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High-Efficiency Class-E Power Amplifiers—*Part 2*

Class-E operation permits low-cost MOSFETs to develop considerable power.

Last month[7] we talked about Class-E amplifier fundamentals and began construction of a 40-meter unit. Now we'll tackle the power supply, keyed-waveform shaper and develop some power.

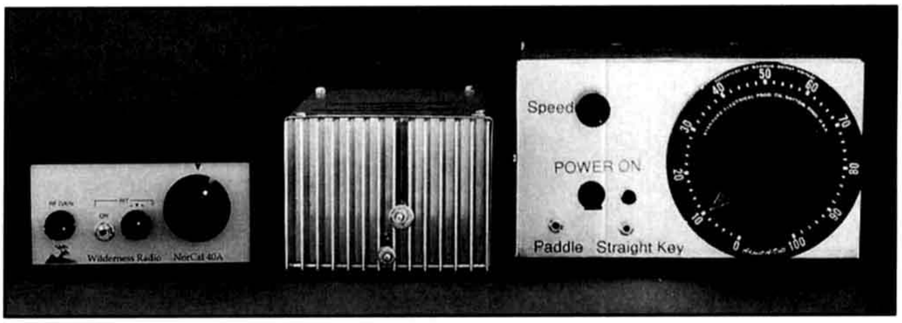
A Keyed Power Supply

Nonlinear Class-E operation sharpens the CW keying envelope, causing annoying key clicks. To prevent this, we key the power supply to shape the supply voltage. A separate 4×7×12-inch (HWD) enclosure houses the dc supplies, a stretcher circuit that delivers a stretched pulse to the driver and a shaper that produces the shaped pulse for the amplifier. Figure 8 shows how these circuits connect.

So that the RF drive does not end before the shaping pulse, the keying pulse to the NorCal 40A driver is stretched a few milliseconds. The stretcher (Figure 9) takes a keyer's CMOS logic signal and provides a buffered keying waveform to the shaper and a stretched keying waveform to the NorCal 40A driver. Dc supplies (Figure 10) provide 12 V dc to run the ICs and 0 to 120 V dc for the amplifier. A wave shaper (Figure 11) gives this 0 to-120 V dc supply voltage a controlled rise and fall time to avoid key clicks. Figure 12 shows the keyed power supply with its cover removed.

There are other advantages to using a keyed power supply to control the output power. The amplifier power dissipation is low at all supply voltage levels, so that loss is kept low throughout a keying pulse. Because the keyed power supply also acts as a solid-state TR switch, a relay is not needed. This is because the supply voltage is zero except during key down. (This feature works well with the NorCal 40A, because it, too, does not use a relay for switching.) At zero voltage, the drain-to-gate capacitance in a MOSFET is quite large, and the signal from the antenna is fed through the amplifier with a loss of only about 7 dB. The NorCal 40A receiver sensitivity is excellent,[8] and a 7 dB signal loss does not hurt reception at all. A 7-dB loss degrades the MDS to −130 dBm, still far below typical 40-meter antenna noise levels of −90 to −110 dBm. On the positive side, with 7 dB attenuation, the receiver is less susceptible to intermodulation distortion from other signals in the 40 meter band. In addition, the amplifier reduces AM broadcast signals by about 20 dB. The 7-dB loss does need to be made up at the audio end. For this, we mount a 2-inch-diameter speaker in a cardboard mailing tube cut to

[7]Notes appear on page 42.



Transceiver, amplifier, and power supply for a 40-meter, 500-W station. The NorCal 40A transceiver driver is on the left, a 500-W amplifier is in the center and the power supply on the right. The amplifier's heat sink and transistor mounting screws are visible. The large dial controls the variable autotransformer, varying the RF output power.

