60-watt switching power supply comes together for just $37

Off-line unit uses a single integrated control circuit in a flyback-regulator design for a minimal parts count

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□ Though more efficient, smaller, and lighter than linear power supplies, switching-regulator supplies have also cost more except for outputs of more than 100 to 200 watts. But within the last two years or so their price per output watt has dropped far enough to make them attractive even under 100 W.

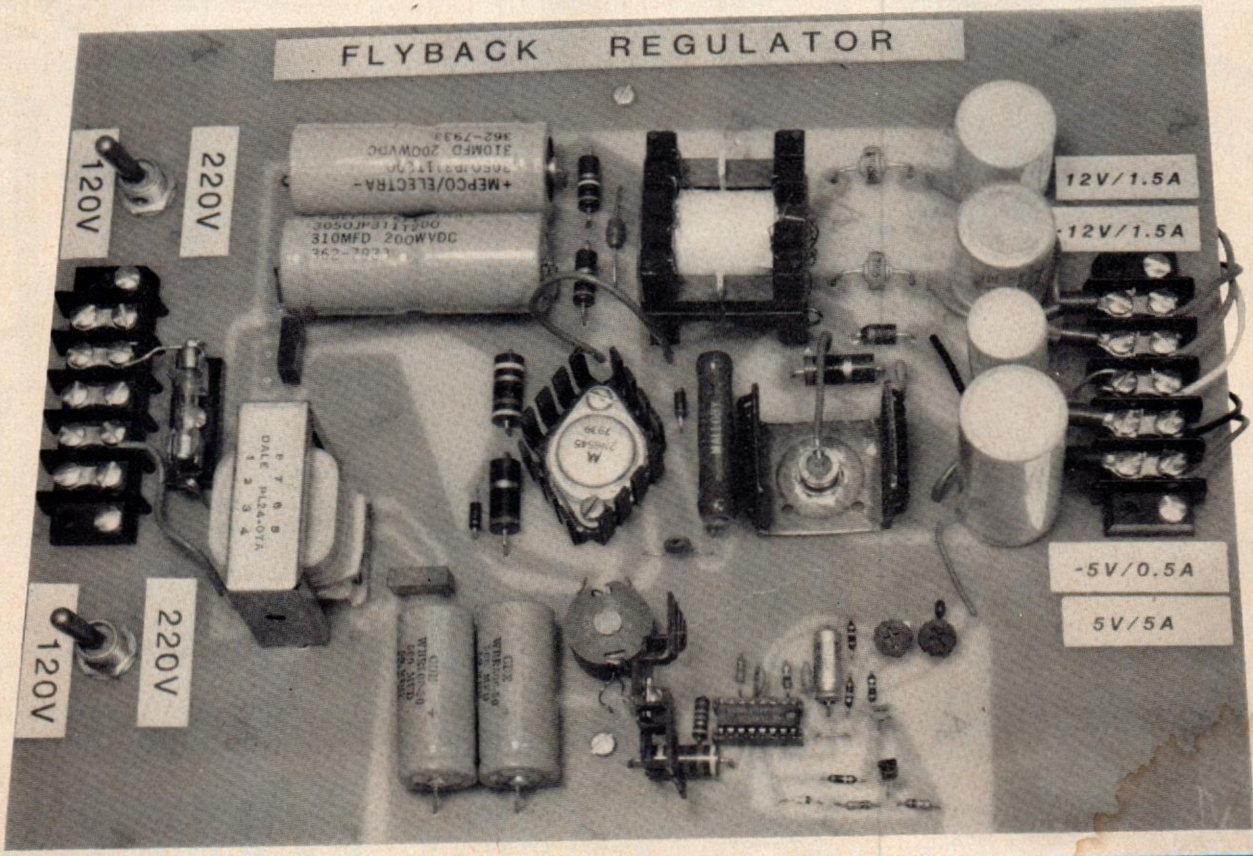
Control and protection integrated circuits as well as transformer designs have advanced so rapidly that, for instance, a 60-W switching supply, operating off line from 120 or 220 volts ac and providing outputs of ±5 and ±12 V, can be constructed with parts worth a mere $37. Yet it performs admirably (Fig. 1).

