

Overload Protection for High Voltage Power Supplies

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Introduction

Designs for high voltage power supplies have evolved over many years, and have been published in numerous places, so it may seem that there is nothing more to be said. On the other hand, some issues must remain, since one often hears of serious problems. Seen recently on an internet website was the following sad complaint, posted during a rare African EME DXpedition lasting only a few days:

"I had an arc in the tank circuit which took out a bunch of stuff in the power supply and the amplifier."

We hope it all got fixed before the DXpedition was over. This is just one example of the importance of power supplies for serious ham radio operating. Here we describe circuits used in two new high voltage supplies built especially to include overload protection, and with special regard for reliability.

Features

Overload protection. An overload circuit must deal with any possible arcing or other shorts in the amplifier; it must prevent destruction of expensive power supply components, and it must protect the amplifier. A good high voltage relay is essential. For high voltage disconnect, one power supply described here uses a Jennings vacuum relay rated at 50 kilovolts and 50 amperes; the other supply uses an open relay with 2-inch contact spacing. The circuits provide high voltage disconnect, timed high voltage capacitor discharge, and power supply shut-down.

Reliability. A power supply ought not to break down just when a rare DXCC country begins to be heard in your area, or in the middle of a contest.

Op amp metering. This method virtually eliminates any possibility of meter damage.

Heavy-duty construction. After an 8 hour RTTY contest run, at 1500 watts, the heavy-duty transformer is just slightly warm. The 5 kV capacitor is oil-filled, non-PCB. The wire-wound resistors are operated at less than 50% of rating. One supply is built into a sturdy aluminum cabinet, with casters and a lift-up top panel; the other supply is built into a steel cabinet, with casters, hinged lid, and drop-down front panel.

Convenience. A heavy-duty power supply is best built into an enclosure separate from the amplifier. This requires nothing special other than a good high voltage cable.

Other opinions will be encountered. Factory-built amplifiers nearly always have internal power supplies; the reasons probably include cost, portability, ease of installation, prevention of unsafe handling by the inexperienced, and safety regarding the high voltage cable. None of these factors is decisive for the experienced homebrewer. Only the safety issue requires special attention; these supplies use high-quality coax with unique connectors for the high voltage cable. The weight limitation imposed by an internal power supply nearly always results in an amplifier with limited capabilities for 100% duty cycle operation, such as RTTY and WSJT.

Remote control. A small control head on the operating bench near the amplifier can provide full metering and control of a power supply. The bulky power supply cabinet can be placed out of the way, under or behind the bench. The remote units used here include metering, ON/OFF buttons, and neon indicators. The power supply panels have duplicate buttons and indicators for local control.

Step-start. This circuit, using an op amp timer, is an improvement over the usual circuits.

Variac tolerance. The high voltage may be adjusted with a variac on the 240 volt line, without causing malfunction of the control

circuits.

Independence. A high voltage power supply should be usable with any amplifier having demands within its capabilities; a restrictive one-to-one amplifier-supply correspondence is undesirable. A single-operator station can have several amplifiers simultaneously connected to a single high voltage power supply; each amplifier draws current only when it is transmitting. This idea is no more complicated than having several items connected to one 13.6 VDC power supply, or several lamps connected to one household circuit. Each amplifier on line has full internal metering; contains its own filament, bias, screen, and control power supplies; and requires no separate B-minus connection to the power supply.

The B-minus lead from the rectifier in the power supply runs directly through a metering shunt to ground. A special B-minus connection to an amplifier for metering purposes is inconvenient, unnecessary, and potentially unsafe. Even grounded-grid triode amplifiers can be configured for this independence; a differential op amp circuit can be arranged to measure plate current as

$$I_b = I_k - I_g$$

where I_k is cathode current and I_g is grid current.

Power supplies

This article will describe two power supplies which incorporate the features listed above. Although the supplies are not intended for exact duplication, details will be given as fully as possible, so that some of the circuit ideas might be applied to similar projects.

The K5AM homebrew station includes three high voltage power supplies. HVPS1, built in 1961, with few special features, still powers the original push-pull pair of Eimac 4-400A tetrodes on 6 meters. HVPS2 was destroyed by an overload.

The new power supplies, HVPS3 and HVPS4, will be described in this article. They provide the high voltage for two homebrew Eimac 4CX1000A tetrode amplifiers, one covering 1.8 to 54 MHz, the other 144 MHz. The supplies provide only the high voltage for the plate circuits. Heater, grid bias, screen, control, and antenna relay power supplies are all included in each amp. One supply is on line, connected to both amps simultaneously, the other is set aside as a spare.

The two supplies are shown in the following photos:



HVPS3. A surplus aluminum cabinet and panel were used for this power supply. In the original commercial application, the cabinet was installed with the panel on the side, resulting in a large awkward footprint. For this project, the cabinet was turned up, two feet (60 cm) tall, with the panel on top, and casters were added; the power supply is easy to handle. Hinges were added to the panel, and the front of the cabinet can be removed, so all components are accessible.

The exhaust fan is directly over the bleeder resistors. At the top center is a DIN socket for the remote control head. The red banana jacks to the right are test points for meter circuit adjustment and for local tests.



HVPS4. This high voltage power supply is built into a steel cabinet with casters. The ON/OFF buttons and neon lamps are for local control. The white tip jacks labeled E and I are the meter test points. The Jones socket is for the remote control head. The exhaust fan, not seen here, is at the rear of the cabinet near the bleeder resistors.

The cabinet and panel, rescued from a junk pile, had been used previously by several other hams — hence the extra holes. I repainted the panel, but now it's clear from the photo that I should have also repainted the cabinet. Too late now!

Attempts to install the hinge at the rear of the panel, for improved appearance, were thwarted by the recessed mounting of the panel, but a hinge expert could probably do it.