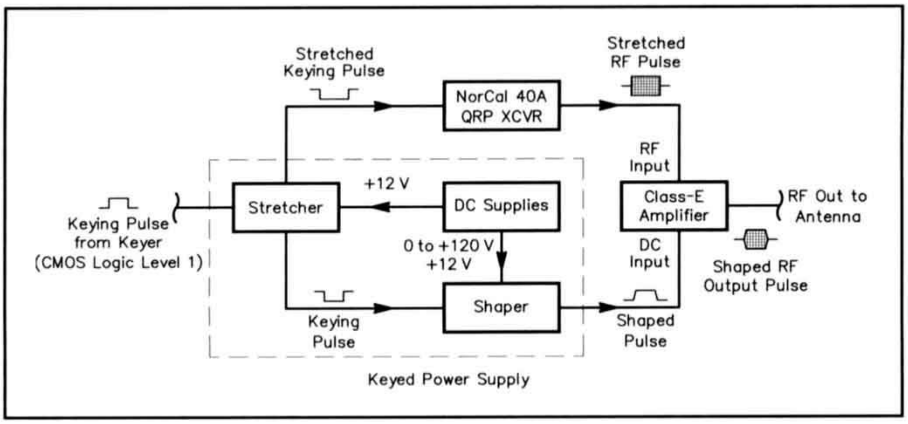


Figure 8—Block diagram showing the connections between the stretcher, dc supplies, shaper, NorCal 40A and the Class-E Amplifier. The stretcher, the dc supplies, and the shaper are in the keyed power supply. Power supply keying is done by a Curtis keyer IC (not shown) that provides a CMOS logic-level 1 during key down. The Curtis keyer IC and application note are available from MFJ Enterprises Inc, Box 494, Mississippi State, MS 39762, tel 800-647-1800, 601-323-5869, fax 601-323-6551; e-mail **mfg@mfjenterprises.com**; WWW **http://www.mhjenterprises.com**.(Keyer circuits using Curtis ICs can be found in recent editions of *The ARRL Handbook.—Ed.*)

resonate at 650 Hz for CW reception. This gives a sound level that is quite adequate.[9]

The Diplexer

For greater reduction of spurious emissions, we recommend following the amplifier with a band-pass diplexer (see Figure 13) to terminate out-of-band spurious components in a 50 Ω load.[10] Our diplexer (in a 3.5×6×10-inch [HWD] box) uses the equivalents of a 100-pF series capacitor, an 1800-pF shunt capacitor and air-wound inductors. Stretch or compress L2 to achieve minimum SWR. The measured loss of 40-meter signals was extremely low, only 4%. Our experience shows that a diplexer can reduce all spurious components to more than –55 dBc.

Tune-Up

Refer to Figure 3 in Part 1. There are two amplifier coil adjustments. First, with the cover on and the dc input off, L1 is set for minimum input SWR with full RF input. Typically, the SWR can be reduced to 1.5:1. If it cannot be brought below 2:1, try adding or subtracting a turn from L1.

Output power is peaked by stretching or squeezing L2. Note: For safety, the amplifier's cover should always be attached when the RF drive is applied. The cover also significantly lowers the inductance of L2. Be sure to turn off the supply voltage before you touch *any* amplifier parts! A high RF voltage will burn the skin. RF burns are deep and heal slowly. Having a keyed power supply helps here, because the amplifier supply voltage is zero except during key down.

Attach a dummy load and power meter to J2. With the RF input applied continuously, slowly increase the dc input voltage, while monitoring the gate and drain voltages using an oscilloscope with 10× high-impedance

