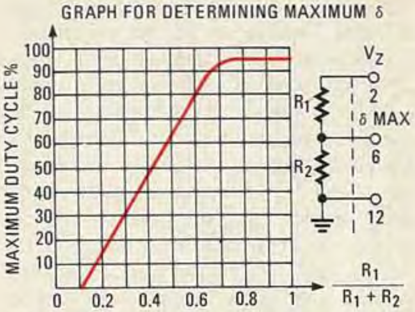


FIG. 2—THE RATIO of R1 to R2 determines the maximum duty-cycle δ of the system.

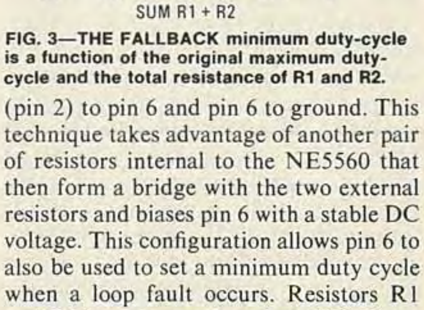


FIG. 3—THE FALLBACK minimum duty-cycle is a function of the original maximum duty-cycle and the total resistance of R1 and R2.

ferent duty cycles so long as two basic criteria are kept:

1. The duty cycle must be large enough to insure that at maximum load and minimum input voltage, the resulting feedback voltage to pin 3 must exceed 0.6 volts.
2. It must be small enough to limit the amount of energy to the output stage when a loop-fault occurs.

The relationship of the minimum duty cycle and maximum duty cycle to the values of R1 and R2 is shown in Fig. 3.

Another critical feature of switched-mode power supply design is to be able to control the duty cycle during "power up" conditions—to gradually increase the amount of power to the load until full output is reached. An electrolytic capacitor from pin 6 to ground will provide this function. During "power up" C1 (Fig. 4) is initially discharged. When power is applied C1 begins to charge through R1 and the voltage on pin 6 gradually increases to its final value (determined by R1 and R2).

Capacitor C1 serves another important function; that of protecting the entire system when an over-curent condition exists. The output current is monitored by pin 11 on the NE5560. This pin senses a rise in voltage across a sense resistor (R15–R18 in parallel) indicating a rise in current. This feature can be examined in the step-up configuration (Fig. 4).

In actuality four 2.2-ohm resistors are used in parallel in this application so that you can experiment with the over-current protection feature of the IC. With only one of the 2.2-ohm resistors in place, the effect of increasing the load current (reducing the load resistance) increases the voltage on pin 11 greater than .48 but less than .6 volt. This activates an internal comparator that in turn resets an internal latch and shuts off the pulse to the output switch. The feature of cycle-by-cycle control reduces the duty cycle of each pulse individually. The new duty cycle is a function of how quickly the over-current condition can cause a greater than .48-volt drop across the sense resistor.

By reducing the sense resistance (adding the other three 2.2-ohm resistors) the voltage sensed will now exceed .6 volt that activates another comparator internal to the NE5560 which in turn sets a latch that completely inhibits the output. The latch also turns on a transistor whose collector is connected internally to pin 6. This discharges C1. When the voltage on C1 drops below .6 volt, another comparator resets the latch. Capacitor C1 then begins to charge creating the soft-start effect of gradually increasing duty cycles. If the fault condition remains the procedure repeats itself. This is called the "hiccup mode." In major systems it is not advised to let a system oscillate in the hiccup mode for long periods of time.

Use of the remote on/off (pin 10) can prevent this problem. A simple CMOS counter can be used to sense hiccups by connecting the input to the slow-start capacitor (C1), programming for some number of counts (i.e. 5, 10 etc.) and the output can then be connected to pin 10. This way with a permanent major fault the entire system will be shut down after say five hiccups.

Switching-power supplies use feedback techniques to sense what's happening at the output and internally correct for any deviations that may be detected. An error amplifier is provided on the NE5560 to sense the output voltage sampled through R3 from the divider R4–R5 (see Fig. 4). The gain of the error amplifier is controlled by the feedback resistor R6. Capacitor C3 is for loop compensation. Typical open-loop gain of the error-sense amplifier is 60 dB.

