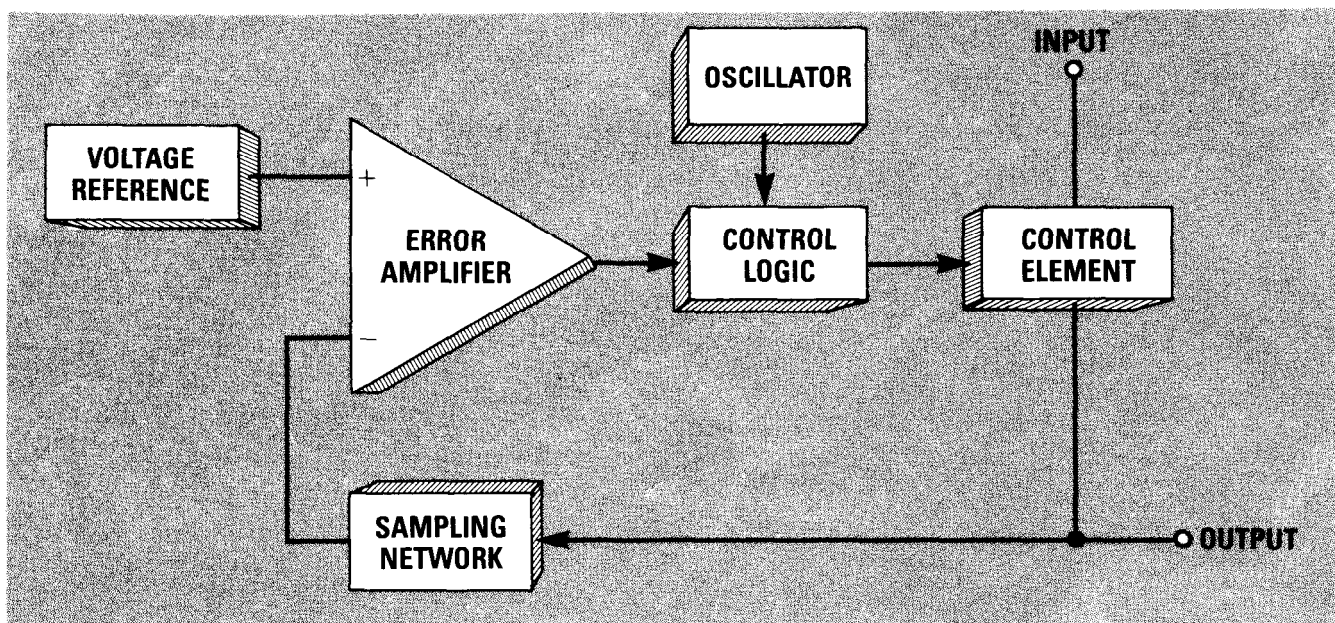


Switching Power Supplies



You too can design switching power supplies! In this article we present you with the theoretical background and several experimental circuits.

VAUGHN D. MARTIN

SWITCHING POWER-SUPPLY DESIGN HAS long been regarded as something of a black art practiced only by magicians and wizards. However, recent innovations in electronics have provided us with components that simplify such designs considerably: high-density IC's, high-permeability ferrite inductor cores, and high-power, high-speed switching transistors. We will review fundamental power-supply operation, discuss underlying switching-supply theory, and then present theoretical and practical information on how to design switching supplies using two popular LSI IC's. To simplify your design tasks, we include complete schematics, parts lists and PC artwork for several functional switching power supplies.

Regulator basics

Any regulated DC power supply—switching or linear—is governed by a feedback mechanism that senses changes in the output voltage and generates a control signal to compensate for those changes. As shown in Fig. 1, the basic linear voltage regulator has four major components:

- 1) A voltage reference
- 2) An error amplifier
- 3) A feedback mechanism
- 4) A control element

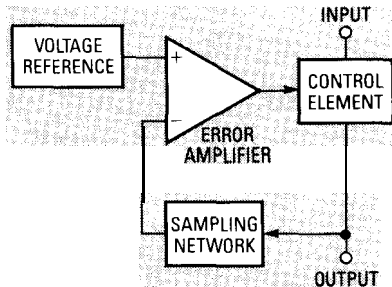


FIG. 1—THE FOUR BASIC COMPONENTS of a linear regulator are shown here. The control element is a transistor operated in the common-base mode.

The control element is usually a transistor operated in the common-base mode. Its base current determines the current flowing through its emitter-collector circuit, and thus, indirectly, the output voltage of the regulator. That base current is supplied by the error amplifier, usually an op-amp. The op-amp compares an internal reference voltage to a portion of the control element's output voltage. The op-amp's output is proportional to the difference between those voltages, and that is what controls the base current, and hence the collector current, of the control element.

Not shown in Fig. 1 is additional cir-

cuitry that protects the regulator from over-current and over-heat conditions. Like the error amplifier, the protection circuit samples a portion of the output voltage; the output of the protection circuit would be connected to the base of the series pass transistor, and would force the transistor into cutoff when it sensed an overload condition.