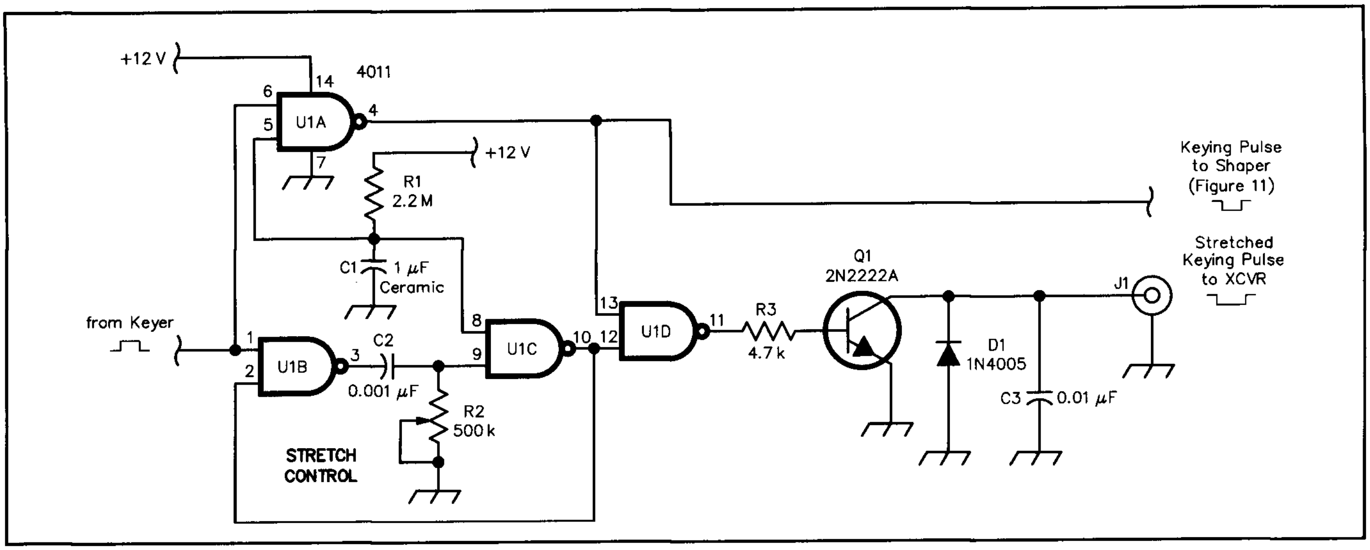


Figure 9—Stretcher circuit diagram. NAND gate A acts as a buffer and produces a keying pulse for the shaper. One input has an RC delay to prevent keying glitches when the power is turned on. Gates B and C are connected by an RC network that causes a pulse to be triggered on a falling edge. R2 is adjusted to ensure that the RF output from the NorCal 40A lasts longer than the shaping pulse. The components are assembled on perfboard.