Special protection features not found in any other control circuit include a completely protected loop. If for some reason the loop opens, an internal current source pulls pin 3 voltage up giving the false impression that the output voltage is high. This information is then delivered to the pulse-width modulator and the duty cycle is reduced to a safe level preventing a runaway condition.

A second safety feature on the loop protects the system in the event the feedback loop somehow gets shorted to ground. In this case an internal comparator senses that the amplifier input (pin 3) is below 0.6 volt. This too reduces the duty cycle by affecting the pulse-width modulator. A shorted loop also results in the soft-start capacitor being discharged through an internal 1K resistor. This short remains as long as the voltage on pin 3 remains below 0.6 volt. This results in a greatly reduced duty cycle (a function of the forced voltage on pin 6) further protecting the switching power supply.

PARTS LIST

Resistors ¼ watt, 10% unless otherwise noted
R1, R2—10,000 ohms
R3—1000 ohms
R4, R7—3600 ohms
R5, R12—20,000 ohms
R6—100,000 ohms
R8—8200 ohms
R9, R13—2000 ohms
R10—180 ohms
R11—68 ohms
R14—360,000 ohms
R15–R18—2.2 ohms
C1—47 µF, 16 volts, electrolytic
C2—470 µF, 50 volts, electrolytic
C3–C5—.003 µF disc
D1—BYW29-150 (Amperex) or equivalent
IC1—NE556ON (Signetics)
L1—0.9 mH inductor (Ferroxcube 2213 PL00-3C8 pot core and 2213 F1D bobbin)
Q1—BU407 (SGS)
Q2—2N3638A
Q3—2N2222A
Miscellaneous—double-sized PC board, 3 feet of No. 18 enameled magnet wire, nylon screw and nut for mounting L1.

Note: A kit of two 2213 PL00-3C8 pot cores (two are required for one enclosed inductor) and a 2213 F1D bobbin is available for $3.00 including postage and handling, from Elna Ferrite Labs, PO Box 395, Woodstock, NY 12498.

A complete kit of parts (No. SMP-1) to build the power supply as described is available for $36.50. A boost kit No. SMP-2 includes higher power drive transistors and larger pot core for converting the basic SMP-1 for approximately 3 amperes output; $13.50. California residents add 6½% sales tax. Order these kits from Advanced Analog Systems PO Box 24, Los Altos, CA 94022. Phone: (408) 377-7148.

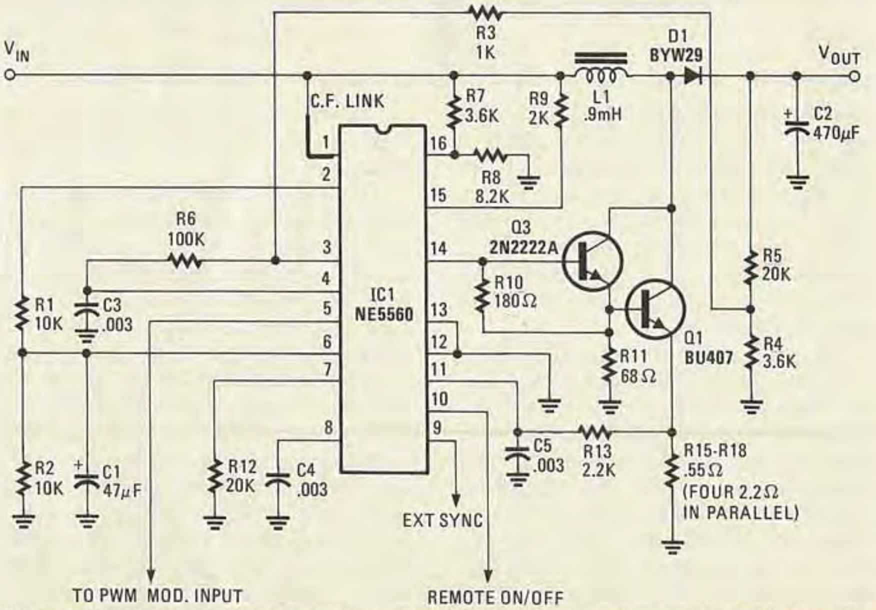


FIG. 4—STEP-UP CONFIGURATION. Output voltage V out is 24 volts and can be adusted by changing the value of R5. Output changes 1 volt for every 1000 ohms change in R5.

