By Manfred Mornhinweg, XQ2FOD

A 13.8-V, 40-A Switching Power Supply

Part 1—Ever want a really big power supply that can handle all your 12-V needs around the shack? Here's one that is amazingly compact and lightweight too, thanks to its efficient switching design!

Switching power supplies ("switchers," as they are often called) offer very attractive features—small size, low weight, high efficiency and low heat dissipation. Although some early switchers produced objectionable amounts of RF noise, nowadays you can build very quiet switchers using proper design techniques and careful EMI filtering. This power supply produces 13.8 V, regulated to better than 1%, at a continuous load current up to 40 A and with an efficiency of 88%. No minimum load is required and the ripple on the output is about 20 mV.

The supply produces no detectable RF noise at any frequency higher than the main switching frequency of 50 kHz. I checked this with a wire looped around my supply, tuning my TS-450 from 30 kHz to 40 MHz. The completed supply weighs only 2.8 kg (6.2 pounds)!

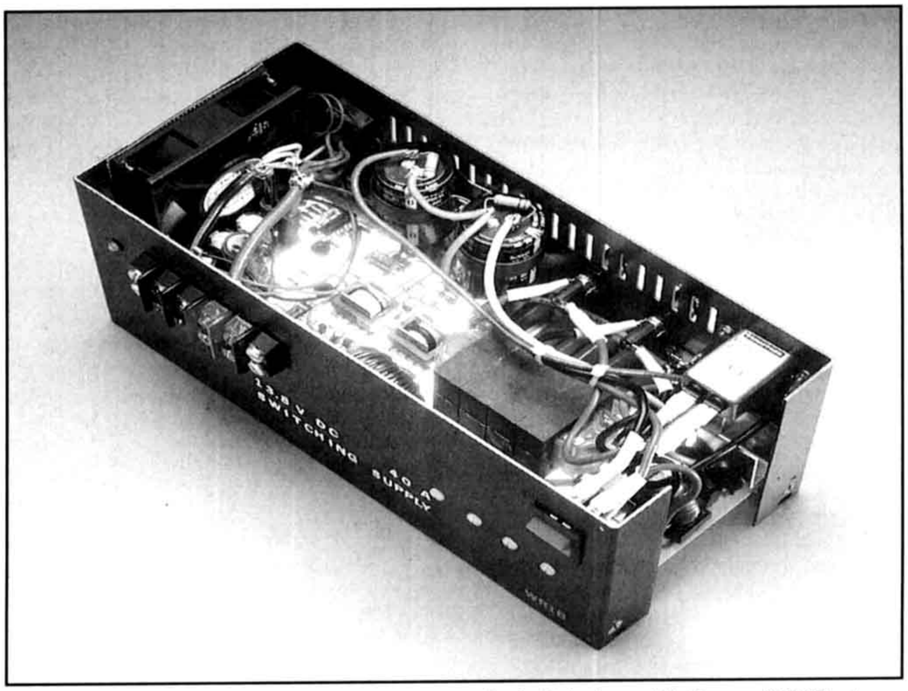
Linear Versus Switching Supplies

A typical linear regulated power supply is simple and uses few parts—but several of these parts are big, heavy and expensive. The efficiency is usually only around 50%, producing *lots* of heat that must be removed by a big heat sink and often fans.

In this switching supply the line voltage is directly rectified and filtered at 300 V dc, which feeds a power oscillator operating at 25 kHz. This relatively high frequency allows the use of a small, lightweight and low-cost transformer. The output is then rectified and filtered. The control circuit steers the power oscillator so that it delivers just the right amount of energy needed, so that little energy is wasted.

While MOSFETs can switch faster, bipolar switching devices have lower conduction losses. Since very fast switching was undesirable because of RF noise, the author used bipolar transistors. These tend to be *too* slow, however, if the driving current is heavier than necessary. If the transistors must switch at varying current levels, the drive to them must also be varied. This is called *proportional driving* and is used in this project.

The switching topology used is called a *half-bridge forward* converter design (also known as a *single-ended push-pull* converter.—*Ed.*) The converter is controlled using pulse-width modulation, using the generic 3524 IC.