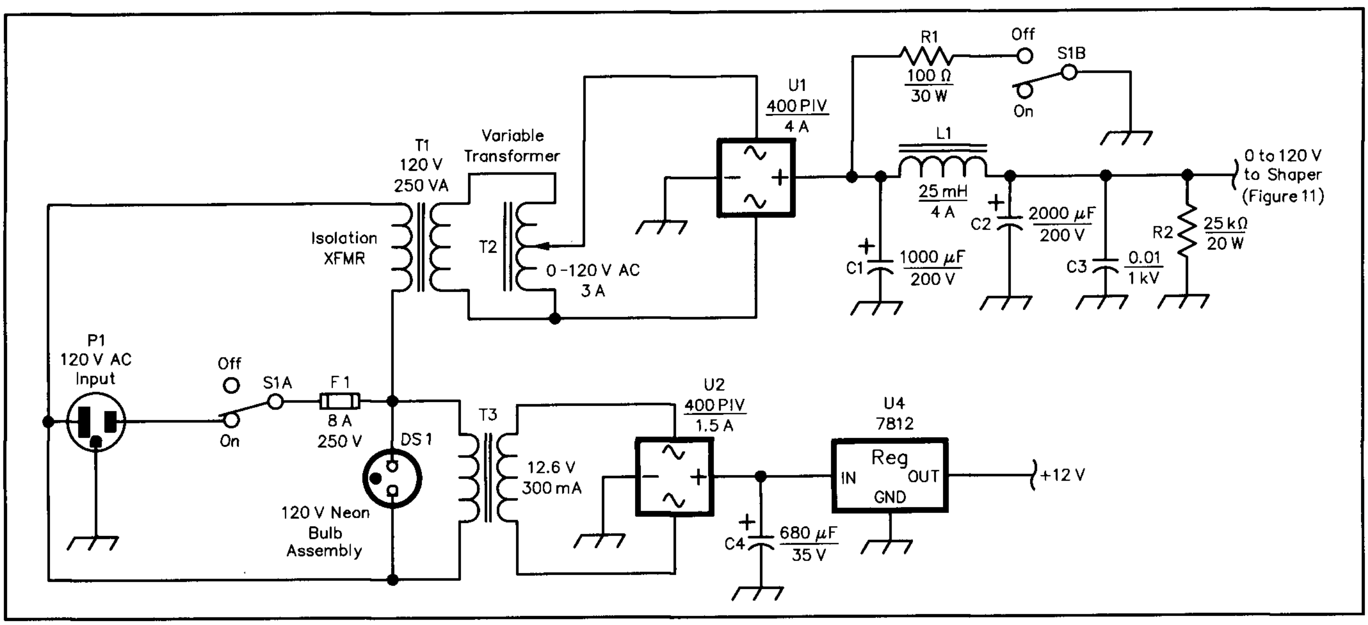


Figure 10—Dc supplies diagram. There are two isolated supplies: one with an unregulated 0 to 120-V output controlled by an autotransformer, and another with a +12-V regulated output. Two bleeder resistors help keep capacitor voltages at safe levels when the supply is turned off or its output reduced. The 4-A bridge rectifier is an RS404LR by Diodes, Inc, available from Digi-Key. The Panasonic 1000 and 2000-µF electrolytics in the filter are available from Digi-Key. The Stancor C-2686 25-mH choke is available from Newark. We scrounged the isolation transformer and variable autotransformer from old equipment. Look for them at swap meets, or purchase equivalents from Newark (Magnetek N55M 250-VA isolation transformer and the Staco 291 3-A variable autotransformer).

probes. (You should see waveforms similar to those in Figure 15, although the peak drain voltage should be about half of that in the figure.) The RF output should begin to rise. Increase the dc input until the forward RF output power is 25% of full power. Make sure the output SWR is 1.5:1 or less. Measure the dc input voltage, and adjust L2 to give 25% power at 60 V dc. Stretching L2 reduces its inductance and increases the output power, but usually lowers the amplifier's efficiency. Squeezing L2 reduces the output power and usually increases amplifier efficiency.

Increase the dc input voltage until the amplifier reaches maximum output power. The dc voltage should now be between 115 and 120 V, and the peak drain voltage of the RF-stage MOSFET should be between 380 and 420 V. Larger peak drain voltages run the risk of transistor failures. Lower voltages may indicate an excessive drain current, which can lead to a failure. If the voltage is too high, stretch the coils a bit more. If the voltage is too low, squeeze the coils. Check the RF drive and input SWR again. You may find that they have changed somewhat and that readjustment is needed. Measure the dc supply current and voltage, and calculate the amplifier efficiency to ensure that it is 85% or above. Use a 0.001-µF capacitor to bypass the voltmeter terminals because an RF voltage there can cause a significant measurement error. (In addition, you should realize that RF power meters often have error factors as high as 10%.)

Keyed-Waveform Shaping

The keying envelope is controlled by the three potentiometers in the shaper and stretcher circuits. R3 in the shaper circuit sets the rise time, R4 sets the fall time. R3 also helps control the power supply droop as