A flyback-regulator circuit (Figs. 2 and 3) with a single drive transistor needs only a few main parts:

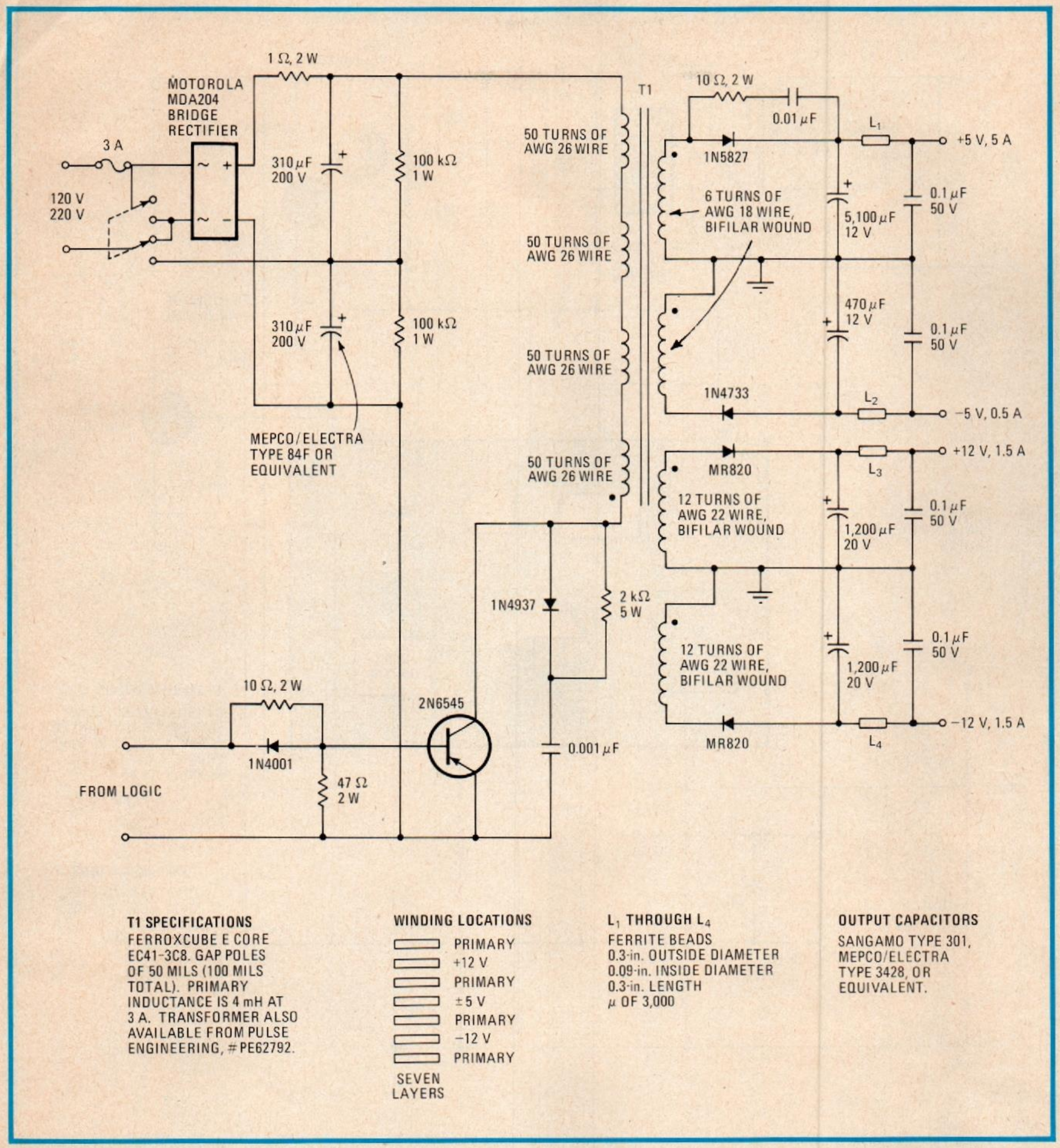
- A unique flyback transformer.
- A single control IC.
- A rapid-switching high-voltage transistor.
- Single output filters in each of the four outputs.
- The flyback base-drive circuit.
- Ac-line input voltage doublers.