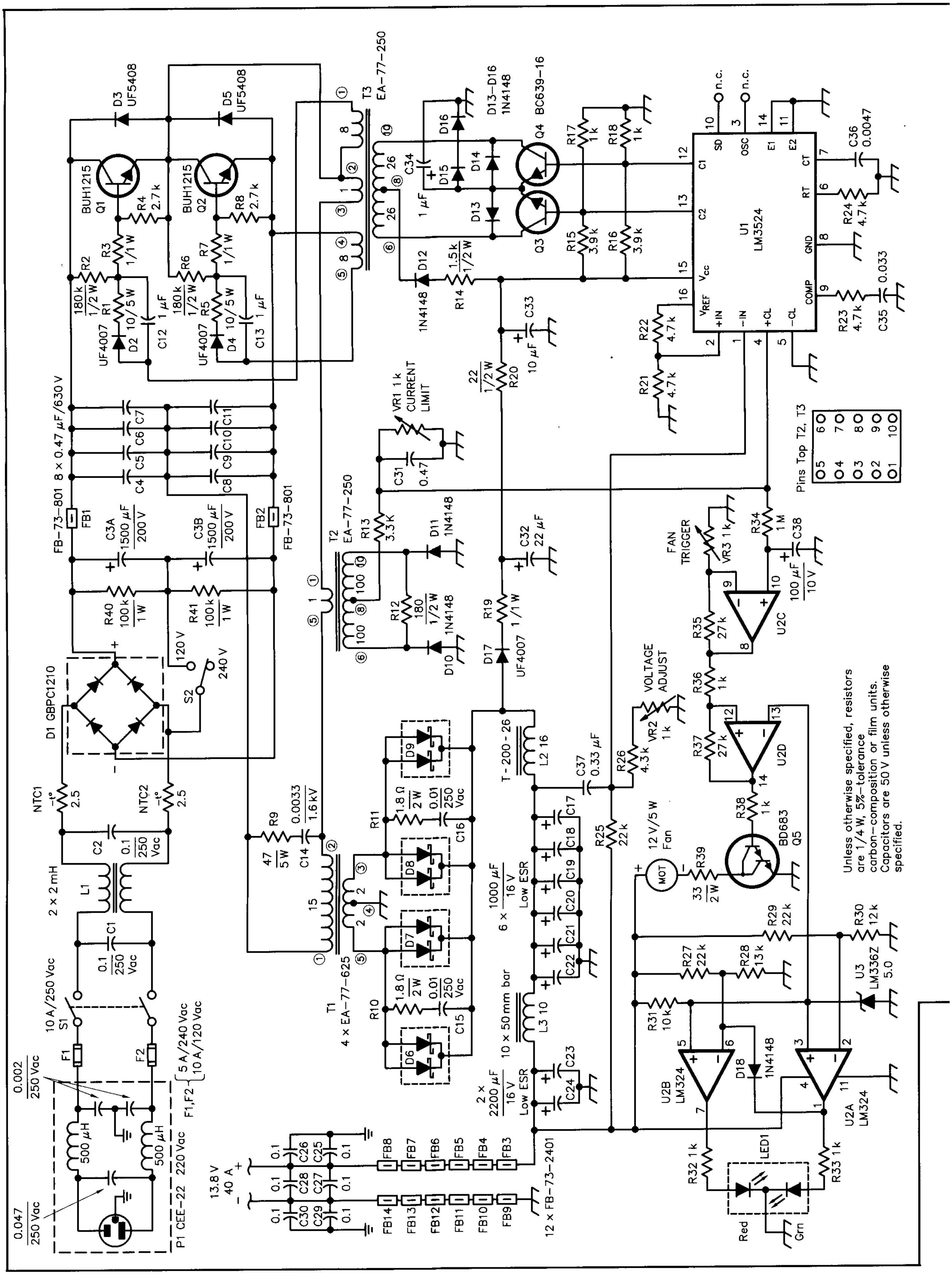


The finished 13.8-V, 40-A switching power supply, built by Larry Wolfgang, WR1B, at ARRL Headquarters.

Circuit Description

Refer to the schematic diagram in Figure 1. Line voltage enters through P1, a connector that includes EMI filtering. It then goes through fuse F1, a 2-pole power switch and an additional common-mode noise filter (C1, L1, C2). Two NTC (negative temperature coefficient) resistors limit the inrush current. Each exhibits a resistance of about 2.5 Ω when cold and then loses most of its resistance as it heats up. A rectifier delivers the power to C3A and C3B, big electrolytic capacitors working at the 300-V dc level. The power oscillator is formed by Q1, Q2, the components near them and the feedback and control transformer T3. T2 and associated components act as a primary-current sensor.

T1 is the power transformer, delivering a 20-V square wave to the Schottky rectifiers (D6 through D9). A toroidal inductor L2 and six low equivalent-series-resistance (ESR) electrolytic capacitors form the main filter, while L3 and C23 and C24



Unless otherwise specified, resistors are 1/4 W, 5%-tolerance carbon-composition or film units. Capacitors are 50 V unless otherwise specified.

Figure 1—Schematic diagram for the 13.8-V, 40-A switching power supply.

C1, 2—0.1 µF, 250 V ac polypropylene, Digi-Key P4610ND.
C3A, C3B—1500 µF, 200 V electrolytic.
C4 to C11—0.47 µF, 400 V polypropylene, Digi-Key P3496ND.
C12, C13—1 µF, 50 V ceramic multilayer.
C14—0.0033 µF, 1.6 kV polypropylene.
C15, C16—0.01 µF, 250 V ac polypropylene.
C17 to C22—1000 µF, 25 V low-impedance (low-ESR) electrolytic.
C23, C24—2200 µF, 16 V low-impedance (low-ESR) electrolytic.
C25 to C30—0.01 µF, 50 V ceramic.
C31—0.47 µF, 50 V ceramic multilayer.
C35—0.033 µF, 50 V polyester.
C36—0.0047 µF, 50 V polyester.
C37—0.33 µF, 50 V polyester or ceramic multilayer.
D1—Rectifier bridge, 1 kV, 12 A, GBPC1210 or similar.
D2, D4, D17—Ultrafast diode, 1 kV, 1 A. UF4007 or similar. Lower voltage (down to 100 V) is acceptable. The ARRL Lab used UF1007 diodes, Digi-Key UF1007DICT-ND.
D3, D5—Ultrafast diode 1 kV, 3 A. UF5408 or similar, Techsonic.
D6 to D9—Dual Schottky diode, 100 V, 30 A total. PBYR30100CT or similar. Single diode would also be suitable. ARRL Lab used International Rectifier 30CPQ100, Digi-Key 30CPQ100-ND.
D10 to D16, D18—1N4148 switching diode.
F1—Fuse, 10 A for 120-V ac operation; 5 A for 240-V ac operation.
FB1, FB2—Amidon FB-73-801 ferrite bead, slipped over wire. Available from Bytemark.
FB3 to FB14—Amidon FB-73-2401 ferrite beads, slipped six each over the two 13.8 V dc output cables. Available from Bytemark.
L1—Common mode choke, approximately 2 mH each winding, 6 A. Author used junk box specimen. We used a Magnatek CMT908-V1 choke (Digi-Key part 10543-ND) in the supply built in the ARRL Lab.
L2—20 µH, 60 A choke. 16 turns on Amidon T-200-26 toroid, wound with ten #16 enameled wires in parallel.
L3—5 µH (uncritical), 60 A choke. 10 turns on ferrite solenoid, 10 mm diameter, 50 mm long. Wound with two #10 wires in parallel. Amidon #33-050-200 used in ARRL Lab.
LED1—Dual LED, green-red, common cathode, Digi-Key LU204615-ND (pin 1 is red; pin 3 is green).
M1—12 V, 5 W brushless DC fan, approximately 120 × 120 × 25 mm, Digi-Key P9753-ND is 120x120x38 mm and 5.5 W.
NTC1, NTC2—Inrush current limiter, 2.5 Ω cold resistance, Digi-Key KC003L-ND.
P1—Male ac connector with integrated EMI filter, 250 V ac, 10 A, Newark 97F8256.
Q1, Q2—High voltage switching transistor, BUH1215 or similar. Motorola MJW16010 was used in ARRL Lab; Newark 08TMJW16012.
Q3, Q4—BC639-16 transistor, available from Newark. Must resist 100 V and 0.5 A.
Q5—BD683 Darlington transistor, from Techsonic. The back of the transistor should be facing the outside of the board.
R1, R5—10 Ω, 5 W, low inductance preferred.
R9—47 Ω, 5 W, low inductance preferred. For the supply built in the ARRL Lab, we used three 150-Ω, 1 W film resistors wired in parallel.
R10, R11—1.8 Ω, 2 W, low inductance preferred.
S1—2-pole power switch, 250 V ac, 10 A.
S2—120/240 V ac power selector slide switch, 250 V ac, 10 A. A locking tab made of aluminum locks the switch in either 240 or 120-V position.
T1—Primary 15 turns, secondary 2+2 turns. Wound with copper foil and mylar sheet. Uses four Amidon EA-77-625 ferrite E-cores (8 halves). Equivalents include Thompson GER42x21x15A, Phillips 768E608, TDK EE42/42/15.
T2—Secondary is 100+100 turns #36 enamel wire. Primary is one turn #14 plastic insulated cable, wound on secondary (wound on Amidon EE24-25-B bobbin). Uses an Amidon EA-77-250 core. Equivalents are Thompson GER25x10x6, Phillips 812E25Q, TDK EE25/19.
T3—Control winding is 26+26 turns #28 enamel wire. Base windings are 8 turns #20 each. Collector winding is one turn #14 plastic insulated wire. Bobbin and core like T2.
U1—Pulse-width modulator IC, LM3524, SG3524, UC3524 or similar.
U2—Quad single-supply operational amplifier, LM324 or similar.
U3—5 V voltage reference, LM336Z-5.0 or similar.
VR1 to VR3—1 kΩ PCB mounted trimpot, Digi-Key #3309P-102-ND.
Cabinet—Hammond Manufacturing, PN 1426Y-B, 12x6x5.5 inches, and internal case mounting rails, Hammond Manufacturing 1448R12, used in ARRL Lab.

are there for additional ripple reduction. The 13.8 V is delivered to the output through a string of ferrite beads with RF decoupling capacitors mounted directly on the output terminals.