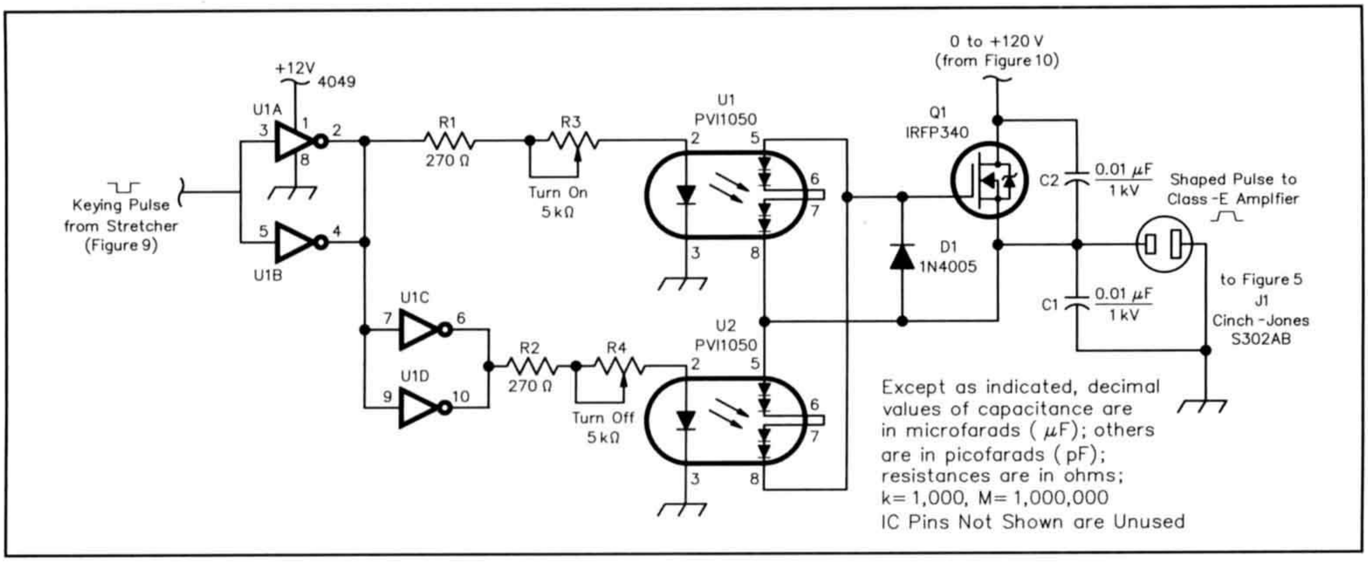


Figure 11—Shaper circuit diagram. A pair of optically isolated MOSFET drivers (type PVI1050) turn Q1 on and off to bring the supply voltage up and down. Keying waveform rise and fall times are adjusted by R3 and R4, which control the current to each MOSFET driver. The 270-Ω resistors limit the LED current to a safe level. The **TURN-ON** potentiometer is also used to keep the overshoot from the unregulated power supply to a reasonable level. D1 prevents Q1's gate voltage from drifting negative. C1 and C2 are RF bypasses. To keep the supply voltage from appearing across exposed contacts, a female socket is used at J1. All components are available from Digi-Key. Point-to-point wiring on perfboard is used.

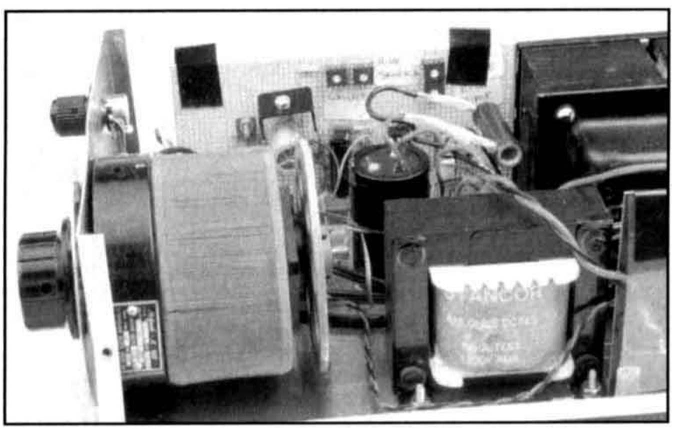


Figure 12—The keyed power supply with the cover removed, viewed from the side. T1 is mounted on the back plate, along with the fuse and connectors for the dc output, a keying line to the NorCal 40A and the ac line input. The **TUNE** switch keys the amplifier for testing. The variable autotransformer is on the left, mounted to the front panel. In the center foreground, mounted to the base plate, is L1, the 25-mH choke. Mylar sheets are taped to the perfboards for electrical isolation. The large components are attached directly to the box. The IRFP340 is mounted on the bottom of the box using a Berquist K10-104 Kapton insulating pad, #6-32 screw and a torque of 10 inch-pounds. The other shaping circuit components are mounted on perfboard. Layout is not critical.

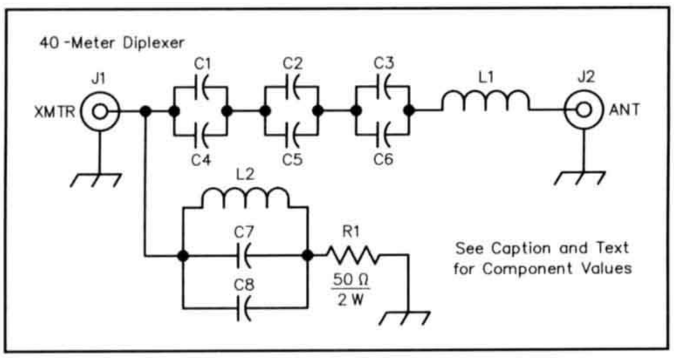


Figure 13—Schematic of our diplexer. It uses six 150 pF capacitors, two 910-pF capacitors and air-wound inductors made of 3/16-inch-wide copper tape (see Note 1).