Sandwiching the windings

The flyback transformer uses an EC-41 ferrite core made by the Ferroxcube Corp., Saugerties, N. Y. It has a 40:1 turns ratio and is wound by a sandwich technique that improves the coupling between its primary and secondary windings. It can also be purchased from Pulse Engineering Inc., San Diego, Calif. (part no. PE62792).



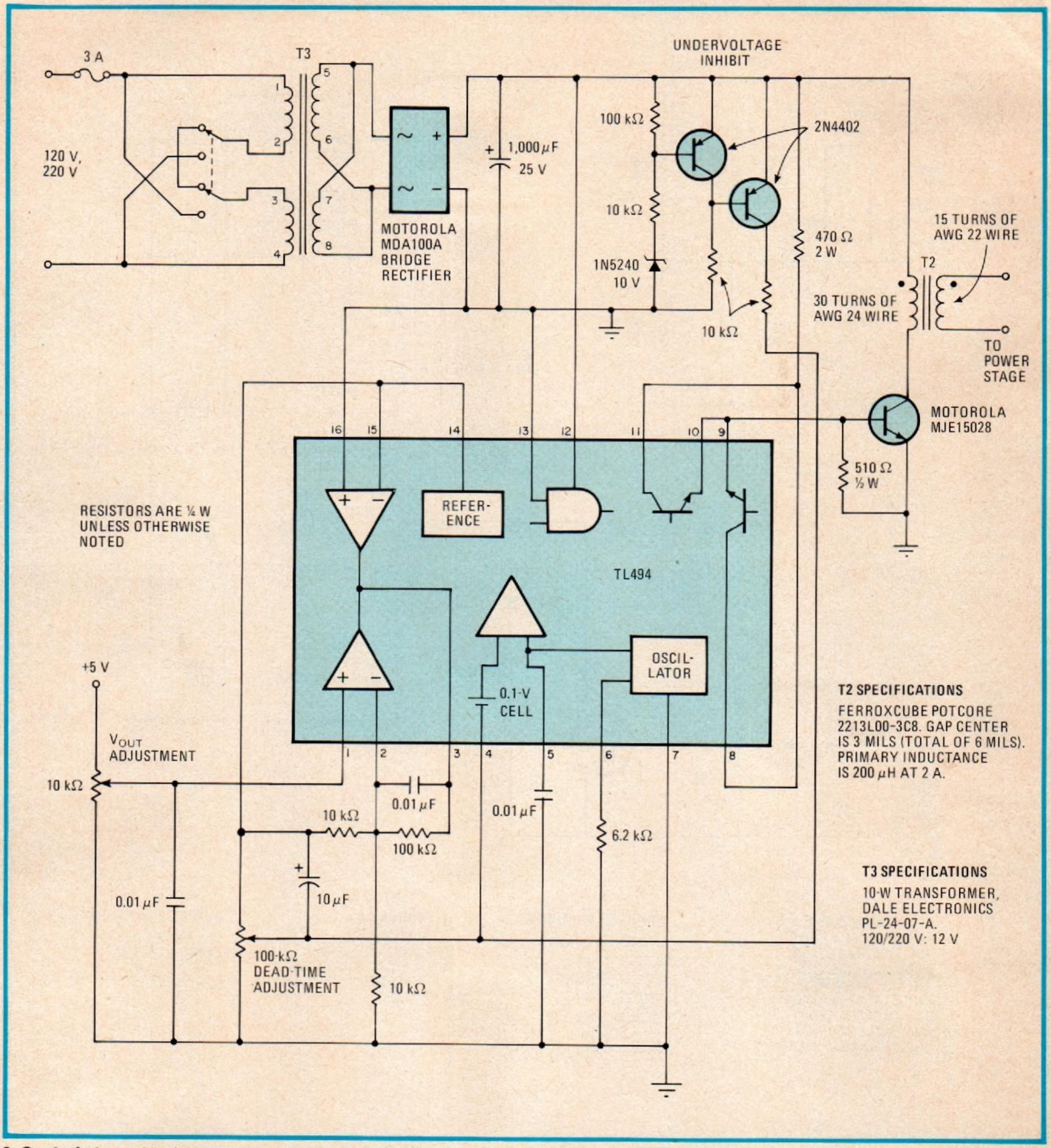
1. Compact switcher. This tiny 60-watt switching power supply is built from a design that requires only $36.99 worth of assorted components (in 1,000-unit lots). The off-line unit makes use of a single control integrated circuit and a flyback-regulator switching scheme.