The control circuit IC, U1, is powered from an auxiliary rectifier D17. U1 senses the output voltage and the current level and controls the power oscillator through Q3 and Q4. C37, C35 and R23 are used to implement a full PID (*proportional-integral-derivative*) response in the control loop.

A quad operational amplifier, U2, controls the cooling fan according to the average current level and also drives the voltage indicating tricolor LED, which glows green if the voltage is OK, orange if the voltage is too low and red if it is too high.

More Design Details

When the unit is powered up, the operating voltage builds up on C3A and C3B, and R2 and R6 bias the two power transistors Q1 and Q2 into their active zones. They start conducting a few mA, but for only a short time, because the positive feedback introduced by T3 quickly throws the system out of balance. One of the two transistors receives an increased base current from T3, while the other one sees its base drive reduced. It takes just a fraction of a microsecond for one of the transistors to become saturated and the other cut off. Which transistor will start first is unpredictable, but for this analysis let's suppose it is Q1. Because the control circuit is not yet powered, Q3 and Q4 are off at startup.

T1 sees about 150 V ac across its primary, producing about 20 V ac on the secondary. Schottky rectifiers D6 through D9 rectify this, so L2 sees 20 V across it. The current in L2 will start rising and this is reflected back to the primary side of T1. The primary current passes through the 1-turn winding of T3, forcing one-eighth as much current to flow into the base Q1, the transistor assumed to be conducting at this moment. After some time, the ferrite core of T3 will saturate, causing the base drive of Q1 to decrease sharply. Q1 will stop and Q2 will start conducting. Now the flux in T3's core decreases, crosses zero and increases in the other direction until it saturates the core again, shutting Q2 off and turning Q1 back on. Meanwhile, the current in L2 continues to build up and the filter capacitors C17 through C22 are charged.

For safe startup, it is essential that T3 saturates completely before T1 starts to do so. If this were not the case, the transistors would have to switch under a very high and potentially destructive current. The power supply will oscillate freely for only a few cycles, because D17 is already charging C32 and C33, powering up the control circuit so that it takes over the control of the power oscillator. Note that the self-oscillation frequency must be lower than the operating frequency for the feedback loop to be able to control things properly.

Q3 and Q4, together with D13 and D14, can place a short on T3's control winding. This holds the voltage across that transformer close to zero, regardless of any current that may be flowing in the windings. When U1 wishes to switch Q1 on, it simply switches pin 12 to ground, switching off Q4 and ending the short circuit on T3. Through R14 and D12, about 15 mA flow into the control winding center tap, returning to ground via Q3. This puts about 50 mA into the base of Q1, which quickly switches on. Now the heavy collector current (up to 8 A at full load) adds up to the total current flowing in T3 and puts enough drive into Q1 to keep it saturated at that heavy current. Note that by this method the strong drive current for the power transistors comes from the collector current through T3 so the control circuit does not have to provide any substantial driving power.

If U1 now determines that Q1 has been conducting long enough, it simply switches

Parts Substitution

Don't be afraid to substitute parts when you can't find the exact one specified. Here is some information for hard-to-find parts:

- D1: Any rectifier bridge that can handle 8 A at 240 V ac (or 12 A at 120 V ac), with enough headroom for spikes, will do the job. Try to find one that fits the PCB or modify the board accordingly. You may also use single diodes, but mount them close to the board to get suitable heatsinking through their terminals.
- D2, D4, D17: Any ultrafast diode rated for at least 100 V and 1 A is suitable. The author used the UF4007, which is an ultrafast equivalent to the 1N4007 (1 kV, 1 A). *Do not* use 1N4007 diodes! They are not fast enough for this job. You need a switching speed in the 50-ns class.
- D3, D5: You can use any ultrafast diode rated for 600 V, 3 A or higher. The UF5408 is rated at 1 kV, somewhat of an overkill here. Again, *do not* use the low speed 1N5408.
- D6, D7, D8, D9: PBYR30100CT dual Schottky diodes were used. A good replacement is any single or dual Schottky rectifier rated at least at 100 V and 30 A total current, that comes in a TO-218 or similar package. If you use single diodes, you may have to bend the pins to fit the board properly. These 100-V Schottky diodes have been widely available only for a few years, although they are becoming more common.
- Q1, Q2: BUH1215 transistors were used, which can work at a higher voltage than actually necessary in this circuit. If you need to replace them, look for any NPN power switching transistors that have a V_{CEO} of at least 400 V, I_C of at least 15 A, an h_{FE} of at least 12 at 8 A, and come in a TO-218 or similar package. The power transistors *must* maintain their beta up to at least 8 A, otherwise they will cut short the conduction cycles when the load increases. Motorola MJW16010 transistors are a suitable alternative. Some power switching transistors have a reverse protection diode and a base-to-emitter resistor built in. Beware of these! The resistor would not allow this power supply to start. If in doubt, take a multimeter and measure the resistance between base and emitter. If you get the same low resistance (typically 50 Ω) in *both* senses, the transistor is unsuitable for this project. If you get a diode behavior, the transistor is okay.
- Q3, Q4: Instead of the BC639-16 you can use any small TO-92 cased NPN transistor that has a V_{CEO} rating of 100 V and an I_C of 1 A. Be careful with the pinout, because not all TO-92 transistors use the same pinout. You may have to bend the leads to fit the printed circuit board.
- Q5: Instead of the BD683 you can use any small NPN Darlington transistor that has an I_C of at least 1 A.
- U3: If you have trouble finding the LM336Z-5.0 voltage reference, you have several options. You may use a reference at another voltage (2.5 V is typical) and modify the values of R27 to R30 accordingly. Or you may replace U3 with a 3-terminal regulator like the 7805, modifying the circuit as necessary. Finally, you could completely eliminate U3 and R31 and use the 5 V reference provided by U1 at pin 16. In this case you would lose the voltage indicator's independence from U1. Note that using a simple Zener diode instead of U3 is not suitable because Zeners are not stable enough for this application.