In a linear regulator the series-pass transistor operates in the linear region; that is, current flows through the transistor continuously as long as the input voltage exceeds the minimum necessary to keep the regulator working. (Output may also be cut off, as we discussed above, because of thermal or over-current shutdown.) But a regulator does not necessarily have to operate in such a fashion. It is possible for it to switch rapidly between saturation and cutoff, remaining in the linear region only for the short period of time required to perform the switching action. That is the basis of the switching regulator.

Fight or switch?

Although it might seem odd to operate a power supply in such a manner, with proper circuit design much greater efficiency can be obtained than with linear operation. Output voltage in the switch-

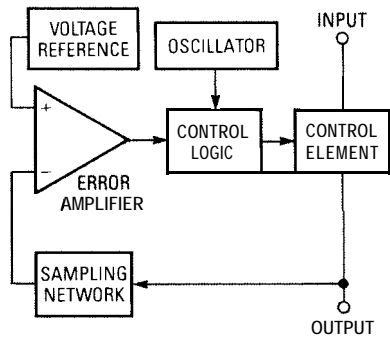


FIG. P-SWITCHING REGULATORS differ from linear regulators by the addition of control logic and an oscillator; the latter allow control of frequency, duty cycle or both, and those parameters determine the regulator's final output voltage.

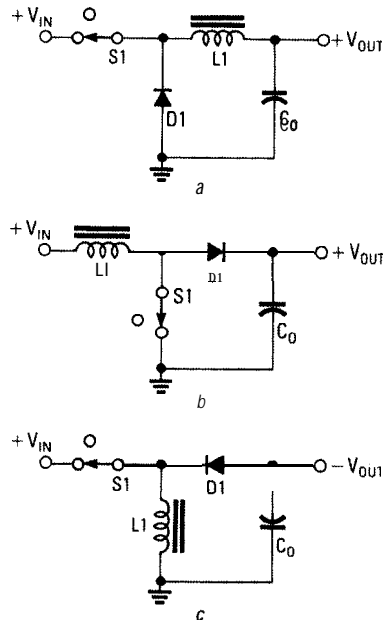


FIG. 3-THREE BASIC switching regulators are shown here. Step-down, step-up, and inverting regulators are shown at a, b, and c, respectively.

ing mode is controlled by varying the duty cycle, the frequency, or both, of the signal that turns the transistor on and off. As shown in Fig. 2, the switching regulator is conceptually similar to the linear regulator. The blocks labeled "control logic" and "oscillator" are what allow the duty cycle or frequency to be controlled.

Switching supplies allow greater efficiency than linear supplies, but that is not their only advantage. As shown in Fig. 3, by rearranging a few components, the same basic circuit can be made to step the input voltage down (a), to step it up (b), or to invert its polarity (c). And inversion may happen simultaneously with the step-up and step-down functions.

In each of the circuits shown in Fig. 3, SI is represented as a mechanical switch, but in the circuits we will be concerned with, it is actually an electronic multi-

vibrator whose duty cycle, frequency, or both may be varied by connecting appropriate components. In the past (that is, before the invention of high-voltage, high-power semiconductors, and LSI IC's), that switching action was performed by rotating machinery.

In Fig. 3-a, the coil-capacitor network may be thought of as an energy reservoir that is fed by the power source each time the switch is closed. The diode serves two functions. First, it provides a discharge path for the coil so that when the switch opens, there will be no arcing. Second, it also provides a path through which the current that is stored in the coil and the capacitor may flow while the switch is open. That helps smooth the rough sawtooth that is the normal product of such switching into a fairly "flat" triangle wave. Thus, less noise is generated, and the average DC value of the output voltage is higher than it would be without the return diode. That type of circuit is known as a *series* switching supply, because the switching device is in series with the input voltage source.

By contrast, the step-up circuit in Fig. 3-b is called a *shunt* switching supply, because the switching device is in parallel with the input voltage. When the switch opens, energy stored in the magnetic field of the coil is released as a large spike that serves to charge capacitor C₀. Diode D1 here serves to prevent the capacitor from discharging through the switch while it is closed.

The inverter scheme in Fig. 3-c combines elements of both the step-up and step-down circuits. Again the switching

device is connected in series with the voltage source; the coil again dumps its stored energy to the capacitor when the switch is opened. Here the diode ensures that the discharged energy flows "backward" through the load.

Modern switching regulator IC's usually contain the voltage reference, switching mechanism, protection circuitry and a low- to medium-current series-pass element. The circuit designer usually supplies discrete components to set the oscillating frequency of the switching supply, an appropriate inductor, and additional series-pass elements to increase the circuit's current output.

The three most popular switching voltage regulator IC's today are probably Signetics' NE5560N, National's LM3524 and Fairchild's μ A78S40. Robert Frostholm explained the Signetics IC in the February 1980 issue of **Radio-Electronics**, so for the remainder of this article, we will concentrate on the latter IC's.