2. Power stage. A flyback regulator transformer employing a single drive transistor is used for switching. The transistor, Motorola type 2N6545, is capable of switching 1 ampere of current in 40 nanoseconds and of blocking voltages of up to 800 volts.

The primary winding consists of four split windings in series with each other. The four windings of the secondary alternate in a sandwich construction with the four primary windings. Total core gap is 100 mils, and primary-winding inductance is 4.5 millihenries at 2.5 amperes. Transformer performance can be gauged from the fact that although the output current ratings for the secondary transformer windings are specified as 5, 1.5, and 0.5 A for 5, ±12, and −5 V, respectively, actual respective current values are 8, 3 and 4 A (Fig. 4).

All of the power-supply control functions reside in a single IC, the TL494. Available from both Texas Instruments Inc. and Motorola Inc., it requires a minimum of external resistor and capacitor components. It includes a 20-kilohertz oscillator, a dead-time adjustment (50% maximum) for preventing transformer saturation, two error amplifiers to process both current and voltage feedback signals, and an output stage that produces 400-milliampere pulses to drive the power transistor. An undervoltage-inhibiting circuit is added externally to the



3. Control stage. All of the power supply's control functions are obtained from the Texas Instruments' TL494 IC, which is also available from Motorola. Besides minimizing the number of control components, the IC also minimizes the number of external parts.

control IC. Consisting of two transistors and a zener diode, it inhibits output pulses when the drive voltage is less than 10 V.

For rapid switching, a Motorola type 2N6545 transistor is used. It is capable of switching 2 A in just 40 nanoseconds and can block up to 800 V under worst-case conditions. Because of the transistor's high speed, losses due to the snubber (the RC network in the collector circuit) are low—typically 2 W, or less than 2% of the total delivered power.

Each of the four output stages employs one filter capacitor and one diode. The capacitors (series 301 from Sangamo, 3428 from Mepco/Electra, or UPT from Cornell-Dubilier), exhibit low equivalent series resistance, typically 10 to 100 milliohms. Noise spikes are reduced dramatically (by as much as a factor of four) by the addition of a ferrite bead and ceramic capacitor across each of the output filter capacitors. Ripple test data for various types of capacitors is shown in Table 1.

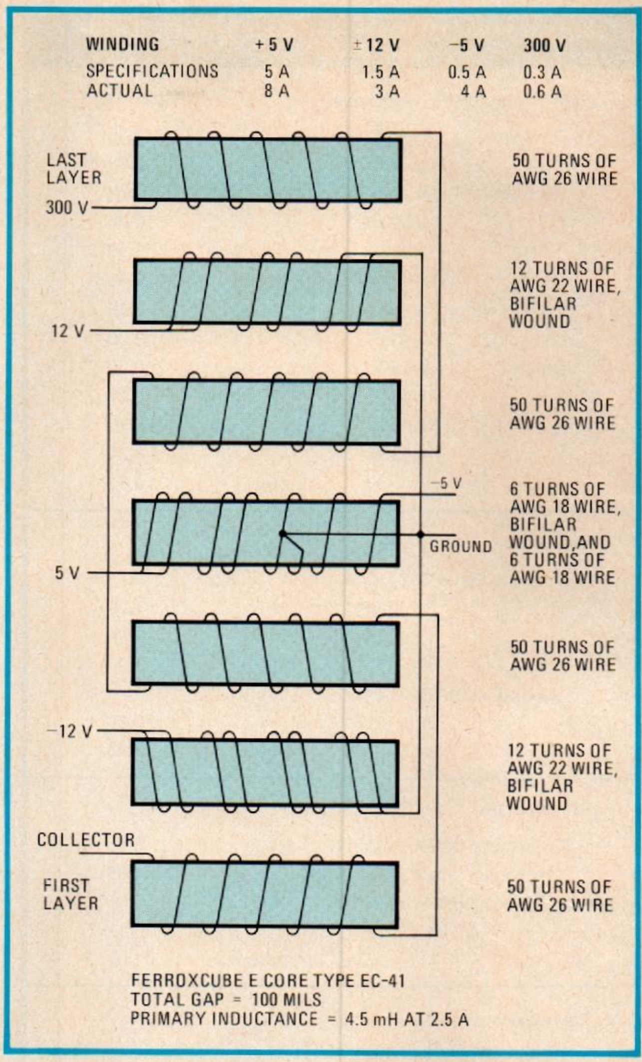
The use of a flyback transformer for base drive greatly simplifies the drive circuit. Besides the transformer, only three other components are employed: a drive transistor capable of handling 2 A, a resistor, and a diode. The flyback transformer turns on the transistor with a 5-V drive pulse while simultaneously storing the energy from the 2-A current drawn by the transistor. This stored energy becomes the reverse bias drive when the pulse from the transformer is terminated. The reverse bias drive removes stored charge quickly—within 2 microseconds—and then causes the transistor's base to avalanche for the short while it takes to reset the transformer. Typically, if the transistor was initially turned on for 20 μs with a 5-V pulse, a 10-μs 10-V pulse is needed to reset it after it has been turned off.