Modular construction

To facilitate assembly and servicing, HVPS4 is built with detachable sections. Only the main high voltage components are permanently installed in the steel cabinet. This allows the various sections — panel, control chassis, and overload relay — to be removed and taken to the test bench.



Panel swings down. For minor repairs, the panel will swing completely down, with all components accessible. If extensive work is required, the panel may be unplugged from the control board and removed. At the left is a #6 cable bonding the panel to the cabinet.

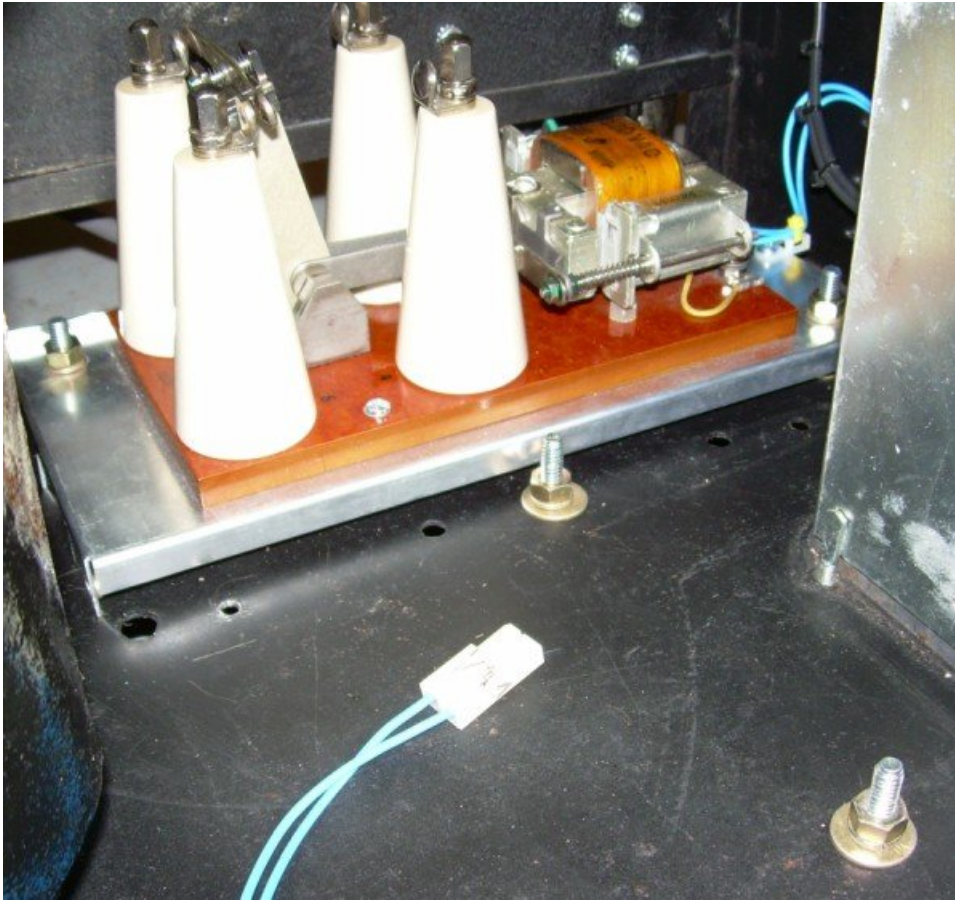
The main method for the modular construction is installing nearly all small components on the control chassis and control board. The control chassis is mounted to the cabinet floor on two 1/4 inch studs permanently attached to the cabinet. The chassis is removed by disconnecting the four Molex plugs and loosening two nuts.



Control chassis. Molex plugs make it easy to remove the control chassis for test or repairs. To the right is one of the 1/4 inch studs that secure the chassis to the floor of the cabinet. The 1/4 inch bolt in the foreground secures one end of the #6 ground cable bonding the panel to the cabinet.

No unsoldering is required to remove a section. The panel has two cables with Molex plugs which connect to the control board. From the main cabinet two more cables plug into the control board, one from the meter sensing components and one leading to the overload relay.

The overload relay is designed to mount with three #6 screws; this would be rather inconvenient, working under the heavy steel cabinet. Thus the relay is first permanently mounted to a metal plate. In turn, the plate slips over two 1/4 inch studs permanently attached to the cabinet floor. The relay plate can be removed simply by loosening two 1/4 inch nuts and disconnecting the Molex plug from the control board. The installed relay is shown below:

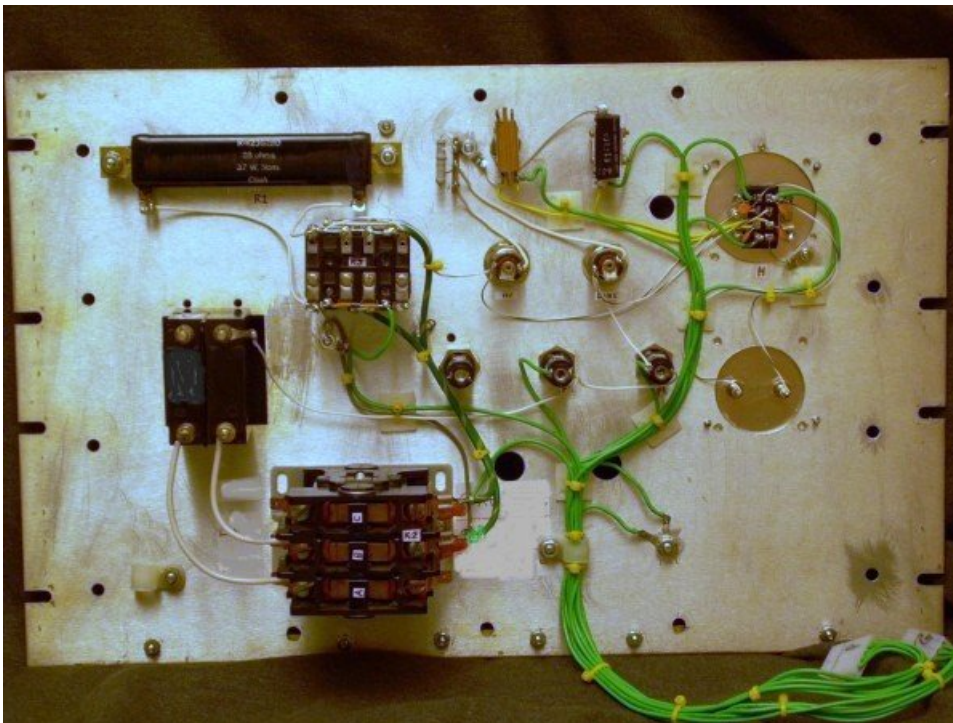


Overload relay installed. The relay is permanently mounted on a metal plate; it is installed in the power supply cabinet by simply dropping the plate over the two studs and fastening two nuts. The two studs in front are for mounting the control chassis.

The panel holds the primary circuits; it is shown in the next two photos.

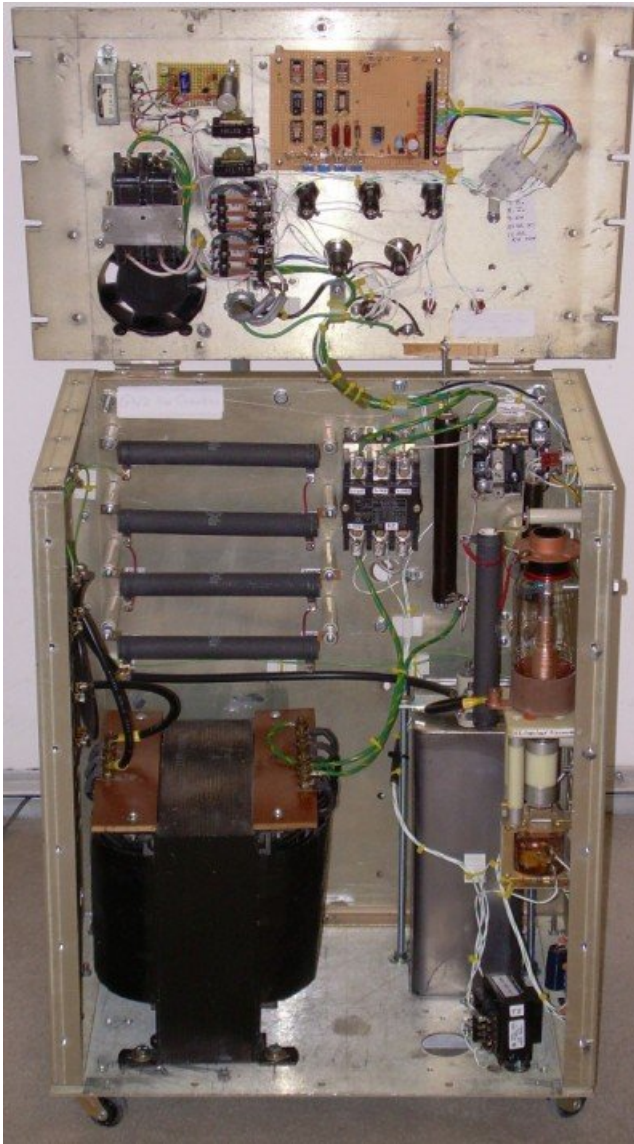


HVPS4 panel. The Jones socket is for the remote head. The push buttons and neon lamps are for local control and testing.



HVPS4 panel. The generous use of cable ties and tie-downs prevents any motion of the wires at the connection points.

HVPS3 is also built in a manner which facilitates repairs and modifications; the panel hinges up and the front cover is removable, as seen in the next photo:



HVPS3 open for inspection. The four resistors above the transformer make up the bleeder; the exhaust fan is in the panel directly above. The overload relay, rated for 50 kilovolts and 50 amps, is at the right.

Circuits

The circuits used in the new power supplies will be described below. The components are listed along with the schematic diagrams; a few alternative component choices are also noted.

Simplified schematic note: Schematic diagrams are shown in a simplified form, with minimum labeling, sufficient for experienced builders. Component sources will be given when available, but surplus sources cannot be listed, since the dealers are sold-out for the items used here. Unless otherwise specified, the following components are used: The transistors are 2N4401 and 2N4403, or similar types. The op amps are type LM324; pin-outs will be selected by the builder. The ordinary diodes are 1N4007; lower voltage types can be used in some places. Resistors are 1/4 watt. Not shown is the bypassing of most terminals, all diodes, and all transistor BE junctions with

0.01 μF disc capacitors, with suitable voltage ratings. The 7824 and 7812 regulators each have 2.2 μF tantalum capacitors at input and output terminals. Each DC relay coil has the usual diode clamp. Each op amp package has a 0.1 μF monolithic ceramic capacitor soldered directly across the power terminals at the socket. Electrolytic capacitors are labeled with capacity in μF ; suitable voltage ratings may be determined by each circuit. Not shown is the numbering on the various inter-module connectors, terminals and wire labels; this task is left to the builder to adapt to individual requirements. Components with references to Mouser may be located at www.mouser.com.

Primary circuit

A panel on the amplifier rack includes a main 240 VAC disconnect switch, a neon indicator, a circuit breaker, and a variac, as shown below:



Variac panel. This panel powers the several high voltage power supplies plugged into the 240 volt outlets at the rear of the amplifier rack; only one power supply is in use at a time. The 120 volt variac is connected to just one side of the line; this allows high voltage adjustment from one-half to full voltage. Mounted behind the panel is a two-pole 20 amp line filter.