The LM3524

A Pulse Width Modulator (PWM) is a circuit that varies the duty cycle of a pulse train while keeping its frequency constant. The LM3524 has a built-in PWM that is used to vary the "on" time of the series-pass elements. As shown in Fig. 4, the output of the oscillator drives a flip-flop that in turn drives two NOR gates. Note that they are driven out of phase by the flip-flop's Q and \bar{Q} outputs. Also note that the IC's output is disabled by the comparator whenever its output goes high. That will happen whenever the error amplifier determines that the internal ref-

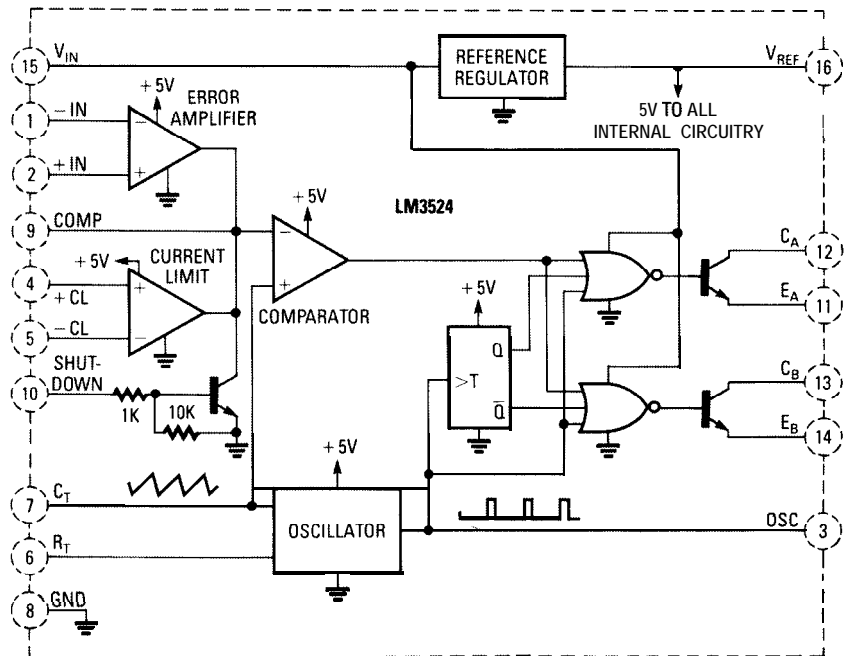


FIG. 4-NATIONAL SEMICONDUCTOR'S LM3524 can tolerate a maximum input of forty volts, and can provide as much as 100 ma of output current.

PARTS LIST—LM3524 CIRCUIT

All resistors ¼ watt, 5%

- R1, R2, R4, R5—5000 ohms
- R3—0.15 ohms see text
- R6—6500 ohms
- R7—30,000 ohms
- R8—510 ohms
- R9—420 ohms
- R10—560 ohms

Capacitors

- C1, C2—.01, ceramic disk
- C3, C5—.1, ceramic disk
- C4—10 µF, 35 volts, electrolytic
- C6—500 µF, 10 volts, electrolytic

Semiconductors

- IC1—LM3524, switching regulator
- D1—MR850
- Q1—BD344
- Q2—2N5023

Other Components

- L1—500 µH

Note: L1 is 40 turns of 22-gauge wire wound and evenly spaced on a Ferro-cube No. 502T300 toroid core, available from Permag Corporation, 400 Karin Lane, Hicksville, NY 11801; 516-822-3311.

PARTS LIST—µA78S40 STEP-DOWN CIRCUIT

All resistors ¼ watt, 5% unless otherwise noted

- R1—1 ohm, 2 watts
- R2—100 ohm trimmer potentiometer
- R3—1300 ohms
- R4—50,000 ohm trimmer potentiometer
- R5—R7—not used

Capacitors

- C1—100 µF, 35 volts, electrolytic
- C2—.01, ceramic disk
- C3, C4—1 µF, 50 volts, tantalum
- C5—470 µF, 35 volts, electrolytic

Semiconductors

- IC1—µA78S40, switching regulator
- D1—1N4001

Other Components

- J1, J2, J3—Banana jacks
- L1—300 µH, Ferrite Potentiometer Core (Indiana General F1153-1-06-620); PC mounting bracket (Indiana General B662), and PC bobbin (Indiana General B657-12). See text.

PARTS LIST—µA78S40 STEP-UP CIRCUIT

Note—unless otherwise specified, all components are identical to components specified in the µA78S40 step-down circuit.

- R5—180 ohms, ¼ watt, 5%
- D1—not used

PARTS LIST—µA78S40 INVERTER CIRCUIT

Note—unless otherwise specified, all components are identical to components specified in the µA78S40 step-down circuit.