If you cannot find low-ESR electrolytic capacitors, simply use normal capacitors. The circuit is designed to place a low ripple current on these capacitors, so standard components can be used. The noise at the output will be slightly higher, however.

off pin 12. Q4 starts conducting again, shorting out T3. The current in T3 is dumped into Q4, which may have to take up to 300 mA. The voltage on T3 falls and Q1 switches off. Some time later, U1 grounds pin 13, starting the conduction cycle for Q2.

U1 uses two input signals to decide what to do with its outputs. One is a sample of the output voltage, taken through R25 and nearby components, while the other is a current sample taken through the primary of T2. This current transformer produces 200 times less current from its secondary than what goes through its one-turn primary. At full load, about 40 mA goes into R12, producing a maximum voltage drop of about 7 V. This is rectified and half of it is taken at the center tap, divided down by R13 and VR1 and smoothed by C31. When VR1 is properly adjusted, there will be 200 mV at pin 4 of U1 with the power supply running at full load.

A second amplifier inside U1 is used for current limiting. Its inputs are at pins 4 and 5. This amplifier is ground-referenced and has an internal offset of 200 mV. The amplifier will pull down the main error amplifier's output if the difference between pin 4 and pin 5 reaches 200 mV.

U1 also contains an internal oscillator, whose frequency is set by R24 and C36 to approximately 50 kHz. The sawtooth output of this oscillator is connected to an internal comparator, which has its other input internally connected to the output of the error amplifier. The output of the comparator is a square wave whose duty cycle depends on the dc voltage at the output of the error amplifier.

During operation at medium to high loads, the duty cycle is about 70%. At the cathodes of the Schottky rectifiers you will see a square wave that stays at about 20 V for some 14 µs, and then goes slightly below ground level for 6 µs. L2, which has its output end at a constant 13.8 V, will therefore see about 6 V for 14 µs, followed by –14 V for the rest of the time. Given its inductance of about 20 µH, the current in L2 will increase by about 4 A during each conduction cycle and decrease by that same amount during rest time. As long as the current drawn from the power supply is more than 2 A, the current in L2 will never cease completely. For example, if the current is 20 A on average, the current in L2 will vary between about 18 and 22 A. As the ripple current stays basically constant while operating at up to the maximum current of the power supply, filter capacitors C17 to C22 are never exposed to more than about 1.5 A RMS total ripple current, assuring that they have a long lifetime. This is an advantage over some other types of switching power supplies, where the ripple current is much higher, forcing the designer to use more expensive capacitors or to accept reduced lifetime in these components.

If the load is less than about 2 A, the current flow in L2 is no longer continuous. The duty cycle of the power transistors starts to drop, until at zero load the duty cycle almost becomes zero too.

C37 serves several purposes. For higher frequencies it couples the first filter stage (L2 and C17 through C22) to the error amplifier, while for lower frequencies (and at dc) the output of the supply is sampled. This is necessary because each filter stage introduces 180° of phase shift at the higher frequencies. After two stages the phase shift goes through a full 360°, making it impossible to stabilize the control loop without additional circuitry. But for dc, sampling the output is desirable to compensate for the voltage drop in L3. C37 gives the error amplifier a nice PID response, together with R23 and C35. This affords the best possible transient behavior with unconditional stability. In addition, C37 provides some measure of soft starting, so the voltage does not overshoot too much when first switching on the power supply.

R34 and C38 average out the current level over a period of about 2 minutes. U2C amplifies the resulting voltage by an amount that can be adjusted. U2D acts as a Schmitt trigger to switch the fan cleanly on and off when the current average crosses the trigger level set by VR3. R39 limits the speed of the fan to a rather low value that is more than enough to keep the power supply cool. At this low speed the fan produces almost no noise and it will probably last longer than its owner.

Snubbers and EMI Filters

No transformer is perfect. Each winding has some inductance that is not magnetically coupled to the others. There is also the magnetizing current, which can be a considerable part of the total current in small transformers. At the end of a conduction cycle, a strong current flows in T1. After switching the power transistors off, some means must be provided to discharge the energy stored in the magnetic field of the core and in the leakage inductances. D3 and D5 are included for this purpose. They recover most of this energy and dump it back into C3. Another portion flows through the Schottky diodes into L2, but this cannot be more than the current flowing in L2 at the moment of switchoff.

A problem arises if the magnetizing current is bigger than the actual load current, a situation that can occur during startup. Also it must be taken into account that diodes, even fast ones, take some time to switch, and the transformer cannot wait to start dumping its energy. So some absorbing RC networks have to be included. These are commonly called *snubbers*. R9 and C14 form the primary snubber, absorbing energy during the switching of D3, D5, Q1 and Q2. On the secondary side of T1, R10, C15, R11 and C16 protect the Schottky rectifiers from inductive spikes.

Some RF noise is generated and it must be cleaned up. Between C3 and the power oscillator, two Type-73 ferrite beads FB1 and FB2 perform a critical noise-absorbing task. On the output side, L2 already absorbs most of the noise. It is wound on a high-permeability iron-powder toroid that is very lossy in the HF range. The main filter capacitors have low equivalent-series-resistances for good filtering.

L3 is another noise absorber. To minimize capacitive coupling, a ferrite solenoid was used instead of a toroid so that the input windings are well separated from the output ones. The ferrite used starts absorbing at HF, so this coil not only blocks but also absorbs RF energy. Finally, the output leads are passed through a dozen 73-material ferrite beads. The filtering is completed by bypass capacitors on the output leads to the cabinet. Note that the ground on the printed-circuit board is floating to reduce stray HF currents on the enclosure.

Running on 240/120 V ac

I live in a country where the mains supply is 220 V at 50 Hz. This supply will accept input voltages between about 95 to 250 V ac, using S2 to switch from 240 to 120 V ac operation. For 120-V ac operation the fuse F1 should be rated at 10 A, 5 A for 240 V ac operation.

Next month in Part 2, I'll give construction details for the more specialized magnetic components, along with procedures for setting up and testing the unit.

Manfred Mornhinweg, XQ2FOD, was born in Chile in 1965 and has been building all sorts of electronic gear since the age of 12. Even today, much of his station is homemade. Manfred was first licensed in 1980 and holds the equivalent of the US Extra Class license. Manfred has a wide range of interests in Amateur Radio, including HF and VHF mobile, but his main activities are packet and satellites. He's participated in the building and installation of no less than six VHF repeaters, plus two mountain-top packet nodes. Manfred is employed as an electronics engineer at the European Southern Observatory (see **http://www.eso.org***), where his job is "building toys for the astronomers, and fixing whatever they break." You can contact Manfred at Buenaventura Osorio 720 Dpto I, La Serena, 112 Chile*; **mmornhin@eso.org.** QST

By Manfred Mornhinweg, XQ2FOD

A 13.8-V, 40-A Switching Power Supply

Part 2—This month we describe construction details and pull all the loose ends together.