Circuit breaker, surplus, 25A.

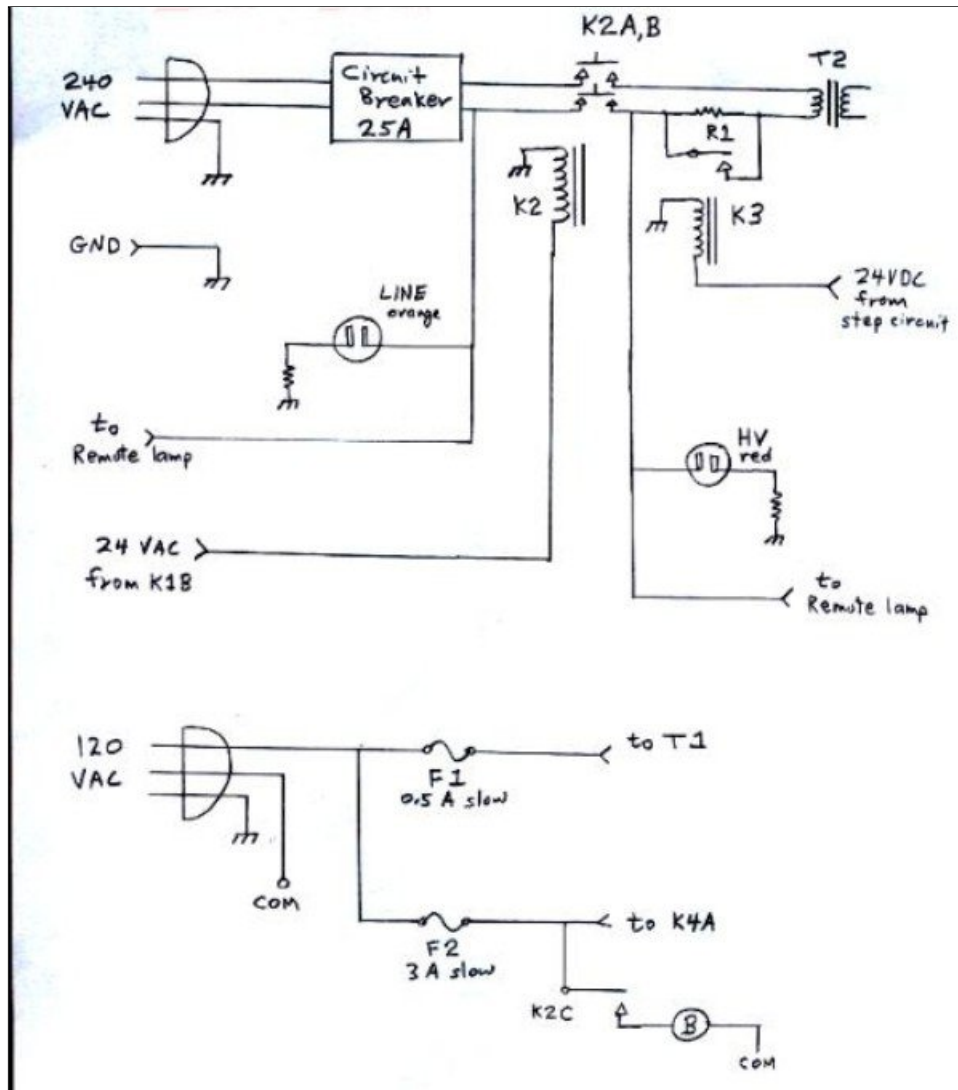
Neon lamp, NE51.

Switch, surplus, DPST, 25A. Suggested: Mouser #633-S6A-RO. Most circuit breakers are not designed for repeated on/off service, so the switch is necessary.

Using a variac means that we must make special arrangements for the control circuits. In addition to the 240 volt line cord, a separate 120 volt cord powers the control circuits; they will run properly no matter what the setting of the variac, and the ON/OFF circuit will respond to the push buttons on the remote head. The 120 volt circuits are live only when I am in the shack, with the master switch on the operating bench set ON.

The primary circuit is shown below. The 240 VAC runs through the circuit breaker, then to the contactor K2. The ON/OFF circuit, when

triggered from the remote head, engages relay K1 on the control chassis; this sends 24 VAC to the contactor K2 on the panel and 24 VDC to the step-start delay circuit. From the contactor, the line voltage runs through the step resistor R1, and then to the high voltage transformer T2. One will often see two resistors used in a step-start circuit, but one is sufficient. After one second, the step relay K3 takes the step resistor out of the circuit.



Primary circuit. The separate line cord for 120 VAC is for the control circuits. The terminal labeled GND is a heavy-duty post for connection to the station ground bus; see details in section *Safety*.

B. Exhaust fan, 4 inch, 120 VAC, surplus.

Circuit breaker, 25 A, surplus. An alternative is an ordinary household breaker with a special bracket fabricated to clamp it to the panel.

K2. Contactor, 40 A per pole, 24 VAC coil. Surplus contactors are often available at www.mpja.com. Contactors or relays with 24 volt DC coils could be used with a minor circuit change. Alternative: see K3.

K3. Step-start relay, 25 A, 24 VDC coil. Suggested: P&B #PRD-7DY0-24, Mouser #655-PRD-7DY0-24.

Neon lamps, NE51. The resistors are 180k, 2 watt.

R1. Step resistor. Suggested: 25 ohms, 50 W, Vishay/Dale #HL05006Z25R00JJ, Mouser #71-HL50-06Z-25. The HV meter reads

about 75% of full voltage before the step relay closes. Making some rough assumptions, the step resistor sees 25% of full line voltage and dissipates 144 watts for one second. The resistor data sheet at www.vishay.com states: "Short Time Overload, 10 x rated power for 5 seconds". To remove all chance for trouble, a 150 watt resistor could be used.