At the ac line input, two axial-lead 310-microfarad 200-V capacitors (Mepco/Electra series 84F) are connected in series with each other across the bridge rectifier output, thus acting as a voltage doubler when operating from 200 to 400 V. A nominal 320-V bus is thus provided across the transformer's primary winding, regardless of whether it operates from a 120-V or a 220-V ac line input.

Why flyback

One of the most popular switching-regulator power supply circuits for low-wattage supplies is the forward converter. Its transformer, having only a 15:1 ratio of primary to secondary turns, is simpler than the flyback type approach, but requires four expensive filtering chokes. In addition, its secondary windings are unregulated, so its output voltages vary with line and load variations more than they need do in the case of a flyback transformer.

A flyback transformer with a control IC placed at the secondary windings (as is done here) has a number of advantages. Feedback signals can be coupled directly to the transformer. Also, current-limiting protection on any or all of the output windings is simplified. Since the control IC has an extra amplifier, the addition of a single sense resistor to the high-current 5-V output makes it



4. Transformer. The flyback transformer can be hand-wound over an EC-41 ferrite core obtainable from Ferroxcube Corp. The four secondary windings alternate in a sandwich construction with four split primary windings that are connected in series with each other.

TABLE 1: RIPPLE TEST DATA FOR VARIOUS CAPACITORS

Output	Test	Sangamo 301	Mepco/Electra 3428	CDE UPT	Mallory VPR	Sprague 432D
+5 V	Capacitance/volts	5,100 μF, 12 V	800 μF, 7.5 V	5,000 μF, 12 V	5,300 μF, 20 V	5,600 μF, 10 V
	Ripple (P-P)	200 mV	360 mV	170 mV	250 mV	200 mV
	Spikes (P-P)	660 mV	640 mV	980 mV	880 mV	580 mV
	Cost	$1.70	$1.58	$1.95	$1.70	$4.69
+12 V	Capacitance/volts	1,200 μF, 20 V	1,400 μF, 20 V	1,000 μF, 20 V	1,200 μF, 12 V	1,200 μF, 20 V
	Ripple	210 mV	260 mV	200 mV	200 mV	n.a.
	Spikes	740 mV	1,100 mV	1,800 mV	1,440 mV	n.a.
	Cost	$1.43	$1.41	$1.95	$0.45	$4.24
−5 V	Capacitance/volts	470 μF, 12 V	2,100 μF, 10 V	680 μF, 12 V	1,200 μF, 12 V	560 μF, 40 V
	Ripple	160 mV	160 mV	180 mV	140 mV	180 mV
	Spikes	540 mV	1,300 mV	680 mV	360 mV	440 mV
	Cost	$1.27	$1.41	$0.53	$0.45	$4.24