All resistors ¼ watt, 5%

- R3—1000 ohms
- R6—680 ohms
- R7—100 ohms
- Q1—2N6051

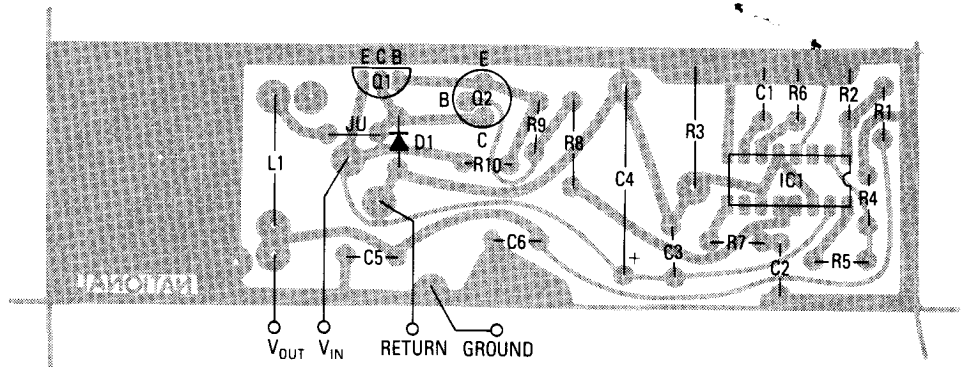


FIG. 8.—COMPONENT PLACEMENT DIAGRAM for the switching supply shown in Fig. 7.

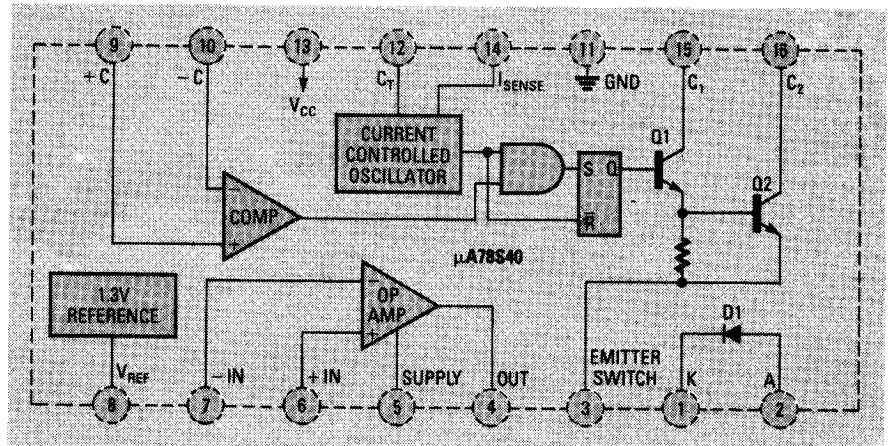


FIG. 9—FAIRCHILD'S µA78S40 is very similar to the LM3524. However, the Fairchild part also contains an uncommitted diode and an uncommitted op-amp that is similar to the popular 741.

input within its acceptable range. Each of the LM3524's output transistors is on for about 45% of the time, and they have been wired in parallel. That allows a duty cycle of as much as 90%, thus resulting in a lower input-voltage requirement, and greater overall efficiency. The output voltage is given by

$$V_O = V_{NI}(1 + R1/R2)$$

where V_{NI} is the voltage present at the error amplifier's non-inverting input (pin 2). The circuit's current limit is established by the value of R3 and is stated as: $I_L = 0.2 V/R3$. In that case, $I_L = 0.2 V/0.15 \Omega = 1.3 A$. Fabricate R3 by winding 1.45 feet of 30-gauge wire around a 100-ohm, ½-watt resistor.

Table 1 shows the characteristics of the power supply; and full-size artwork for a printed-circuit board may be found in the "PC Service" section of this magazine. A component-placement diagram is shown in Fig. 8.

The µA78S40

Whereas the LM3524 is a pulse width modulator, Fairchild's µA78S40 may be considered a variable pulse-width, variable frequency modulator. It is capable of operating from a supply as low as 2.4 volts, and it has a standby mode that draws only 2.4 mA at five volts. That is

rather remarkable when you consider that the IC can handle 40 volts at 1.5 amps. Anyway, its low power requirements make the µA78S40 ideal for battery-powered operation.

A block diagram of the µA78S40 is shown in Fig. 9. The current-controlled oscillator (CCO) is probably the most important part of that IC. Its purpose is to generate the gating signal that turns output transistors Q1 and Q2 off and on. A single external capacitor controls the frequency of the CCO, which may vary from 100 Hz to 100 kHz. The duty cycle of the CCO is set internally to a ratio of 6:1, but that may be varied by manipulating the current-limiting circuitry attached to pin 14 (I_{SENSE}).

The µA78S40's manner of output-voltage control is somewhat more complex than that of the LM3524. The AND gate shown in the block diagram of Fig. 9 is fed by the CCO and a comparator. The comparator, as you have probably guessed, functions as the error amplifier we discussed above. The comparator is a high-gain differential type with a common-mode input range extending from ground to within 1.5 volts of V_{CC} . It functions to inhibit the µA78S40's "on" cycles. The comparator can inhibit several "on" cycles, one "on" cycle or any portion of an

“on” cycle. After such a cycle has begun, the comparator cannot inhibit output until the beginning of the next “on” cycle.