C1-C6—150 pF, 1 kV mica 5%-tolerance (Cornell Dubilier type CDV19; available from Newark Electronics, see Note 1)

C7, C8—910 pF (same type as above)

L1—24 turns of 3/16-inch-wide copper tape, 1 3/8 inch ID; see Note 1.

L2—4 turns of 3/16-inch wide copper tape, 1 inch ID; see Note 1.

R1—50-Ω, 2-W (approx) termination, Jameco part number 71458; available from Jameco Electronics, 1355 Shoreway Rd, Belmont, CA 94002, tel 415-592-8097; fax 415-592-2503 and 415-595-2664)

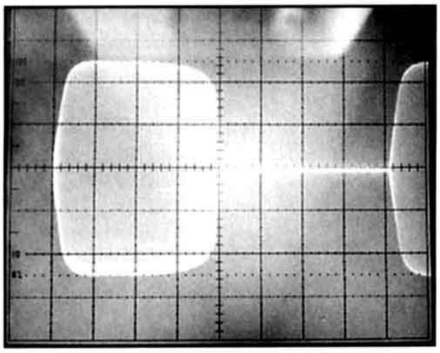


Figure 14—Keying waveform of the 500-W amplifier at 30 WPM. The horizontal axis is 10 ms per division. The rise and fall times are about 3 ms.

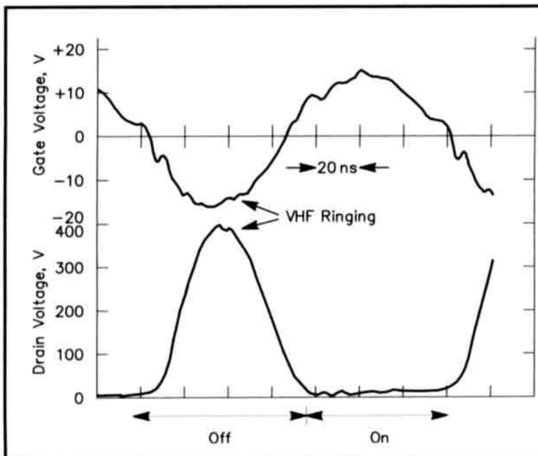


Figure 15—Drain waveform and ringing. Oscilloscope trace of the gate and drain voltages of the 300-W amplifier with 3 W drive. The dc supply voltage is 120 V; the input SWR is 1.6:1. Time scale is 20 ns per division; the transistor off and on times are shown. The transistor is off when the gate voltage is below the threshold, typically 4 V, and on when the gate voltage is several volts above the threshold. Peak gate voltage is 16 V, and the peak drain voltage is 400 V, safely within the manufacturer's ratings of 20 and 500 V, respectively.

the amplifier is keyed. R2 of Figure 9 determines the stretch in the pulse that keys the NorCal 40A, so that it does not stop transmitting before the end of the shaped pulse. We recommend using a keyer with adjustable weighting to offset the pulse stretching. The potentiometer settings interact somewhat, and there are variations at different sending speeds, so it is best to set them at the speed you commonly use. Adjust the controls for rise and fall times between 2 and 5 ms, and for a smooth keying envelope. Figure 14 shows keying at 30 WPM with rise and fall times of about 3 ms.

VHF Ringing

In many Class-E amplifiers, ringing in the VHF range can be seen on the gate and drain waveforms (Figure 15). This ringing can be quite pronounced, with bumps several volts high on the gate or drain or both. The bumps disappear when the RF input is removed, and that is why we refer to this as *ringing* rather than *oscillation*. We have compared measured spectral plots with *PSPICE* simulations and believe that the waves are driven by the sudden turn-on and turn-off of the transistor, acting rather like the gong of a bell.

