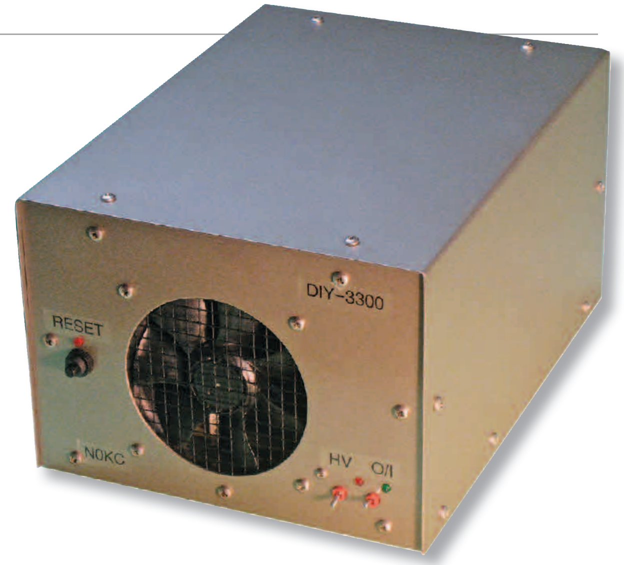
A Small, Lightweight High-Voltage Switch-Mode Power Supply



Pair this modern power supply with the NØKC Centennial Amplifier or other projects.

Ralph J. Crumrine, NØKC

Old ham radio equipment has the reputation of making good "boat anchors." The high-voltage power supply for the linear amplifier is probably the piece of equipment most often given this pejorative term. The high-voltage transformer alone might weigh upwards of 50 pounds for a homebrewed 1500 W vacuum tube amplifier. The finished package might weigh 60 pounds.

There has been little guidance for the builder of high-voltage supplies of the switching type since it was offered in *QEX* some years ago.[1] There was a product offered in *QST* a few years after the *QEX* article published, based on the information from the article.[2] This afforded the ham with the opportunity to rid the ham shack of the boat anchor and have a modern high-voltage supply. For a time, the unit described in the *QST* advertisement could be purchased as a kit to satisfy the home builder. The use of this unit, with its problems — including a particular problem to be dealt with in its entirety here — is described in a *QST* article by Dick Hanson, K5AND.[3]

In recent years, there have been remarkable improvements in high-power semiconductor components. Several of the builders of the NØKC Centennial Amplifier asked if I was going to do a switch-mode power supply as a follow-on project.[4] Why get into something as arcane as a power supply? Maybe because Peter Dahl, of Peter W. Dahl Co., has left the transformer business. Large iron-core transformers that will honestly power a continuous key-down full legal-limit amplifier are getting hard to find as surplus and are very expensive when new. Maybe it's like asking why someone climbs a mountain — because it is there. Using this reasoning, I got into this design.

A Switching-Mode Power Supply

The power supply design described here brings a significant weight reduction — 60 pounds down to 8 pounds. To see why, take a look at Figure 1, where the 3 kW rated transformer in this power supply can be seen resting next to a 1 kW rated 60 Hz high-voltage transformer.

That's not an apples-to-apples comparison. This little transformer has three times the power-handling capability of its big brother. Weight reduction starts with slimming down the high-voltage transformer, which is achieved by radically increasing the frequency of operation of the transformer — in this case to 60 kHz.

Simplifying the construction can help in a small way to reduce weight. This project is built up entirely on a single printed circuit board. Anyone who can