These two protective features can be investigated by looking at the output duty cycle with a scope while opening then shorting the loop.

While the feedback loop looks at the output and tries to compensate for changes due to such things as load variation, a *feedforward* circuit looks at the input line and modifies the duty cycle to compensate for line variations. Resistors R7 and R8 sample the input voltage to the feedforward circuit (pin 16.) When the voltage on pin 16 exceeds an internal reference voltage (V_z, typically 8.4 volts), the charging current for the timing capacitor on pin 8 is increased. The higher the voltage the larger the charging current and consequently the shorter the duty cycle. Conversely, if the voltage on the feedforward pin decreases, the duty cycle increases to compensate for the change. Ideally, the NE5560 should be operated with the feedforward in its active area, i.e. between V_z and V_{cc}, so that it has plenty of headroom to compensate for variations in the line voltage, up or down. The feedforward function improves the line regulation of the switching power supply by almost a factor of 15.

Another area where protection must be provided against a fault is the switching regulator output. Of primary concern is the power switching elements. Excessive currents, due to output shorts, shorted windings in a choke or transformer etc., can quickly destroy the switching transistor.

Two types of output problems can develop. The first, excessive current, was discussed earlier and was resolved with the aid of pin 11. The second is saturation of the magnetics, especially critical in forward-converter transformers. Pin 13 is used to sample the voltage present in the transformer. Again its output is a comparator with a 0.6-volt threshold which, when activated, will completely inhibit the output pulse until the saturation problem goes away and the voltage drops below 0.6 volt.

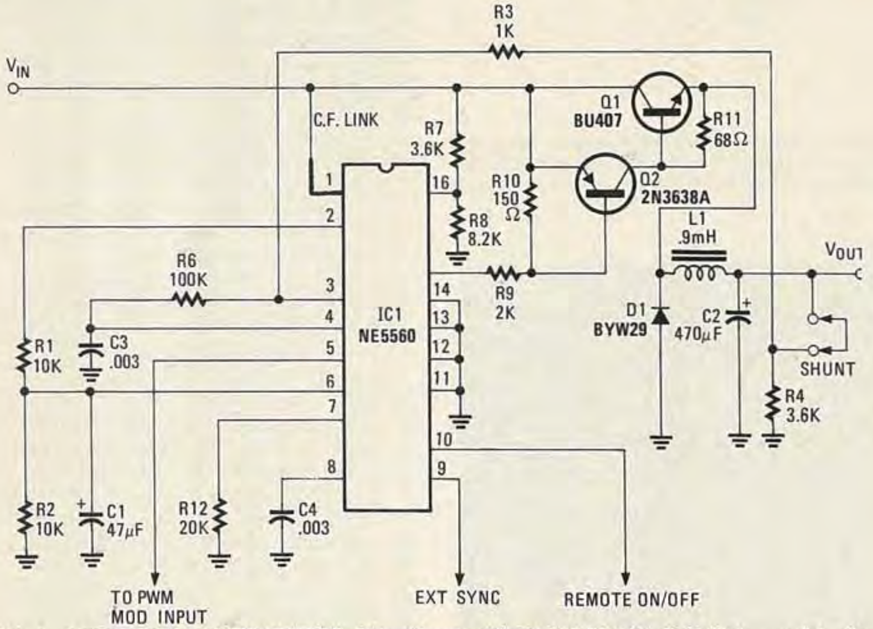


FIG. 5—STEP-DOWN CONFIGURATION. Output is approximately 3.75 volts. Substitute a resistor for the shunt and output can be increased by 1 volt for each 1000 ohms of resistance inserted.