The comparator samples a portion of the output voltage and compares it to the on-chip reference voltage. As long as the sampled portion of the output voltage is less than or equal to the reference voltage, the comparator remains high, so the flip-flop may be set and reset by the normal operation of the oscillator. If the output voltage exceeds the reference voltage, the comparator goes low. In that state, the AND gate cannot turn on, the flip-flop cannot be set, so the transistors will remain off.

The flip-flop is always reset during the negative-going ramp of the oscillator. And once the flip-flop is set, it will remain set until the negative-going ramp of the oscillator cycle. However, the current-

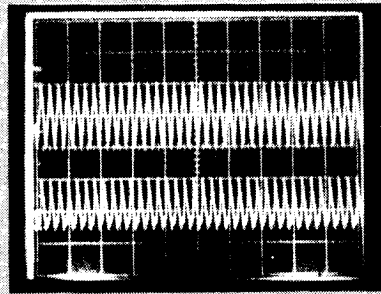
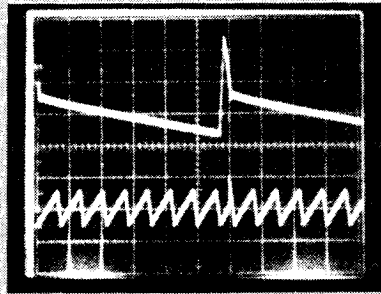


FIG. 10—KEY POINTS IN A μ A78S40 circuit are shown in these scope photos. In both, the upper trace represents the output ripple, and the lower trace represents the voltage across the timing capacitor.

limiting circuitry, which is temperature compensated, can speed up the reset action. The limiting circuit senses the output transistors' current across an external resistor. Current limiting is initiated when a 300 mV potential appears between pin 13 (V_{CC}) and pin 14 (I_{SENSE}).

Normally there is a steady current flow of about 50 μ A into the timing capacitor, but when an overload condition is detected, that current is boosted to about 1 mA, and that causes the positive-going oscillator threshold to be attained more rapidly than it would without the additional current. Operation under such cir-

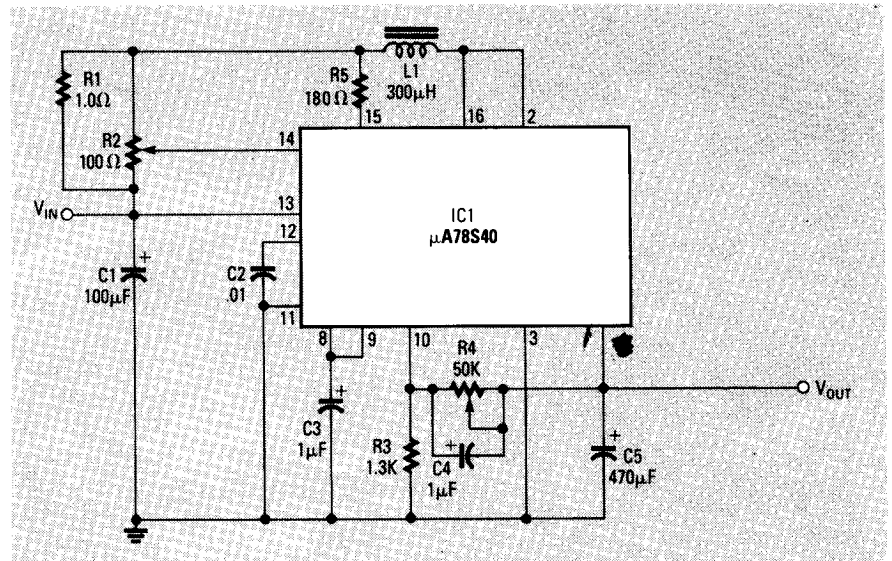


FIG. 11—THE μ A78S40 USED IN A STEP-DOWN CONFIGURATION. Given a +25-volt input, the circuit provides +10 volts at 500 mA.

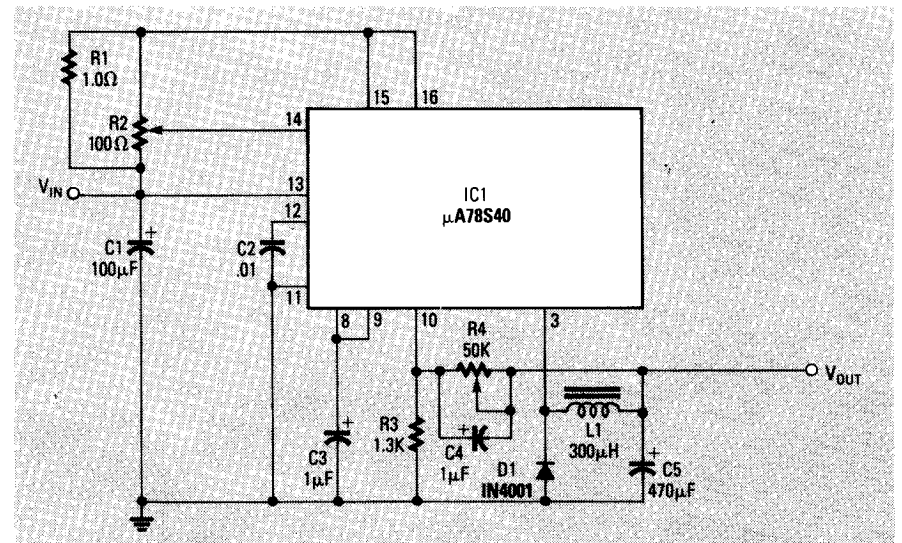


FIG. 12—THE μ A78S40 USED IN A STEP-UP CONFIGURATION. Given a +10-volt input, the circuit provides 25 volts at 100 mA.

cumstances then causes a very short “on” time followed by the normal “off” time that is provided by the negative-going ramp of the oscillator.