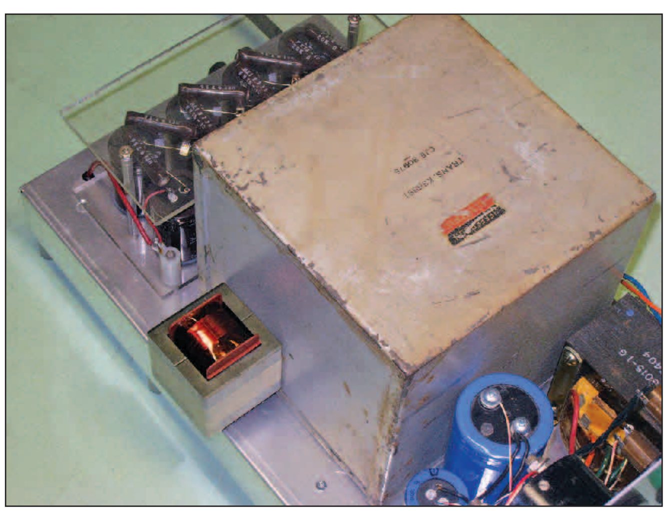


Figure 1 — The 3 kW rated transformer of this power supply can be seen resting next to a conventional 1 kW rated 60 Hz high-voltage transformer.

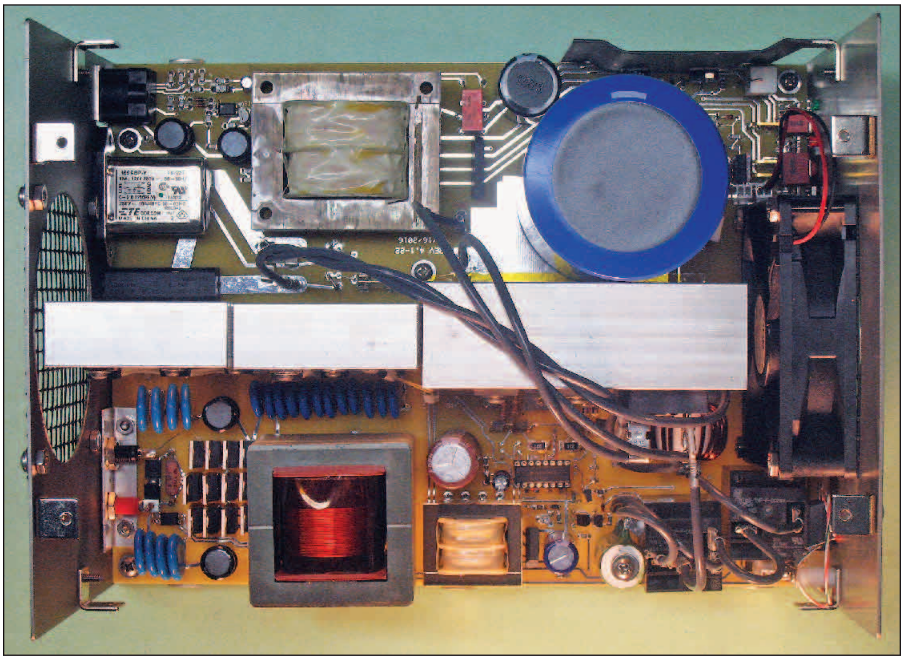


Figure 2 — A top view shows the heatsinks across the mid-section of the single printed circuit board, and the high-voltage transformer mounted beneath it.

stuff a printed circuit board can build this power supply (see Figure 2).

Features and Advantages

There are many features and advantages of this type of power supply.

1) High-speed, high-voltage switching is done with the latest silicon carbide (SiC) semiconductor parts, both the MOSFETs, and the rectifier diodes.

Now, just two MOSFETs do the switching. This design uses single diodes in each leg of a bridge rectifier. The SiC diodes have nearly zero recovery time, greatly cutting heat and potential failures. These parts allow a switching speed of 60 kHz. At such switching speeds, silicon insulated-gate bipolar transistors (IGBTs) and high-current silicon diodes — even the ultra-fast (UF) rated diode parts — are really considered marginal in performance.

2) Voltage-versus-load regulation.

Regulation is better than on most 60 Hz big iron supplies. See the test results in Table 1.

3) Outstanding size and weight reduction.

The 3 kW output power supply is 5.5 inches high by 7.5 inches wide by 10 inches deep, and weighs just 8.25 pounds.

4) High-voltage output fully isolated.