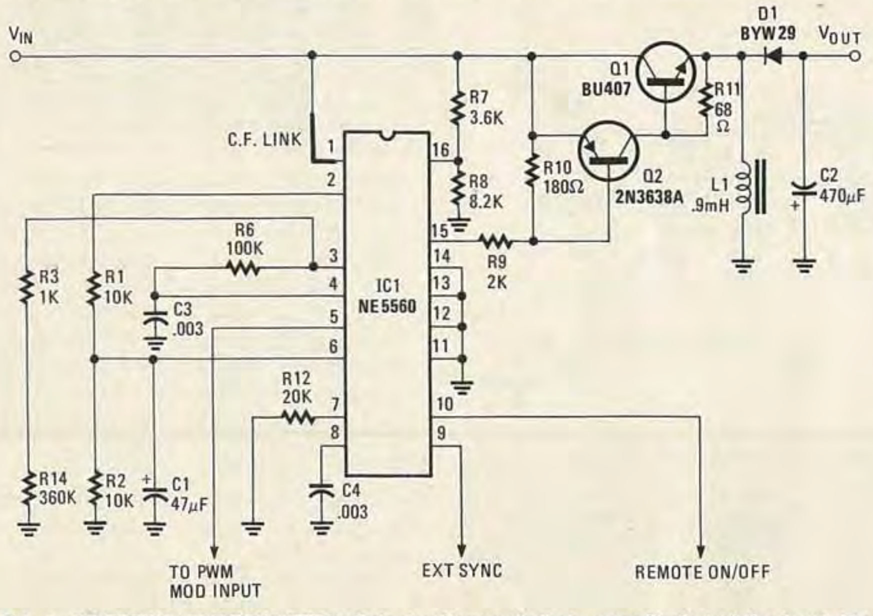


FIG. 6—INVERTING CONFIGURATION. Output voltage polarity is opposite that of the input. This circuit delivers −5 volts.

Since switched-mode power supplies operate at extremely high efficiencies they can easily control very high power systems where low voltages are not necessarily available to power the NE5560. This potential problem is overcome due to a unique ability of the NE5560 to operate in either a *voltage-fed* (conventional operation) or a *current-fed* mode. When only high voltages (30 volts or above) are available, the IC can be current-driven through a limiting resistor. In this mode internal Zener diodes will limit the drop across the NE5560 to typically 23 volts at 10-mA and 30 volts at 30 mA. A provision for the limiting resistor is made by removing the link connecting pin 1 to V_{in} on Figs. 4, 5, and 6 and inserting a proper resistor with sufficient power dissipation.

Voltage-fed and current-fed modes

The NE5560 operates with either a forced voltage or forced current as the primary power. In the current-fed mode where V_{in} is greater than 30 volts, a series resistor (or current source) is placed between the power source supplying the device and pin 1. [The current-fed (CF) link is removed and replaced by the resistor.] This resistor or current source must be selected to provide a minimum of 10 mA and a maximum of 30 mA. An extra capacitor from pin 1 to ground may be needed to filter noise.

When operated in the current-fed mode, an internal shunt regulator limits the voltage on pin 1 to about 23 volts—this voltage varies from one IC to another and ranges from 20 to 30 volts.

In the voltage-fed mode supply voltage V_{in} must be greater than 9.5 volts (to make the IC active) and less than 18 volts to guard against exceeding the shunt regulator's 20-volt maximum. With V_{in} connected to pin 1 through the CF link. In this mode the IC draws about 8.5 mA.

Remember that any current drawn from pin 2 (V_z) must ultimately come from pin 1 and should be added to the 8.5 mA.

Construction

This switching regulated power supply, although designed primarily as a learning tool to familiarize oneself with the three unique modes of operation, does have practical applications as a supply. Both the switching transistor Q1 (BU407) and the switching diode D1 (BYW29) are capable of switching currents in excess of 5 amps at voltages greater than 100 volts.