The exact size of the PC board is 120×272 mm (4.72×10.71 inches). It must be made from good quality, single-sided glass epoxy board—don't try to use a cheaper grade of board. The heavy components would stress it too much and the copper adhesion is not good enough for the heavy soldering required. A circuit board is available from FAR Circuits.[1]

Building the Magnetic Components

The biggest challenge for most home builders will be the magnetic components. To keep things simple, I used Amidon cores. The only exceptions are L1 and L3, which were made from materials found in my junk box. Both of these inductors are not critical, and suitable Amidon part numbers are included in the parts list.

T1, the main power transformer, is the heart of this circuit. I built T1 using a tape-winding technique, stacking four pairs of ferrite E cores to obtain the necessary magnetic capabilities. [Comments from HQ staffer Larry Wolfgang, WR1B, as he constructed the transformers and inductors are included in the construction details below.]

Making T1

Because four cores are stacked there is no factory-made bobbin available for this transformer, so I made a paper bobbin. I wound the transformer using 0.1-mm thick copper strips interleaved with Mylar sheets, because a thick wire needed for the heavy current would be impossible to bend around the sharp corners of the bobbin. Instead of using a lot of thin wires in parallel, it is better to use copper strips. The whole assembly is sealed in epoxy resin, with the magnetic cores glued in place with epoxy.

Cut a piece of hardwood to serve as a form when making the bobbin. As the center legs of the four stacked cores measure 62×12 mm (2.44×0.47 inches), the wood block must be 63 mm (2.5 inches) wide and 12.5 mm (0.5 inch) thick, to allow for some play. The length of the block should be around 100 mm (4 inches). The height of the bobbin will be 28 mm (1.10 inches), so make your block long enough to hold it with the bobbin in place with room for holding on to it. I used a belt sander to trim this wood block to the exact dimensions. Try to be precise—if the bobbin is too big you will waste valuable winding space, running the risk of not being able to fit the windings. If the bobbin comes out too small, your finished winding assembly may not fit the ferrite cores, making it unusable.

Now wrap the wood block with one layer of plastic film, such as "Saran Wrap" used in the kitchen to preserve food. This material allows you to remove the bobbin from the wood block easily. Cut a strip of strong packing paper, 28 mm (1.10 inches) wide and about 1 m (39.4 inches) long. A brown-paper grocery bag is a good source of suitable paper. Mix some 5-minute epoxy glue (I used the type sold in airplane modeling shops, which comes in good-sized bottles) and apply a layer of epoxy to the paper strip. Now wind 6 layers of the paper strip very tightly around the plastic-wrapped wood block. Wrap another sheet of Saran Wrap

DAN WOLFGANG

Figure 2—Larry Wolfgang, WR1B, using a 4-foot straightedge designed as a guide for hand-held circular saws to clamp the copper foil tape to a board on a tabletop. After carefully measuring to ensure a uniform 22 mm width, he cut the foil tape using a Fiskars rotary cutter. Be careful to keep the cutter wheel against the straightedge for the entire length. Move the tape in 4-foot intervals to cut the entire length.

DAN WOLFGANG

Figure 3—Winding the foil tape tightly on the epoxy-coated paper bobbin on the wooden block. The Mylar tape is unrolled and positioned over the foil layer as you wind.

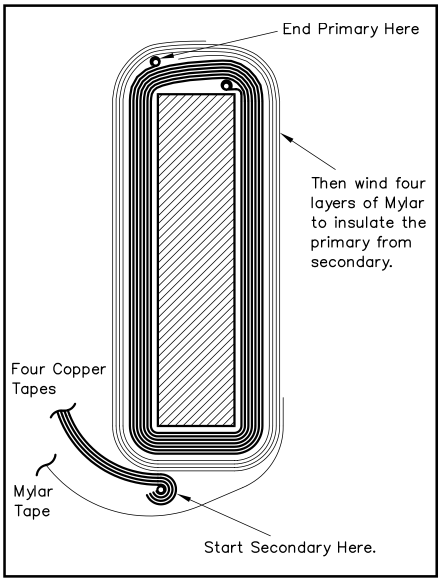
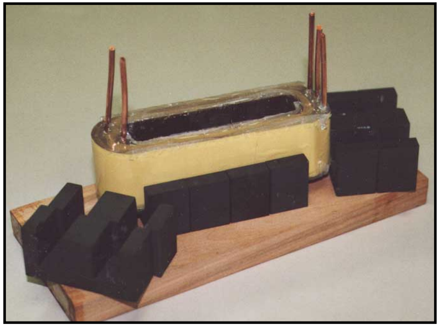


Figure 4—Primary 15 turns on bobbin, with start of 4-turn, center-tapped secondary winding.

---

[1] Circuit boards for this project are available for $19 each plus $1.50 shipping per board. VISA and MasterCard accepted. Orders may be mailed to FAR Circuits, 18N640 Field Ct, Dundee, IL 60118, or faxed to 847-836-9148. A circuit board template for this project may be downloaded from the ARRL Web at **http://www.arrl.org/notes/1816/#correx**. Note: The template included in *The 1999 ARRL Handbook* is incorrect. Use this template instead.



LARRY WOLFGANG

Figure 5—Photo showing how the core halves must fit into the completed transformer after it is removed from the wooden block. You will have to file off the rough edges of epoxy to allow the cores to meet properly.

around your work and press it between two wooden blocks held together with strong rubber bands or wood clamps, so the long sides of the bobbin are flat and smooth against the wood. Now place the bobbin assembly in an oven for about 15 minutes at 50°C (122° F). The epoxy sets much more quickly and becomes somewhat stronger at that temperature.

[Comments from Larry Wolfgang, WR1B: The paper I used for my T1 bobbin was cut from a 36-inch-wide length of “craft paper.” This had been used to wrap some paper my wife had purchased at an art-supply store. It was about as heavy as the paper used for grocery bags. I used 30-minute epoxy for this step, providing a bit more “working time” than 5-minute epoxy allows. It takes *lots* of epoxy, because so much soaks into the paper. My epoxy was the kind with the double plunger, and equal amounts come out of both tubes as you push in the plunger. Wear rubber or plastic gloves to protect your hands. I squeezed out an amount that made a puddle of resin and a puddle of hardener each about $1\frac{1}{2}$ inches across and $\frac{1}{8}$ inch or so deep. This was not enough, and I had to mix more. I used a spring clamp to hold the paper to my workbench and then held the paper in one hand while spreading epoxy with a heavy toothpick. I coated the entire length and then wrapped my plastic-covered wooden block. My electronic-controlled gas oven only allows me to set the temperature as low as 170ºF, so I had to watch the temperature and shut the oven off as the temp rose to about 150ºF, then let it cool down. I ran it twice this way to “cure” the 30-minute epoxy I used for the bobbin.—*WR1B*]