The μ A78S40's voltage reference is derived from an ultra-temperature-stable band-gap reference. A band-gap reference is a combination of several semiconductors that have both positive and negative temperature coefficients; they are arranged so as to exactly offset or cancel one another, and that results in a temperature coefficient of almost zero. In practical terms, that gives us a rock-steady reference voltage that is almost completely insensitive to temperature changes. The reference is capable of providing as much as 10 mA of current without additional circuitry.

Output transistors Q1 and Q2 are configured as a Darlington pair. That mode of DC coupling gives a very high gain that,

as you recall, is the product of the betas of both transistors. For example, if each transistor has a beta of 250, then the overall gain will be beta², or 250 × 250 = 62,500. The collectors of both transistors are brought from the IC to the outside world separately, and their emitters are brought out together. They can handle as much as 1.5 A peak current at a collector-emitter potential of 40 volts, but still have excellent switching times ranging from 300 to 500 nanoseconds.

One special feature of this versatile IC is the inclusion of an uncommitted operational amplifier. It is a bipolar op-amp quite similar to the popular 741 type. However, its output capabilities have been boosted so that it can source 150 mA and sink 35 mA. Another improvement is that its common-mode input range includes ground.

The last major component of the

TABLE 2—JUMPER CONFIGURATION

| Jumper | Down | Up | Invert |
|--------|------|----|--------|
| 1 | | | |
| 2 | ✓ | | |
| 3 | ✓ | | |
| 4 | ✓ | | |
| 5 | ✓ | ✓ | |
| 6 | ✓ | ✓ | |
| 7 | ✓ | ✓ | |
| 8 | ✓ | ✓ | |
| 9 | ✓ | ✓ | |
| 10 | ✓ | | |
| 11 | | ✓ | |
| 12 | | ✓ | |
| 13 | | ✓ | ✓ |
| 14 | | ✓ | ✓ |
| 15 | | ✓ | ✓ |
| 16 | | ✓ | ✓ |
| 17 | | ✓ | ✓ |
| 18 | | ✓ | ✓ |
| 19 | | ✓ | ✓ |
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| 21 | | ✓ | ✓ |
| 22 | | ✓ | ✓ |
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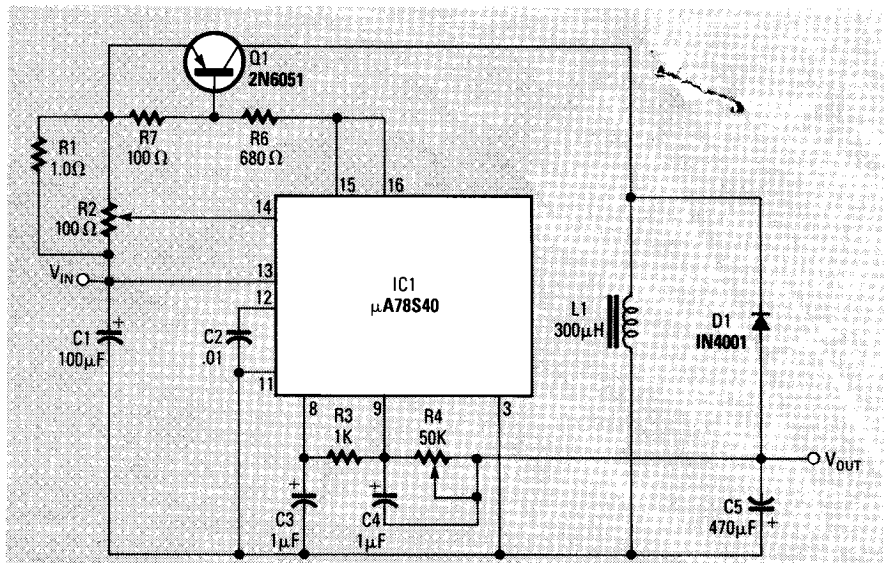


FIG. 13—THE μ A78S40 USED IN AN INVERTING CONFIGURATION. Given a +12-volt input, the circuit provides -15 volts at 100 mA.

μ A78S40 is the uncommitted diode available at pins 1 and 2. That diode can be used as desired, provided that some precautions are followed. Since the IC's substrate is normally at ground potential, the cathode of the diode must not be subjected to a negative voltage; that precludes its use in step-down and inverting configurations. The diode's internal construction results in a current flow from the anode to the substrate amounting to about 10% of the normal anode/cathode current. Because of the high voltage usually present between the anode and ground in step-up regulators, power dissipation will probably limit the diode's usefulness in such applications. The diode is probably most useful protecting the output transistors from reverse-polarity voltage spikes.