The actual current capabilities of the

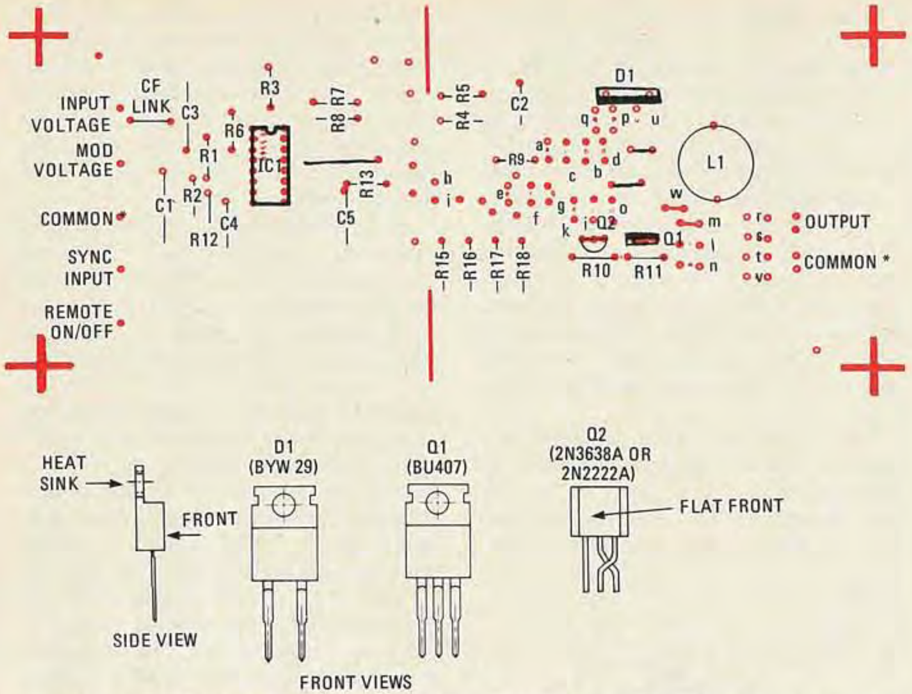


FIG. 7—COMPONENT LOCATION DIAGRAM. Be sure that both common leads (input and output) are soldered to the top side of the ground plane. Note the pin-outs for D1, Q1 and Q2. The board layout makes it necessary to transpose two leads on Q2. The heatsink sides of Q1 and D1 should be toward the center of the PC board.

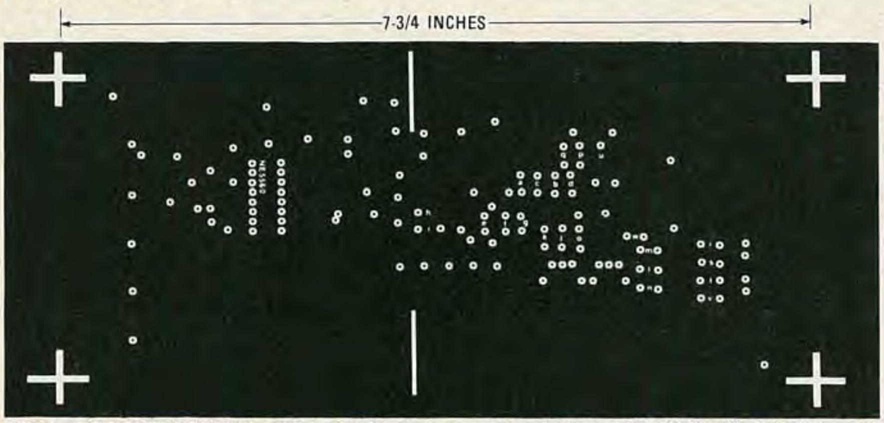


FIG. 8—TOP SURFACE of the PC board is used as a ground-plane. Note that only the circles and lettering are etched away.

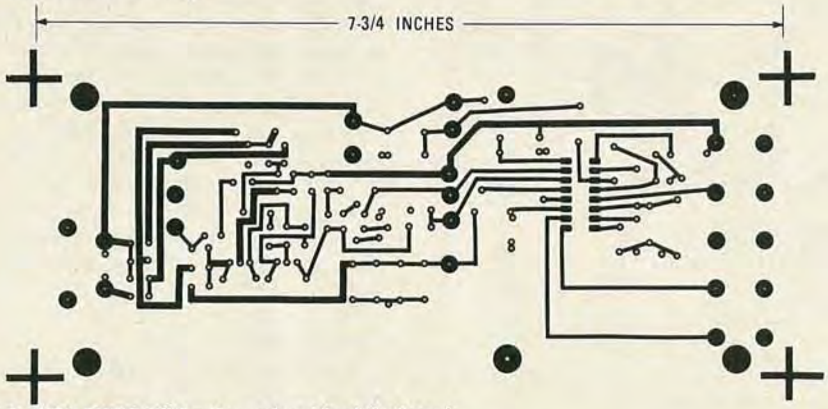


FIG. 9—FOIL PATTERN for the under side of the board.