Now you will need some 0.1 mm (0.004 inch = 4 mils) thick copper tape, and some Mylar sheet of a similar thickness. Cut the copper in strips 22 mm (0.87 inch) wide, and the Mylar in strips 28 mm (1.10 inches) wide. If you can make long strips, say 2 m (6.56 feet), this is an advantage. Otherwise, you will have to solder individual copper strips together. In total, you will need about 7 m (23 feet) of copper tape and slightly less Mylar tape. [I made 7 meters of “double-thickness” tape, using two 3-mil thick, sticky-backed copper tapes that we had in the ARRL Lab. After making the 15-turn winding, I cut the leftovers in four equal lengths to make the “four-layer tape” used in the secondary. There was less than a foot of left-over tape after the transformer was completed. The Mylar tape I used was made by 3M and was 2-mil thick and 1-inch wide with adhesive backing. This thickness is sufficient for the voltages involved, provided that care is taken so that the Mylar isn’t punctured by accident. If like the author, you cut strips from a sheet of copper, you should file down the edges to remove burrs. See Figure 2.—*WR1B*]

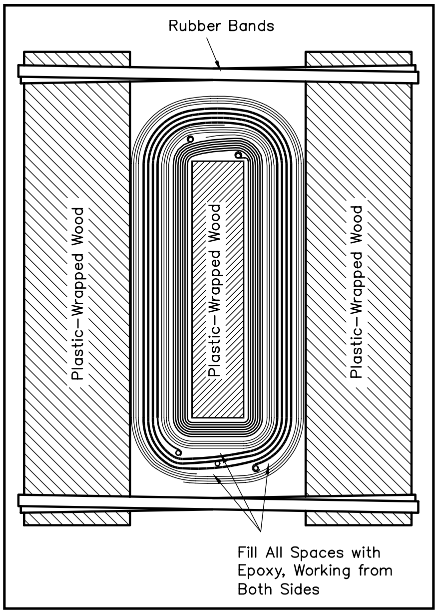


Figure 6—Clamping the T1 assembly and filling with epoxy.

Once the epoxy has had ample time to harden and has cooled, remove the rubber bands, the outer wood blocks, and the outer plastic wrapping (don’t worry if it doesn’t come off completely). Do not remove the plastic wrapping that separates the bobbin from the wood. You now have your wrapped wooden core and the epoxy-paper bobbin on it.

Take a 60 mm (2.36 inches) length of #12 bare copper wire. Wrap the end of one of your copper strips around the wire, so that the wire protrudes out from one side of the copper loop. Use a big soldering iron to flow some solder into the junction. Try to avoid getting solder on the outside, because this could later puncture the Mylar insulation. [I scraped the adhesive off the back of the sticky-backed tape where I soldered the wire. Otherwise, the solder won’t stick to the back of the copper, and the layers may not have good conductivity between them.—*WR1B*]

Now place the copper wire on one of the narrow sides of the bobbin, so that the copper strip is centered on the width of the bobbin, leaving 3 mm (0.12 inch) room on each side. Stick the start of the copper strip to the bobbin with some thin adhesive tape. See Figure 3.

Position the start of a Mylar strip so that it covers all the copper and is centered on the bobbin, and then tape it in place. Now wind 15 turns of this copper-Mylar sandwich, as tightly as you can, keeping the Mylar aligned with the bobbin sides and the copper nicely centered. Don’t lose your grip, or the whole thing will spring apart! If your copper strip is not long enough, fix everything with strong rubber bands or a clamp and solder another copper strip to the end of the first one, allowing 2 mm of overlap. Before doing this, cut the first copper sheet so that the joint will be on one of the narrow sides of the bobbin, because here you have space, while the wide sides will have to fit inside the ferrite core’s window. If the Mylar strip runs out, just use adhesive tape to add another strip. Make the overlap 5 mm to avoid risk of creepage between the sheets and also try to locate the joint on one of the narrow sides of the bobbin. See Figure 4.

When the 15 turns are complete, cut the copper strip so that the second terminal will be on the same narrow side of the bobbin as the first terminal. Solder the second terminal (another 60 mm piece of bare copper wire) to the strip, position it and wind three or four layers of Mylar to make the insulation safe between the primary and secondary. [I started my primary winding with the bulge of the wire on the corner, so that I was immediately winding along the wide side. When I finished the 15 turns, I positioned the end wire so it is on the narrow side, just short of the corner of the long side. This way, the two bulges meet at the middle, but don’t cross each other.—*WR1B*]

If you think this is a messy business, you are right. But it’s fun too! The secondary is just a little bit messier: It is wound with a five-layer sandwich—four layers of copper and the Mylar topping layer. But it’s only four turns total, so take a deep breath and do it. Solder the four copper strips together around a piece of #12 copper wire. Don’t be overly worried if the outcome is not very clean; mine was quite a mess too, yet it worked well on the first try. Just be sure you don’t create sharp edges or pointed solder mounds, because these may damage the insulation. See Figure 4 for details.

Now position the start of your secondary conductor so the terminal wire will come out on the same side as those of the primary, but on the other narrow side of the coil assembly. The goal is to end up with a transformer with its primary leads on one extreme and the secondary on the other, and that will also fit the printed circuit board nicely. Wind two turns, solder the center tap wire between the four copper strips, wind the other two turns, solder the last terminal wire and then wind a finishing layer of Mylar and fix it in place with adhesive tape. This finishes the worst part of making T1.

What you have now is a springy, messy coil assembly that will fall apart if you let it go. You have to seal it, but this is easy to do. Temporarily hold things together with some stout rubber bands. Wrap your two wooden blocks, the same you used to press together

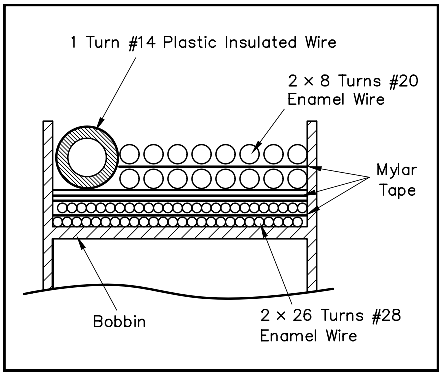


Figure 7—Cross-sectional view of T3 (not to scale), showing distribution of windings.