T2. High voltage transformer, surplus, nearly 100 lb (45 kg).

Line cord, 240 volt. 8 ft, Black SJE00W, 300 VAC, Service Cord 12/3, McMaster-Carr #7082K24.

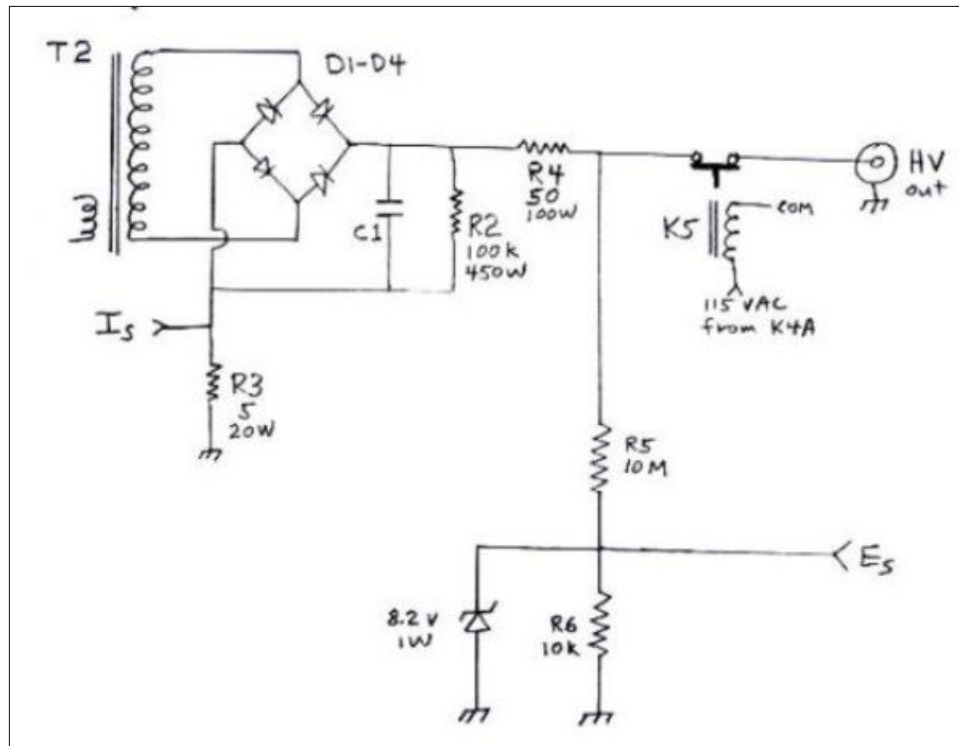
Line plug. Industrial-Grade, NEMA 6-20, McMaster-Carr #7196K33.

www.mcmaster.com

For details not shown, please refer to the *Simplified schematic note* on pages 10-11.

High Voltage circuit

The high voltage circuit is quite standard. Emphasis is on heavy-duty, trouble-free components: high voltage diodes, oil capacitor, resistors run at less than 50% of rating, and an overload relay.



High voltage circuit. K5 is the overload relay. E_s and I_s are sense outputs for the metering circuits.

C1. 53 μ F, 5 kV, oil, surplus.

D1-D4. High voltage diodes, HVCA #HVS10k. Suggested: 1N5408, 1 kV, 3 A, ten or more in each leg. Search at Mouser brings up several manufacturers and good buys in packs of 100.

K5. Vacuum high voltage interrupter; rated 50 kV, 50 A; normally closed, 115 VAC coil; Jennings #R150AC2S115VAC, surplus.

Alternative: open high voltage relay.

R2. Bleeder. 100k, 450 watt; two 50k, 225 watt, in series.

Vishay/Dale #HL22507Z50K00JJ. Mouser #71-HL225-07Z-50K. See

Mouser online catalog page for mounting brackets. See note below concerning insulators. Alternative: 100k, 400 watt; four 25k, 100 watt, in series.

R3. Shunt. 5 ohm, 20 watt; two 10 ohm, 10 watt, in parallel. Vishay/Dale #RH01010R00FC02. Mouser #71-RH10-10.

R4. Limiting resistor, 50 ohm, 100 watt. Vishay/Dale #HL10006Z50R00JJ. Mouser #71-HL100-06Z-50. See Mouser online catalog page for mounting brackets. See note below concerning insulators.

R5. Voltmeter multiplier, 10 megohm, surplus. See note below concerning insulators. Suggested: Ohmite #MOX-750232505FE, Mouser #588-MOX-750232505FE, 25M, change R6 to 25k.

R6. 10k, 10 watt.

T2. High voltage transformer, surplus, nearly 100 lb (45 kg).

Ceramic insulators, 2 inch. Use with minimal length screws, to minimize the internal path length.