Allows use with any amplifier, no matter how metering is done, in the grid and cathode circuits of the amplifier powered by the supply.

5) Fast over-current shutdown protection.

Shutdown can normally occur in a few tens of microseconds.

6) Supply has overheating shutdown protection.

Hot-spot monitoring by a heatsink-mounted thermistor causes shutdown if necessary.

7) Extremely low output filter energy retention.

Should a short circuit occur and the supply shut down, the 0.1 µF high-voltage filter capacitor will dump only 1/400 of the energy stored in the usual 60 Hz design into the short, likely saving the amplifier tube, if that is where the short occurred.

8) EMI considerations.

A total metal enclosure is used with LC filtering on all connections in and out of the enclosure to minimize electromagnetic interference from the supply.

9) +14 V and +24 V auxiliary supplies included.

This supply will completely power

Table 1
Output Measurements

Load, Ω	V_{in}, AC	V_{out}, DC	Power Out, W	T (DB401), °C	T (Q405/6), °C	T (T401), °C	T (HS3), °C
Infinite	247.4	3,632	0	see (2)	see (2)	30	76
17,150	247.2	3,527	725	34.4	26.6	38	69.4
8,750	246.7	3,492	1,425	46	29.2	43	72
5,726	246.4	3,458	2,088	58.4	31.4	47.6	73
4,298	244.7	3,408	2,702	72	36.6	51.8	73.4

1) Ambient 22.7°C measured with Fluke IR meter and corrected.
2) No meaningful heat rise.
3) HS3 is HV bleeder resistor; temperature taken at highest point with no load.
4) No-load data, taken independently of load data.
5) Load data taken over 20 minutes without cover (air stream was not directed compactly over heatsinks).

most any linear amplifier, including the NØKC Centennial Amplifier.

10) Remote operation.

Initiating the turn-on of the low- and high-voltage sections can be done remotely. Turning on the low voltages can be done with either 24 V ac or dc at 10 mA, either two-wire isolated or one wire with respect to chassis ground. Turning on the high voltage requires a switch connection to chassis ground conducting 30 mA.

11) Soft start.

A soft start that uses feedback involving the primary supply bleeder limits the inrush current from the ac mains.

12) Cool, quiet operation.

A small 92 millimeter square, 24 V dc box fan operates at half-rated voltage from a cold start. From that cold start, the fan speed is controlled by a servo loop to apply just enough air to control heat rise, keeping the fan noise at the lowest level possible.

High-Voltage Design Theory

The significant design problems were limited to the high-voltage part of the total power supply. They were, first and foremost, limiting output voltage variation due to varying load; second, voltage breakdown of semiconductor parts; third, current handling capacity of semiconductor parts, and fourth, keeping heat to a minimum.

Taming output voltage variation

Limiting output voltage variation proved to be by far the most difficult design challenge. My first approach was to use a closed-loop feedback control of the output by regulating duty factor (pulse width) drive to the switching transistors. A transformer is a far more critical magnetic component when compared with a single winding inductor that might be used in a buck or boost type of switch-mode supply.

Much effort was put into feedback control circuits and controller chips. What that work revealed was that no feedback system could get around the problems of a less-than-perfectly-ideal transformer. *SPICE* (Simulated Programming with Integrated Circuit Emphasis) modeling showed that with a less-than-perfect transformer — coefficient of coupling *K* less than 1 — and with the resultant leakage reactances in all the windings and parasitic capacitances between windings, feedback control could not be achieved with duty factor variation as the means of control. The transformer will always display a non-monotonic transfer characteristic — it will be double valued at several points (pulse widths). Hence, to be part of a closed-loop system, the system would always demonstrate an instability. After many blown switching transistors, using *SPICE*, I came to an agreeable understanding — a truce. Whole-cycle skipping would be much the same, and was deemed clumsy and impractical as a control means. There was no guarantee of stability with this method, so I didn't try it.

Weight reduction starts with slimming down the high-voltage transformer, which is achieved by radically increasing the frequency of operation of the transformer, in this case to 60 kHz.