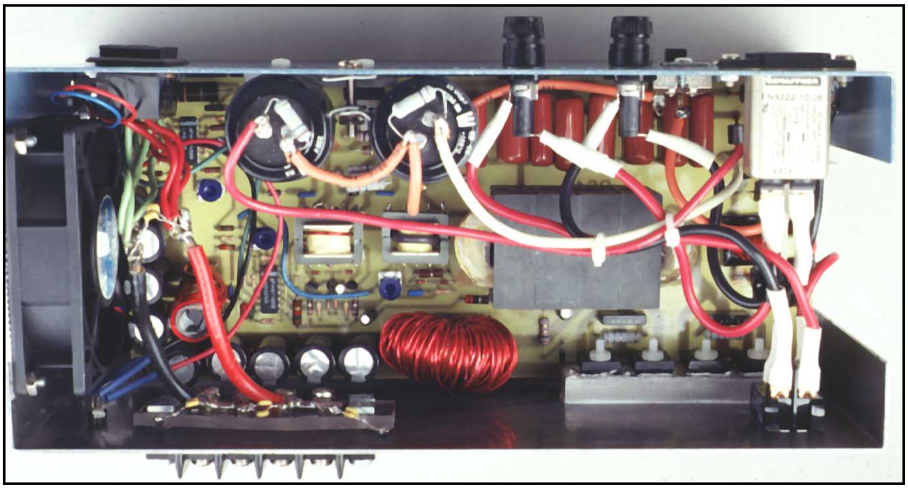


Photo of top of ARRL HQ version, showing PCB mounted in cabinet.

the bobbin, in plastic film. Place them against the sides of the coil assembly, and apply hard pressure, using a clamp or a lot of rubber bands, so that the long sides of the coil straighten out completely, and any slack is displaced to the narrow sides. Now mix a fair quantity of epoxy glue, place the coil assembly so that the pins face up, and let the epoxy run into the coil. Continue supplying epoxy until it starts to set. If it drips out from the other side, no problem. (Just don't do this work over your best rug!) When the epoxy doesn't flow any longer, turn over the coil assembly, mix a new batch of epoxy and fill the other side completely, forming a smooth surface. As the lower side is now sealed, the epoxy will not flow out there. When this epoxy has set, turn the assembly over again, mix some more epoxy and apply it to form a smooth surface there. The idea is to replace all the air between copper and Mylar sheets by epoxy, and especially to fill the room left by the copper strip, which is narrower than the Mylar. This filling is necessary both for mechanical and for electric safety reasons. See Figure 6. [My wooden "screw clamp" worked well for applying strong even pressure to the sides. I don't think rubber bands would apply enough pressure to minimize the air space inside the transformer.—*WR1B*]

Now place the assembly in the oven again. Let the epoxy harden completely, then remove the coil from the oven, remove the clamp, rubber bands, wooden blocks, wooden core and all remains of plastic film. You will be surprised how your messy and springy assembly changed into a very robust, hard, strong and nice coil. Now test-fit the ferrite cores. See if they can be installed easily, so that each pair of facing E-cores comes together in intimate contact, without pressing on the winding. If everything is right, the winding should have some play room in the assembled core. But it is easy to get too much epoxy on the coil. If this happens to you, just take a file and work the epoxy down so that it doesn't disturb the ferrite. The ferrite core *must* close properly; otherwise you will later burn out the power transistors.

When the sides fit, prepare some more epoxy, apply a very thin layer to all contact faces of the ferrite cores and mount them onto the coil assembly. You can hold them in place with adhesive tape until the epoxy sets. Again, use the oven to speed up the hardening. The last thing you have to do is bend the copper wires into the proper shape to fit the printed circuit board holes. Be sure that on the secondary winding the center tap is actually in the center position. The polarity of the other pins doesn't matter. This completes the manufacture of T1. All the other transformers and coils are just child's play after making T1!

Making T2

The current sense transformer T2 has a lot of turns but they needn't be wound nicely side-by-side. You can use a winding machine with a turns counter or you can just wind T2 by hand. Get some #36 or other thin enameled wire, solder the end to one of the outer pins of the EE24-25-B bobbin, and wind 100 turns. Don't worry if your winding is criss-crossed and ugly, and don't feel guilty if you lose count and wind a few turns more or less. As long as you don't overdo it, it will just affect the position of VR1 when you adjust the completed power supply later. Solder the wire to the center pin on the same side, then wind another 100 turns in the same sense. Solder to the other outer pin on the same bobbin side and apply one or two layers of Mylar, just to protect the thin wire.

Now take a piece of #14 plastic insulated wire, wind one single turn over the Mylar and solder the two ends to the two outer pins of the other side of the bobbin. It doesn't matter which end goes to which side. Install the EA77-250 core with a small amount of epoxy cement and T2 is finished. [I used AWG #14 house wire here. The insulation made it a bit tight for the core, but it fit.—*WR1B*]

Making T3

T3 is made using the same type of bobbin and core as T2. Wind 26 turns of #28 enameled wire. The 26 turns should fit nicely in a single layer. Study the schematic diagram to see how the windings connect to the bobbin pins. Bring the wire back to the starting side over the last half turn, for connection to the center-tap pin. Wind one layer of Mylar sheet, then put on the next 26 turns. Again, bring the wire back to the starting side over the last half turn, for connection to the bobbin pin.

Wind 3 layers of Mylar tape, to insulate the primary and secondary properly. Wind 8 turns of #20 wire, and solder the ends to the bobbin pins. Look at the printed circuit board drawing to see which wire is soldered to which pin. Wind a single layer of Mylar, then wind the other 8-turn winding over the first one. This will leave a space at one side of the bobbin big enough to take the single turn of #14 plastic insulated wire. This completes the assembly. See Figure 7 for a cross-sectional view of the windings. Now glue the core in place with epoxy cement and T3 is finished.

Making L2

L2 is wound on an Amidon T-200-26 iron-powder toroid core. As it is too difficult to bend thick wire through a toroid, and tape winding it is not practical either, I chose to make this coil with 10 pieces of #16 enameled wire in parallel.

Cut the wires to about 1.5 m (59 inches) in length and lightly twist them together. Then insert the bundle into the core, and starting from the middle of the wire bundle, wind 8 turns, using half of the core's circumference. Now wind another 7 turns, starting from the middle toward the other end of the wire bundle. The 16th turn is the one you made when you inserted the wire bundle into the core to start.

Making L3

To make L3 you must first find a suitable rod. I used a part of an old ferrite antenna rod about 10 mm (0.39 inch) in diameter and 50 mm long (1.97 inches). (An Amidon number 33-050-200 rod can be used.) Wind 10 bifilar turns of #12 enameled wire. This wire is quite stiff, but it is still no problem to handle. You should wind the coil on a properly sized drill bit, allow it to spring open and place it on the ferrite core. Otherwise you could crack the ferrite trying to wind directly on it. A tapered "drift punch" helped open the turns just enough to fit the core. Fix the core to the winding with some epoxy. Bend the wires so that all four of them point down with the core pointing straight up. That's the position L3 is mounted on the PCB.

Putting It All Together

Install and solder all parts except for Q1, Q2, and D6 to D9. Before installing D1, fashion a simple heat sink from a 30×80 mm (1.18×3.15 inch) piece of 1 mm (0.039 inches) thick aluminum sheet, bent into a U shape. Drill a hole and screw the rectifier bridge onto the heat sink together with a lock washer. Then solder D1 to the board.