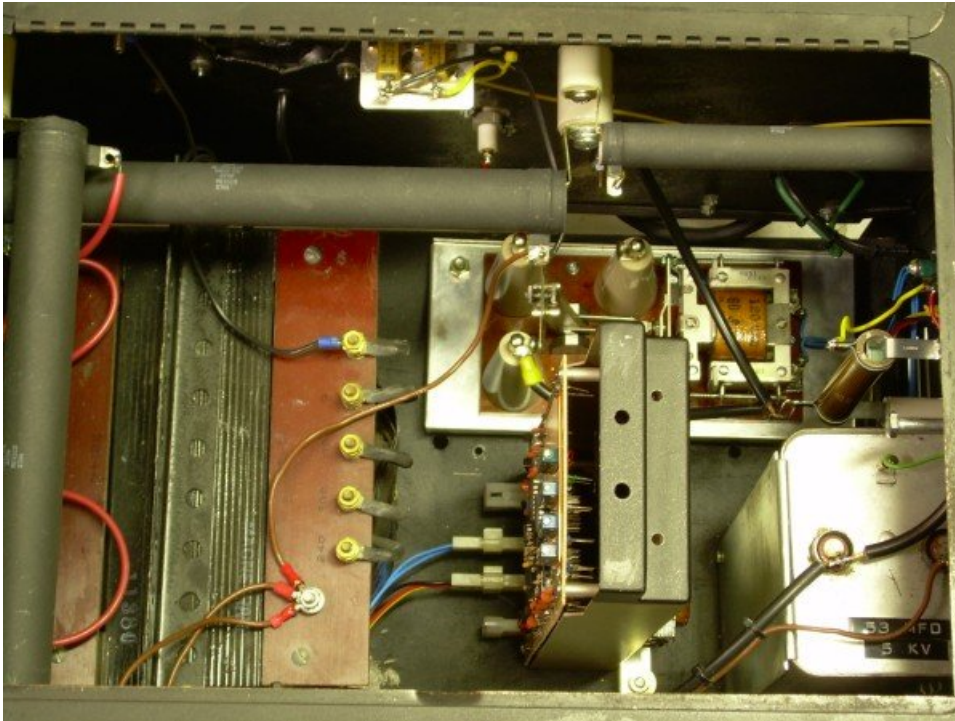
High voltage connector. Type HN.

For details not shown, please refer to the *Simplified schematic note* on pages 10-11.

The parallel arrangement for the shunt R3 is chosen for safety; in no event do we wish the B-minus lead to float far above ground. If one of the two shunt resistors should fail, we would immediately see this as double the normal PA idle current reading in the milliammeter. The normal peak power in the shunt is less than 5 watts; thus we have a four-times safety factor. The resistors specified are high quality chassis-mounting types. The shunts are mounted on a small aluminum plate near the low voltage end of the bleeder; they can be seen at the top of the next photo.

The limiting resistor R4 in the high voltage line is essential. There is some controversy concerning the most effective size and rating, and full agreement is lacking on whether the resistor has merely a limiting function, or may also act as a fuse. With the overload trip system used here, it is expected that this resistor will merely limit, only for the fraction of a second while the overload relay is opening. Even for this short time, the limiting resistor has an important function.

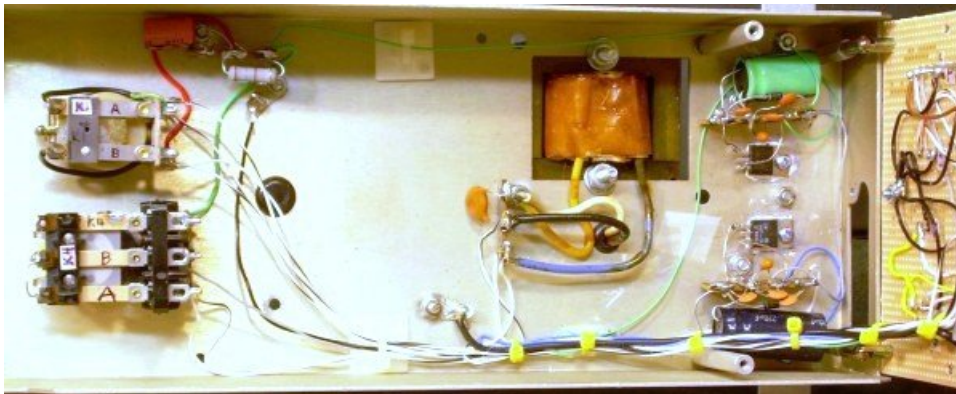
The 10M high voltage resistor R5 is not a simple voltmeter multiplier, but forms a voltage divider with the 10k resistor. This prevents high voltage from reaching the op amp circuit. In case the 10k resistor fails, the zener diode limits the voltage on the line to the control board.



High voltage components. The two 225 watt resistors that make up the bleeder are at the left. At the upper right is the 100 watt output limit resistor. Only two of the four connectors at the bottom of the control chassis are installed in this photo, taken before final assembly. The four high voltage rectifier diodes are out of sight, bolted to the side wall at the left. The shunt resistors are mounted on an aluminum shelf seen at top center in the photo. Below the shelf is the HN connector for the high voltage output. The useless-looking protruding bolt on the right above the capacitor is installed near the top of the cabinet as a convenient place for clipping the ground lead on the crowbar shorting stick — see section *Safety*.

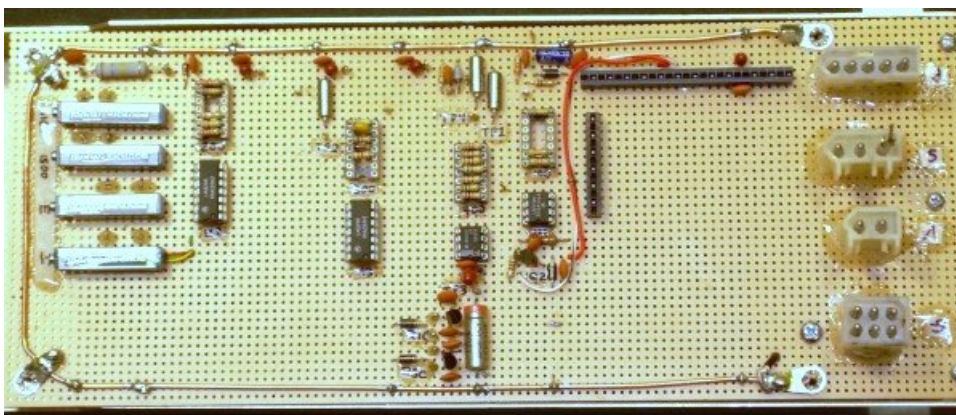
Control circuits

Although producing high voltage is relatively easy, controlling it effectively requires some effort. In traditional high voltage power supplies, one does not usually see much solid-state circuitry in juxtaposition with heavy iron. To obtain the degree of control and protection desired, these power supplies use a few transistors and integrated circuits.