The real effort had to be to improve upon the transformer until it would be good enough to provide satisfactory regulation in an open-loop application, accepting that perfection in coupling was impossible.

The high-voltage transformer

The extreme transformation ratio required for the high-voltage output results in a transformer having a poor coupling coefficient, and in turn, high leakage inductance and parasitic capacitance. As a result of these parasitic circuit elements, the system is greatly under-damped without a load on the power supply, and an oscillation takes place at the end of every switching half-cycle. This oscillation, a decaying sine wave, can cause a voltage greatly in excess of the voltage from the transformer, simply from its turns ratio. The peaks of these cycles are rectified and filtered, and their amplitude added to the basic square-wave shape. The output voltage takes on a life of its own with load variation, greatly exceeding what is expected when the supply is unloaded.

I tried a number of different winding layups, guided by a text on a small transformer design, but all were to no avail.[5] Finally, after much research, trial and error, and *SPICE* analysis, I determined that a transformer with *four* particular improvements would produce satisfactory output regulation without a feedback loop, that is, by using open-loop operation.

First, I relied on the transformer equation, but then doubled the stack of core material. This results in an over-designed transformer with a somewhat improved coefficient of coupling *K* factor. The *K* factor is improved because each turn of any winding has a greater percentage of its length surrounded by ferrite core. Because the core area is doubled, the turns count can be halved. This cuts leakage reactance and parasitic capacitance somewhat — all tending in the right direction.

Second, I separated the primary from the secondary by an electrostatic (Faraday) shield to stop any capacitive interaction between the windings.

Third, I designed the secondary winding to a voltage that is a fraction of the desired output voltage, and then wound multiple secondary windings