The scope photos shown in Fig. 10-a and -b show the waveforms present at several key points in a step-down regulator circuit built from a μ A78S40. In both cases the upper trace represents the output ripple and the lower trace represents the voltage across C_T . The photo in Fig. 10-a was taken at an output current of 22 mA, and the photo in Fig. 10-b was taken at 495 mA. In both photos the rising edge of the C_T wave represents "on" time and the falling edge represents "off" time. Notice

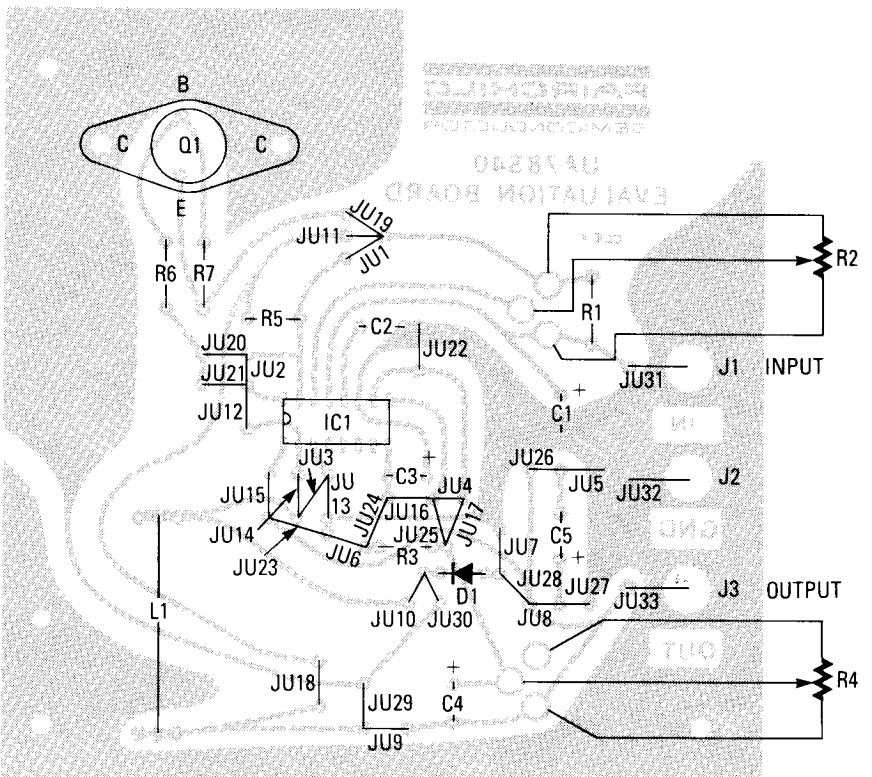


FIG. 14—COMPONENT PLACEMENT DIAGRAM for the switching circuits shown in Fig. 11-13. See TABLE-2 for information on how to install the jumpers for the different circuit configurations.

that as the output current increases, the "off" time decreases to a minimum. Note also that the switching frequency increases with increased output current. In a PWM circuit, that frequency would remain constant; only the ratio of "on" time to the total period of the wave would change.

Sample circuits

Now we present circuits you can use for designing a step-down, a step-up or an

inverting switching supply. The same PC board can be used for any one of those circuits; installation of various jumpers allows selection of the appropriate mode.

The step-down switching supply shown in Fig. 11 allows you to obtain 10 volts at 500 mA from a nominal 25-volt input, which may actually vary between 14 and 35 volts. Efficiency is typically 65% or better.

The step-up switching supply shown in

continued on page 110

PC SERVICE

One of the most difficult tasks in building any construction project featured in **Radio-Electronics** is making the PC board using just the foil pattern provided with the article. Well, we're doing something about it.

We've moved all the foil patterns to this new section, where they're printed by themselves, full sized, with nothing on the back side of the page. What that means for you is that the printed page can be used directly to produce PC boards!

In order to produce a board directly from the magazine page, remove the page and carefully inspect it under a strong light and/or on a light table. Look for breaks in the traces, bridges between traces, and, in general, all the kinds of things you look for in the final etched board. You can clean up the published artwork the same way

you clean up your own artwork. Drafting tape and graphic aids can fix incomplete traces and doughnuts, and you can use a hobby knife to get rid of bridges and dirt.

An optional step, once you're satisfied that the artwork is clean, is to take a little bit of mineral oil and carefully wipe it across the back of the artwork. That helps make the paper translucent. Don't get any oil on the front side of the paper (the side with the pattern) because you'll contaminate the sensitized surface of the copper blank. After the oil has "dried" a bit—patting with a paper towel will help speed up the process—place the pattern front side down on the sensitized copper blank, and make the exposure. You'll probably have to use a longer exposure time than you are used to.