Control chassis. The chassis holds the power supplies for the control circuits, and relays K1 and K4. The control board is mounted to the chassis on hinged spacers. All wiring on the control chassis and control board has teflon insulation.

The control board holds the op amp circuits and other solid-state circuits:

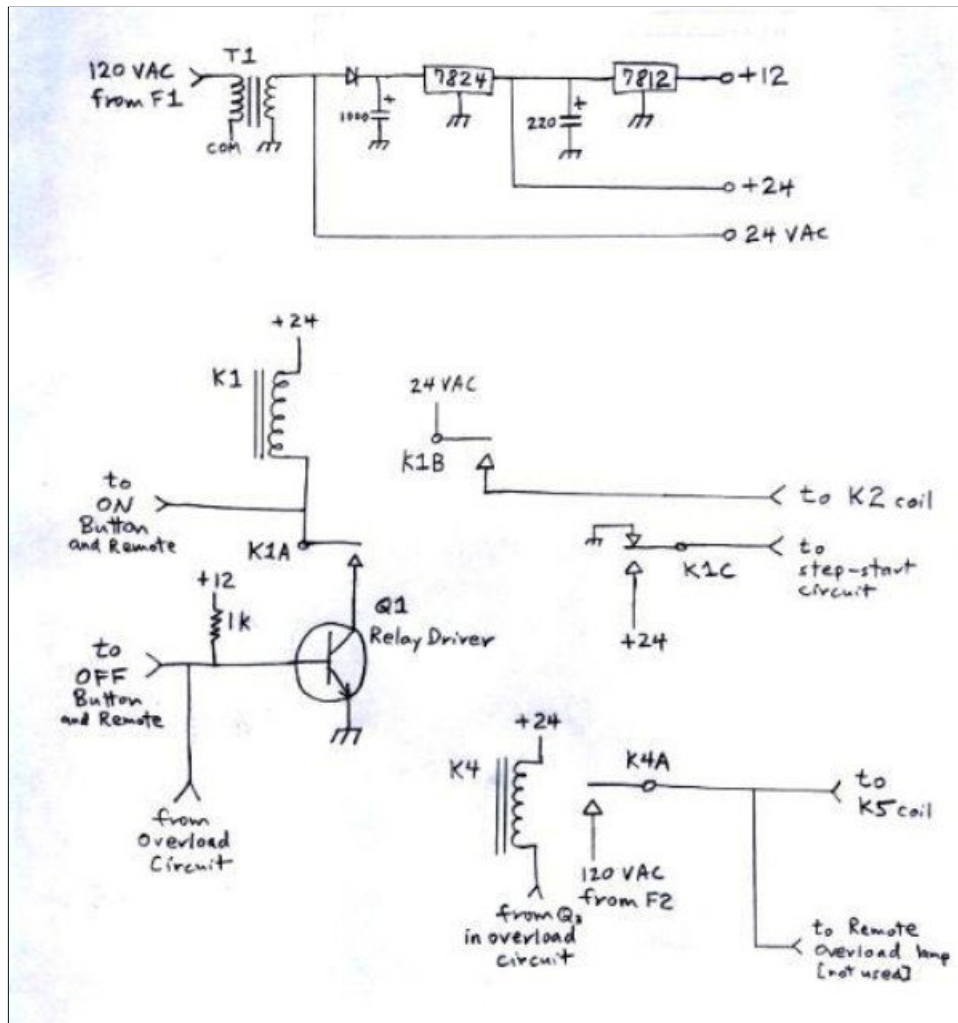


Control board. The control circuits are installed using a combination of wire-wrapping and point-to-point wiring. The op amps are in sockets. Most of the resistors are also socketed; this is convenient for circuit development. Around the edge of the board is a #14 ground wire, connected to the chassis by a heavy lead and by four solid mounting posts. At the left are the four multi-turn trimpots. The hinges are at the far right. The board has extra space for future modifications and additions.

The control circuits are in four parts. The ON/OFF circuit is described directly below. The step-start, metering, and overload circuits will be described in the following three sections.

The ON/OFF circuit is based on relay K1, engaged with a momentary push-button switch and the usual holding contact, with one change. Instead of the holding contact going directly to ground, it goes to an NPN collector. This transistor is biased-on constantly; OFF is executed by momentarily grounding the base. This method allows any number of ON and OFF buttons to be connected with only one lead each. Relay K1 sends 24 VAC to the contactor K2, and 24 VDC to the step-start circuit.

Here is the schematic for the ON/OFF circuit, together with the circuits mounted on the control chassis:



Control chassis circuit. The double regulation for the +12 volt line ensures that the metering and overload circuits will be well-isolated from power-line transients.

K1. Three pole. Coil: 24 volt, 100 mA.

K4. Single pole. Coil: 24 volt, 100 mA.

T1. Primary, 120 VAC; secondary, 24 VAC, 2 A.

For details not shown, please refer to the *Simplified schematic note* on pages 10-11.