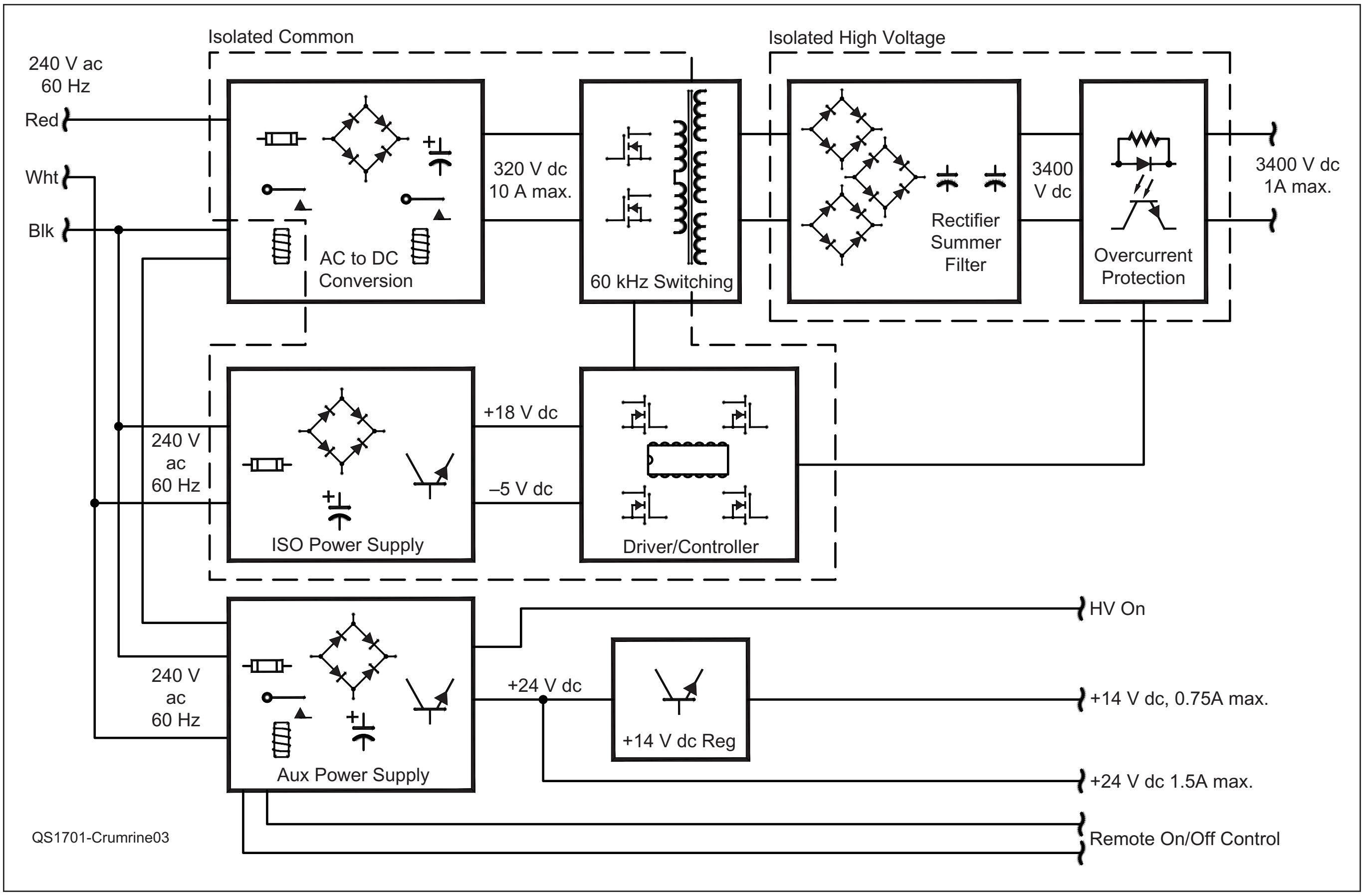


Figure 3 — The blocks in this diagram of the high-voltage supply show the main functions.

based on the inverse of the fraction. This reduces leakage reactance and parasitic capacitance. Each of the three 1100 V secondary windings operates independently, is rectified at each output, and summed in a series connection to get the desired full output. This also avoids series strings of diodes in each leg of a single bridge rectifier along with all the equalizing components that may be necessary to balance voltages across the many diodes.

Fourth, insulation thickness in the transformer is usually governed by voltages between windings. I used four or five times the minimum insulating material thickness of Kapton® tape, that also reduced parasitic capacitance to ¼ or ⅕ of the conventionally designed transformer.

With these transformer improvements in the completed supply, the output dc voltage swing from no load to a 2.75 kW load was nominally ±2.5% (see Table 1). Allowing for 240 V ac input line variation, the regulation is within about ±3%.

Voltage, current, and heat

High voltage and current are not a problem when using silicon carbide (SiC) semiconductor parts. The MOSFETs are rated at 1200 V dc and 36 A. The diodes are rated at 1200 V dc and 2 A. The heatsinks seen in Figure 2 are probably more than needed, but they were available inexpensively on eBay.

Simplified Block Diagram

Circuit operation can be understood by inspecting the block diagram of Figure 3. The blocks include:

Conversion from ac to dc

The 240 V ac line is converted to 320 V dc using a diode bridge rectifier and capacitor filter. Two relays form the soft-start circuit. The first relay is closed by the high-voltage ON control. The second relay is closed by feedback from the supply itself by using the current through the bleeder resistor.

60 kHz switching

The 320 V dc is applied to a pair of switching MOSFETs operating at a frequency of 60 kHz through a center-tapped transformer primary. Each of the three secondary windings produces a peak output of about 1150 V.

Rectifier/summer/filter

Each secondary winding drives a bridge rectifier. The rectified outputs are connected in series and followed by a bank of filter capacitors. A bleeder resistor is in this section, but not shown.

Over-current protection

The output current passes through an optoisolator. Its output will cause the driver to shut down when the high-voltage current exceeds a value set by the bypass resistor on the optoisolator.