TABLE 2: PARTS LIST FOR $37 SWITCHING-REGULATOR POWER SUPPLY

		Cost ($)*
Semiconductors (all Motorola)		
Transistors	2N6545	2.50
	MJE15028	0.98
Rectifiers	MDA100A	0.78
	MDA204	0.96
	1N5827	3.58
	MR820(2)	2.50
	1N4933	0.19
Control IC	TL494	2.00
Other	2N4402(2)	0.36
	1N5240	0.27
	1N4001	0.10
	1N4937	0.30
	subtotal =	14.52
Capacitors		
Sangamo Series 301		
	5,100 μF, 12 V	1.71
	1,200 μF, 20 V (2)	2.86
	470 μF, 12 V	1.27
Mepco/Electra Series 84F		
	300 μF, 200 V (2)	2.56
	subtotal =	8.40
Transformers		
Ferroxcube type EC41-3C8		5.55
Ferroxcube type 2213L00-3C8		2.35
(Core plus bobbin equal 20% of cost)		
Dale type PL-24-07-A		3.17
	subtotal =	11.07
Miscellaneous		
Beads, resistors and fuses		
	subtotal =	3.00
	Total =	36.99

*based on 1,000-unit prices of September 1979

easy to protect that output against short circuits. The addition of three more sense resistors and a quad operational amplifier makes it a simple matter to protect all four outputs against short circuits.

This approach breaks with convention. Other switching-regulator schemes place the control IC at the primary side of the transformer, where the transistor emitter current is sensed for overcurrent protection. Optocouplers then have to be inserted in the feedback loop for proper isolation, but even so do not fully protect the supply against short circuits. Moreover, optocouplers drift with increasing temperatures.

The bottom line

The final determining factor is the bottom-line cost. In quantities of 1,000, the semiconductor parts for this flyback regulator power supply cost $15; the capacitors, $8; the transformers, $1; and miscellaneous parts, $2; for a total cost of $37. (see Table 2).

The power supply's design, which consumed about three man-months of labor, was done in three phases—first the output power stage, then the control logic, and finally the input ac power stage.

The output power stage was checked out by using a pulse generator to energize the drive transistor and transformer and subsequently calculating the snubber values. To improve coupling and reduce the 13-by-14-V nominal output to 12 V, the 5-V secondary winding was increased from an initial five turns to six.

Adding control logic involved designing the base drive transformer and finding values for the feedback network that would provide optimum performance without creating instability. An operational amplifier gain of 20 with a rolloff at 1 millisecond proved sufficient. A dead-time limit of 50% keeps the drive transformer from saturation without interfering with low–line-voltage performance. An undervoltage-inhibiting circuit was added to keep the control circuit from misbehaving at voltages under 10 V (6 to 9 V). Otherwise, the control circuit became incapable of providing adequate drive voltages and excessive output pulse widths resulted.

The first power transformer selected was a 7-W unit, which provided regulation so poor that it confused the undervoltage circuit. Substituting a 10-W version solved that problem. Later on, it was discovered that the 3-A input fuse was failing because of inrush currents. The problem was traced to the 470-μF, 300-V input filter capacitors. These were changed to 300-μF, 200-V units and a 1-ohm inrush-current–limiting resistor was added. The ac ripple voltage rose as a result, but not intolerably, being only 10 V peak to peak at full load.

Impressive results

Despite the power supply's low parts count and simplicity of design, it has an impressive level of performance. For a nominal input of 120 V, it maintains regulation over an input range of 90 to 140 V and load range of 2:1 (half load to full load). For example, line and load regulation for the 5-V output are 2.5% and 1%, respectively. At an input of 90 V ac, full-load output voltages are 4.848, −4.930, −12.78 and 12.68 V, respectively, for the 5, −5, −12 and 12-V outputs. At 120 V ac, full-load output voltages are 5.001, −4.977, −12.98 and 12.94 V. At 140 V, full-load voltages are 5.983, −5.061, −13.16 and 13.10 V.

Half-load regulation is equally impressive. At a 90-V ac input, output voltages are 5.040, −5.075, −13.13 and 13.07 V. At a 120-V input, they are 5.098, −5.162, −13.30 and 13.20 V. At a 140-V input, they are 5.114, −5.191, −13.35, and 13.28 V.

Should it become necessary to work over a wider load range, such as from full to no load, the power transformer would have to be redesigned to protect the drive transistor from load dump conditions. This can be done by increasing the transformer's core size from the present EC-41 to EC-52 and by adding a primary bifilar winding coupled through a diode to the dc bus.

The power supply is also very efficient. At 120 V ac in and a full-load condition, its efficiency was an impressive 89%. The only noticeable heat rise is in the small components like the snubber resistor and Schottky diode. All other components remain cool to the touch. □