TABLE 1

Oscillator Freq	No. of Turns	Inductor	Max Current
20 kHz	14	.9 mH	300 mA
40 kHz	10	.5 mH	500 mA
80 kHz	7	.25 mH	700 mA

FORWARD VS. FLYBACK

There are two basic types of converters used in Switched Mode Power Supplies: the *forward converter* and the *flyback converter*. In both types of converters an inductor is used as an energy-storage element. In the forward converter the inductor is connected in series with the load. Thus energy is passed to the load and the coil during the "ON" condition of the output transistor. In the flyback converter the coil is connected in parallel with the load. Energy is stored in the coil during the "ON" period and transferred to the load during the "OFF" period. These are sometimes known as series or parallel converters respectively. Each approach has its advantages and disadvantages. In the forward converter, for example, the switching transistor conducts current to the load only during the "ON" condition, and the peak value of V_{CE} that the device must withstand is only equal to the input DC voltage. Also the inductor can be smaller and the capacitor has a lower ripple current to deal with. Disadvantages include difficulty in achieving isolation from the input and the full input DC being applied to the load in the event of a shorted switching transistor.

The advantages of the flyback converter are the opposite of the disadvantages of the forward converter. Input/output isolation is very easy to achieve by adding a secondary to the inductive element. Also it is not necessary to protect the load against excess voltage in the event of a shorted switching transistor. Disadvantages complement the advantages of the forward converter. The peak value of V_{CE} the switching transistor must withstand is the sum of the input DC voltage and the output voltage ($V_{CE} = V_{in}$ max $+ V_O$). Thus both the inductor and diode have to pass higher peak current and withstand higher peak voltage. The inductor is larger and the capacitor must pass higher ripple current. And of course the higher switching voltages and currents generate increased amounts of noise.

supply are limited by the pot core for L1 and oscillator frequency selected. The pot core used for the inductor is a Ferroxcube, type 2213-3C8. The core volume is 2 cm². The bobbin is wound with 14 turns of No. 18 enameled wire (approximately 3 feet) leaving approximately 3 inches for connection to the PC board. Depending on the gauge of the wire used, the holes of the PC board may have to be enlarged. Nominal inductance of the pot core is .9 mH. Trade-offs may be made by reducing this inductance, and increasing the oscillator frequency to achieve higher output currents.

Table 1 shows how maximum current is affected by oscillator frequency and the inductance of L1. Another way to in-

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SWITCHING REGULATOR

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crease the output current is to increase the core volume of the inductor (larger pot core). When attempting to achieve higher currents, the drive circuitry to the switching transistor may have to be replaced with devices that provide more base drive to the BU407 (Q1). Recommended replacement for the 2N3638A (Q2, Fig. 5) is a 2N2905A; Q3, a 2N2222A is useful as it is. Reduce R9 to 510 ohms and the four 2.2-ohm sense resistors should be replaced with an equivalent resistance of .1 ohm.

The step-up configuration (Fig. 4) is designed for approximately 24 volts output. This can be altered by replacing R5 (20K) with another value resistor (or potentiometer). The output changes about 1 volt for every 1000-ohm change in R5.

The step-down configuration (Fig. 5) has a nominal output of about 3.75 volts. This value can be raised by replacing the jumper wire shown at the output with a resistor. The output voltage will increase beyond the point where the output voltage is within 5 volts of the input voltage.

When investigating the inverting mode (Fig. 6), the polarity of C2 must be reversed from the other modes.

TABLE 2

Step Down
Short: B,C,G,H,J,L,M,T,U
Step Up
Short: A,D,I,K,N,O,P,Q,S,W
Inverting
Short: B,C,G,H,J,L,M,R,V
Note that R14 is 360K for this configuration. In the two other modes it is called R4 and is 3.6K.

Table 2 shows which jumpers need to be installed to create step-up, step-down, or inverting output. These links are shown in the component layout diagram of Fig. 7.

All holes on the board not relieved by artwork should have the wire soldered to both top and bottom sides. Components with grounded ends have holes for this purpose. Be sure to solder to the top side ground plane. Complete artwork for the double sided PC board is provided in Figs. 8 and 9. If the modulation input (pin 5) is not used, solder pins 5 and 6 together.

The 3C8 ferrite material used in the pot core for L1 is quite brittle so take care not to drop the parts because they will shatter. Also when mounting the core be sure not to overtighten the mounting screw as that, too, could be the cause of an unpleasant cracking problem. **R-E**