Driver/controller

A controller IC provides two pulse trains of proper time and interleaving. These pulse trains are buffered by discrete MOSFET complimentary pair switches. The outputs are applied to the gates of the switching MOSFETs. The pulse trains are fixed at an 85% duty factor so that there is a 2.5 µs OFF period for both switches, avoiding simultaneous ON and OFF transitions for the MOSFET pair.

High voltage and current are not a problem with the use of silicon carbide (SiC) semiconductor parts.

Isolated power supply

A simple isolated 2 W transformer, rectifier, and filter capacitor provides voltage levels for the driver such that the drive signals match the requirements of the switching MOSFET gates. For best efficiency, they require +18 V when ON and –5 V when OFF.

Auxiliary power supply and +14 V dc regulation

A transformer with bridge rectifier and capacitance filter followed by a +24 V regulator IC provides that voltage as an output and drives another regulator IC set to +14 V dc at its output. These voltages are available externally to the amplifier connected to the power supply.

Special Considerations

When the 240 V ac power service is bridge rectified, as it is here, the rectifier output and associated circuitry must be totally isolated from the chassis and any other circuit not directly involved with the switching supply. If an oscilloscope or another ac line-connected instrument is used to test this circuit, then they must be isolated from the ac mains by an isolation transformer. Check the instrument manufacturer's instructions in this case.

Voltages associated with this design are lethal. When testing the supply, wear shoes with thick rubber soles. Keep one hand in your pocket. Do the work only when well-rested and alert. Better still, work with a buddy and operate as a team.

The high-voltage output is entirely isolated from the chassis, or any other circuit, making it useful with linear amplifiers requiring an isolated source. This might apply generally to the grid and cathode metering circuits built into your amplifier.

Construction

This project can be completed from the package of drawings, the schematic, and bill of material that are available on the *QST* in Depth web page.[6] The design is intentionally assembled on a single printed circuit board (see Figure 2). When the board is stuffed and the high-current wiring is in place, you are finished with assembly. High-current connections are accomplished in the third dimension, using wires and quick-connects to avoid wasting board space.

The idea of building a transformer usually puts off most DIYers. The transformer core is made up of two pairs (four pieces) of E-shaped ferrite material. This small transformer uses ready-made bobbins that match the cores, and the turns count is so low that hand-winding the bobbin is practical and easy.

For a discussion of methods used in completing the enclosure, sheet metal fabrication, painting, and lettering, I would direct the reader to my *QST* article (see Note 4) on the NØKC Centennial Amplifier.

With enough interest, I would serve as a source for the special parts for the transformer and printed circuit board. Any questions can be directed to me at **n0kc@arrl.net**.

Notes

[1]Timothy P. Hulick, W9QQ, "Switching Power Supplies for High Voltage," *QEX*, Feb. 1991, p. 3.

[2]Watts Unlimited advertisement, *QST*, Dec. 2005, p. 128.

[3]Dick Hanson, K5AND, "8877 'Lite' — A 50-MHz 20-Pound Travel Amplifier," *QEX,* Jan. 2006, p. 41.

[4]Ralph J. Crumrine, NØKC, "A 1500 W Centennial Amplifier for the 80 – 6 Meter Bands," *QST,* Dec. 2014, p. 30.

[5]Nathan R. Grossner, "Transformers for Electronic Circuits," *McGraw-Hill*, 1967.

[6]**www.arrl.org/qst-in-depth**

Photos by the author.

Ralph J. Crumrine, NØKC, was first licensed as a Novice in 1953 as WN3WFZ. He upgraded to General class and finally, in 1978, to Amateur Extra class. His enlistment in the US Air Force put him to work in radio and navigation equipment repair. After military service, he attended The Pennsylvania State University, where he earned a BSEE degree, graduating with honors. A career followed in the design and development of avionics equipment, beginning work with King Radio Corporation and finally retiring from Honeywell Avionics Division. Ralph is a member of ARRL and has been an active ham in retirement, earning WAS and DXCC in 2002. Antenna and equipment design, and design practices and procedures, have been of particular interest, with several articles published on these subjects with ARRL. You can reach Ralph at **n0kc@arrl.net**.

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