I made my own enclosure, using two 3-mm (0.12 inch) aluminum plates, measuring 300×120 mm (11.81×4.72 inches) for the front and rear walls. They are screwed to the fan, the PCB and to a 120-mm (4.72-inch) long spreader tube of 6-mm (0.24-inch) diameter, so that these parts become integral to the structure. The connections between the PCB, aluminum plates and fan were made with small pieces of 10×10 mm (0.39×0.39 inch) aluminum angle stock. The assembly is surprisingly rigid.

The top and bottom covers were made from 1 mm (0.04 inch) aluminum sheet and measure 126×300 mm (4.96×11.81 inches). The bottom cover has a hole for the PCB's center mount. The side covers were cut from wire mesh to allow unrestricted airflow, and measure 122×126 mm (4.80× 4.96 inches). The panels are held together with 10×10 mm (0.3×0.39 inch) aluminum angle stock, running along all edges and held with small sheet-metal screws. These covers are not installed until the power supply is complete, tested and adjusted.

I painted all the panels flat black on the outside, which looks nice together with the anodized aluminum angle stock. The edges and insides were kept free of paint, in order to get proper electrical contact between the panels for good shielding.

[The version made by WR1B used a Hammond Manufacturing ventilated, low-profile instrument case, catalog number 1426Y-B. This is a rugged case that also looks very nice. Larry mounted the circuit board inside the case using a pair of steel mounting rails, also from Hammond, catalog number 1448R12.]

The components external to the PCB (P1, SW1, C3, the LED and the output screw terminal block) are mounted to the front and rear panels. Q1 and Q2 are mounted to the rear panel, using M3 nylon screws and 3 mm (0.12-inch) thick ceramic insulators. These thick insulators were used not only for safety reasons but also because they reduce the capacitive coupling of the transistors to the enclosure. Do not use metal screws with plastic washers, because this approach does not give enough safety margin to operate at the input line voltage. [The author's junk-box ceramic insulators proved difficult to duplicate for the supply we built in the ARRL Lab. Equivalent new parts would have nearly doubled the cost of the supply! Instead, for good heat-transfer properties, we used thin rubber insulators manufactured by Wakefield Engineering as PN 175-6-250-P, available from Newark Electronics as PN 46F7884. Individual aluminum spacers milled from aluminum blocks were used between Q1, Q2 and the Schottky diodes and the metal chassis. Care must be taken to make sure the surfaces of the spacers are parallel and free of burrs to ensure low thermal resistance.]

The Schottky diodes are mounted using the same kind of insulators and screws, but there is a heat spreader made from 6-mm (0.24-inch) aluminum plate between those insulators and the case. All surfaces requiring thermal contact are covered with heat-transfer compound before assembly. When installing the diodes and transistors, first do all the mechanical assembly and then solder the pins. Otherwise you could stress them too much while fastening the screws.

All wire connections are made next and the output filter is assembled by sliding the ferrite beads over the output cables and soldering the bypass capacitors C25 through C30. Be sure to use a nice thick wire for the output. A 40 A continuous-duty current is no joke.

The tracks on the PCB cannot be trusted to carry 40 A without some help. Use a big soldering iron (100 to 150 W) to solder lengths of #12 bare copper wire cut and bent to fit the shape of all the high-current paths. To prevent any failures due to vibration from the fan, place some drops of hot-melt glue anywhere a wire is connected to the board. Hot-melt glue is also excellent for fixing anything that would otherwise rattle, like ferrite beads.

Testing and Adjusting

Make sure you do a thorough visual check. Set the three potentiometers to mid position. Check that there is no continuity between the ac input and ground, between the ac input and the dc output or between the dc output and chassis ground.

Connect a variable voltage supply (you need 12 to 15 V for the tests) to the output leads, without plugging the switcher into the ac line. You should see the LED light up. Change the voltage fed into your project to see how the LED changes color. If you have a dual-channel oscilloscope, connect its two channels to the base-emitter junctions of the power transistors. [Since you are not connected to the ac power line, you will not be grounding it through the oscilloscope's ground leads connected to the emitter leads.—*Ed.*] With the external voltage at about 12 V, you should see small pulses. As you increase the voltage suddenly the pulses will disappear. If you want, you can preadjust VR2 by setting your lab power supply to exactly 13.8 V and then setting VR2 to where the pulses just disappear.

Now it's time to start up the switcher. Remove your lab supply and the oscilloscope leads and connect the supply to the ac line in series with a 60-W light bulb. This will avoid most or all damage if something is really wrong. Connect a voltmeter to the output and switch on your supply. If everything is right, the bulb will light up, then slowly dim while the power supply starts up and delivers about 13.8 V.

Now, connect a load of about 2 A to the output—a car brake light makes a good load. At 2 A output, the bulb in the ac line will probably glow, with 13.8 V dc at the output. If everything is okay so far, now comes the big moment. Remove the series bulb from the ac circuit. Startup of the supply should now be fast and you can now connect a heavier load to it. With a load of 2 to 10 A connected (the value is uncritical, given the good regulation of this supply), adjust VR2 so that you have exactly 13.8 V at the output.

Next adjust the current shutdown point. For this you need a load that can handle 40 A. You could make one by connecting a lot of car headlamps in parallel or you could use some resistance wire to build a big power resistor. I made a 13.8 V, 550 W heater for testing my supply. Connect the load and adjust VR1 so that the output voltage is just at the limit of shutting down.

The last adjustment is for the fan trigger point. Connect a 65-W car headlamp or similar load that consumes about 5 A. Let the supply run for several minutes, then move VR3 to the point where the fan switches on. Now check out the trigger function by changing the load several times between about 2 and 10 A. The fan should switch off and on between 30 to 60 seconds after each load change. You may have to readjust VR3 until you get the fan to switch on at no more than 7 A continuous load and switch off at about 4 A.

And If It Doesn't Work?

If you are building this project, you probably already have some experience in troubleshooting, so I don't need to teach you the basics. If you used substitute parts for the magnetic cores and made a bad choice, the results could be dramatic. If either T1 or L2 saturates, the power transistors could burn out before the fuse has a chance to open. The protective light bulb in the ac line will avoid damage in this case, so by all means use that bulb for initial testing!

Another possible error is reversing the phase of a winding in T3. If you get one of the 8-turn windings reversed, the results will be explosive unless you have the light bulb in series. If you reverse the 1-turn winding, the power supply will simply not start.

Please note that several resistors are shown with incorrect values in the *Handbook* schematic diagram. The schematic shown in last month's *QST*, however, is correct. A corrected schematic is also available on the ARRL Web site.

You can contact Manfred at Buenaventura Osorio 720 DptoI, La Serena, 112 Chile; **mmornhin@eso.org**.