We can't tell you exactly how long an

exposure time you will need because we don't know what kind of light source you use. As a starting point, figure that there's a 50 percent increase in exposure time over lithographic film. But you'll have to experiment to find the best method to use with your chemicals. And once you find it, stick with it. Don't forget the "three C's" of making PC boards—care, cleanliness, and consistency.

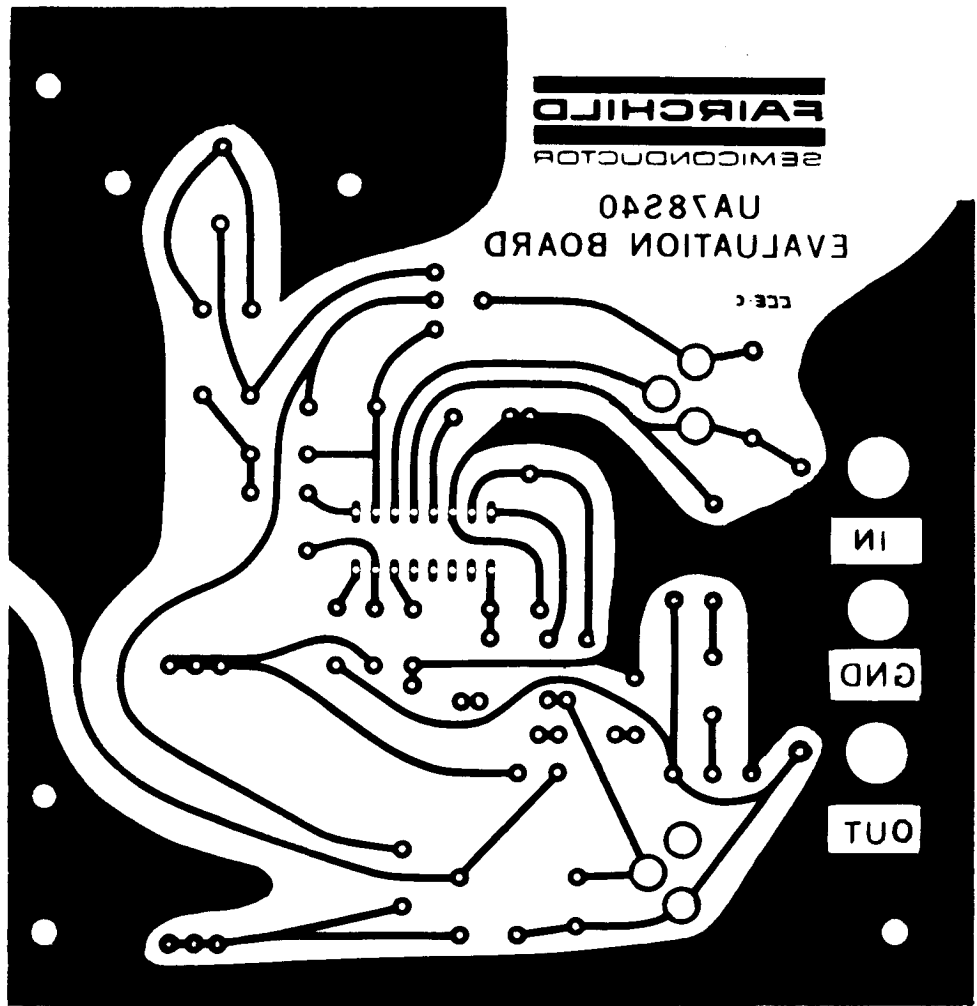
Finally, we would like to hear how you make out using our method. Write and tell us of your successes, and failures, and what techniques work best for you. Address your letters to:

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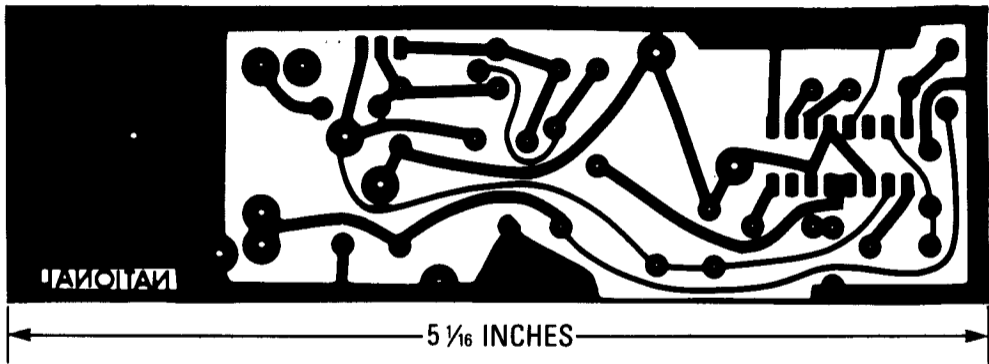
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EVALUATION BOARD

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5 INCHES

SOLDER SIDE of the μ A78S40-based switching power-supply



SOLDER SIDE of the LM3524 5-volt switch power-supply PC-board. For more on switching power supplies, see the story on page 77.