We notice two distinct time periods and frequency ranges for the ringing. During the time the transistor is on, the ringing frequency is about 80 MHz. This appears to be a resonance of the external drain capacitor combined with the internal inductance of the capacitor and the transistor and may indicate a mismatched load. The on-ringing is usually small if the load is matched so that the drain voltage comes smoothly to zero before the transistor turns on.

The ringing while the transistor is off covers a broad range of frequencies—from 130 to 210 MHz. If the output low-pass filter is removed, the ringing can be seen easily on a spectrum analyzer at levels between −40 and −60 dBc. The off-ringing appears to be caused by a resonance of the external drain capacitor and its internal inductance, together with the transistor's internal drain capacitance and its inductance. The internal drain capacitance varies greatly with the drain voltage, so that the frequency is modulated as the drain voltage rises and falls. The low-pass filter reduces these harmonics to the −70 to −80 dBc range.

On the Air

The amplifiers meet the FCC requirements for spectral purity [confirmed in the ARRL Lab—*Ed*.]. NorCal 40A designer Wayne Burdick, N6KR, emphasizes that it is important to correctly tune the bandpass filter following the transmit mixer to minimize spurious emissions from the NorCal 40A.[11]

These amplifiers are excellent for chasing DX, schedules and "ragchews," particularly at this low point of the sunspot cycle. The amplifiers require no warm-up, no tune-up, and produce no fan or relay noise. We can vary the power from 1 W to full power via the variable autotransformer. The antenna SWR should be 1.5:1 or better because the amplifier is not protected against large mismatches. With a high SWR, the transistor will probably overheat. Check the dc voltage when the amplifier is delivering full power to the antenna to ensure that it remains between 115 V and 120 V. Readjust the coils if the voltage is too high or too low.

Our most common problem has been a poorly mounted PA transistor. If the transistor is not flat against the heat sink, heat transfer is poor and the transistor becomes quite hot; efficiency suffers (becoming usually less than 85%) and the amplifier may not reach full power. The output power may also drift downward, a sign that the transistor temperature is increasing and that the transistor is under stress.

Component temperature can be a good diagnostic tool. For the 500-W amplifier, our experience is that for CW QSOs longer than 30 minutes, the temperature of C3, C5 (Figure 5) and the heat sink rises to about 60° C. For the 300-W amplifier, the heat-sink temperature is about 50° C. This is hot to the touch, and it can be checked with a lab thermometer. The temperature will vary according to your operating style, and if the temperature is higher than you like, you can add a fan.

The Future

We see room for improvements: protection against antenna mismatches and employment of an inexpensive keyed *switching* power supply that is as lightweight as the amplifiers. Finally, it would be interesting to develop Class-E amplifiers for the other bands. We have built a 250-W amplifier for the 20 meter band that exhibits an efficiency of 88% with 10 W drive. We believe that Class-E amplifiers provide amateurs with good building challenges and operating fun at modest cost.

Acknowledgments

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Notes

[7]Eileen Lau, KE6VWU, et al, "High-Efficiency Class-E Amplifiers—*Part 1*," *QST*, May 1997, pp 39-42. The amplifier enclosures are 3 1/8×4 1/8×7 1/8 HWD.

[8]Rick Lindquist, KX4V, "Low-Power Transceiver Kits You Can Build," Product Review, *QST*, Jun 1996, pp 45-50.

[9]See J. B. and R. V. Heaton, "An Electro-Acoustic CW Filter," *QST*, Apr 1983, pp 35-36; Wally Millard, K4JVT, "A Resonant Speaker for CW," Hints and Kinks, *QST*, Dec 1987, p 43; and Richard Clemens, KB8OAB, "More on Resonant Speakers," Hints and Kinks, *QST*, Jan 1989, p 37.—*Ed*.

[10]David Newkirk, WJ1Z (now W9VES), and Rick Karlquist, N6RK, "Mixers, Modulators, and Demodulators," *The 1996 ARRL Handbook*, Chapter 15, p 15.22.

[11]Telephone conversation with Wayne Burdick. This tuning is done by carefully adjusting C50 to peak the output power. QST