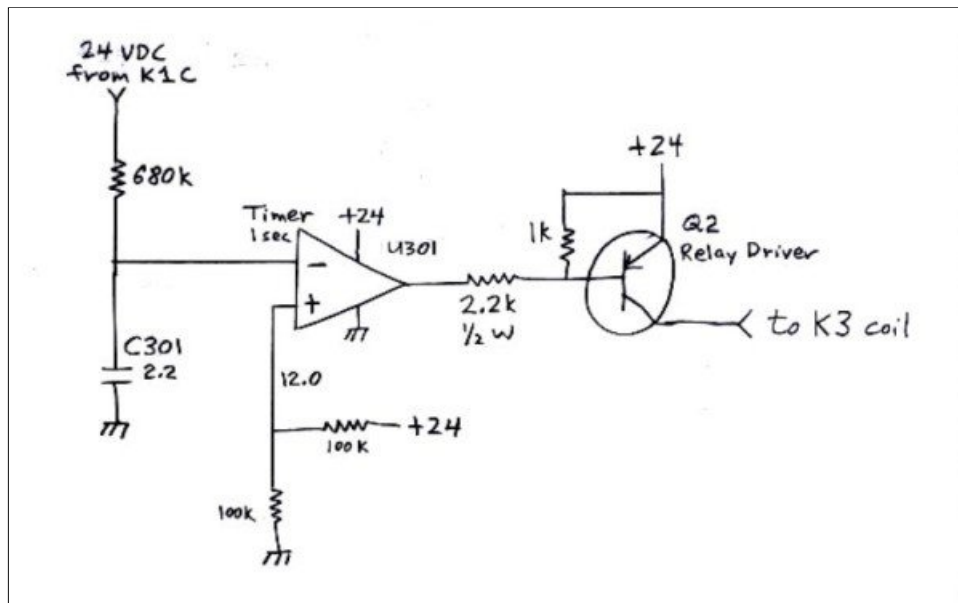
Step-start circuit

The step-start circuit usually seen can sometimes cause trouble; the problem is that the relay coil is part of the RC timing circuit. This means that as the capacitor charges it first reaches a point where the relay armature just begins to move slowly, and then finally the relay closes. Not a snap-action arrangement. This slow closing can cause contact burning and eventual failure, so that the step resistor stays in the circuit. The resistors usually used in a step-start circuit cannot

survive a continuous current.

I did have that problem with HVPS2. When I saw the voltmeter go up to the step level and stay there, refusing to climb to the full level, I went back to the power supply and took a look. The step resistors were glowing brightly; the white-hot windings of the resistors were shining through the ceramic and enamel coatings, revealing the separate turns of the resistance wire. Luckily, the resistors did not explode while I was staring at them, dumbstruck in amazement.

To avoid such troubles, the step-start circuit shown below uses an op amp timer; after a one second delay, full voltage is instantly applied to relay K3.



Step-start circuit. The snap-action of this op amp timer avoids the sluggish relay pull-in that occurs with the usual circuits.

C301. 2.2 μ F. Suggested: Metallized polyester film (polyethylene terephthalate), Mouser #581-BQ0540225K. A tantalum electrolytic capacitor may be substituted if pre-tested for low leakage.

U301. LM358. The other op amps on the control board use the 12 volt rail, so this one must be separately powered.

For details not shown, please refer to the *Simplified schematic note* on pages 10-11.

Metering circuits

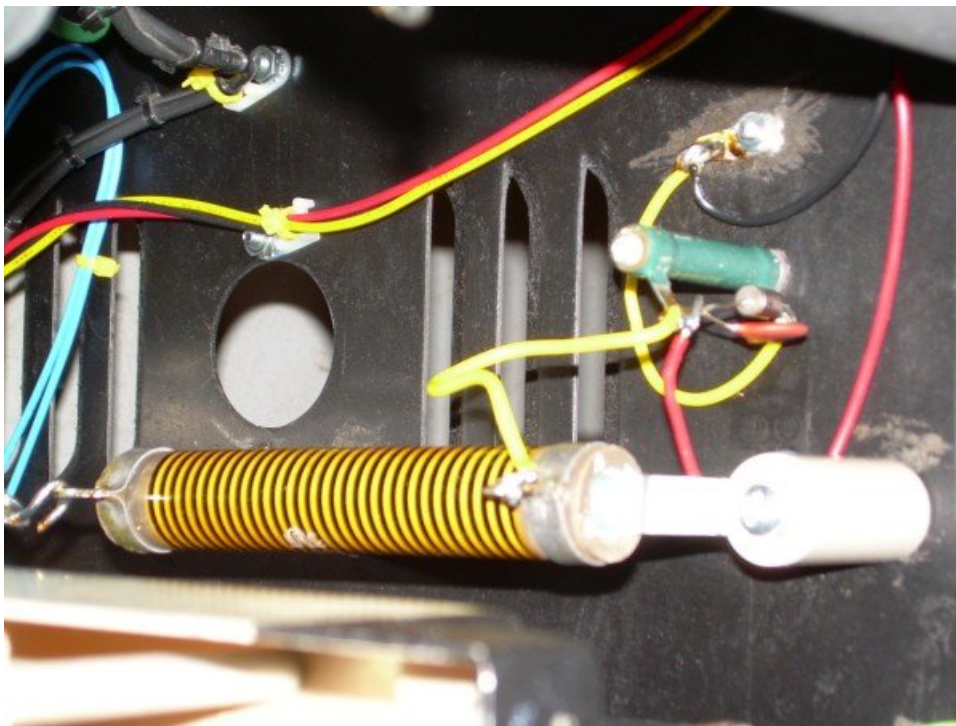
The metering circuits operate as follows: The high voltage and current levels are sensed in the usual way. Then the sense levels are sent to the control board, processed by the op amps, and converted to safe levels for driving the meters. The main feature of this method is the protection it provides; meter damage is virtually impossible. Given the difficulty in finding high quality meters at low prices, this is an essential feature. The op amps are powered from a 12 volt rail.

The meters in the remote heads have full-scale driving voltages of 5.0 or 7.5 volts. Thus the meters will never see more than a minimal overload, which will be survived. This op amp method also makes meter calibration easy.* Another advantage of this method is that several meters may be driven from the same op amp output, without interaction. Meters could be installed on the power supply panel, in addition to those in the remote head.

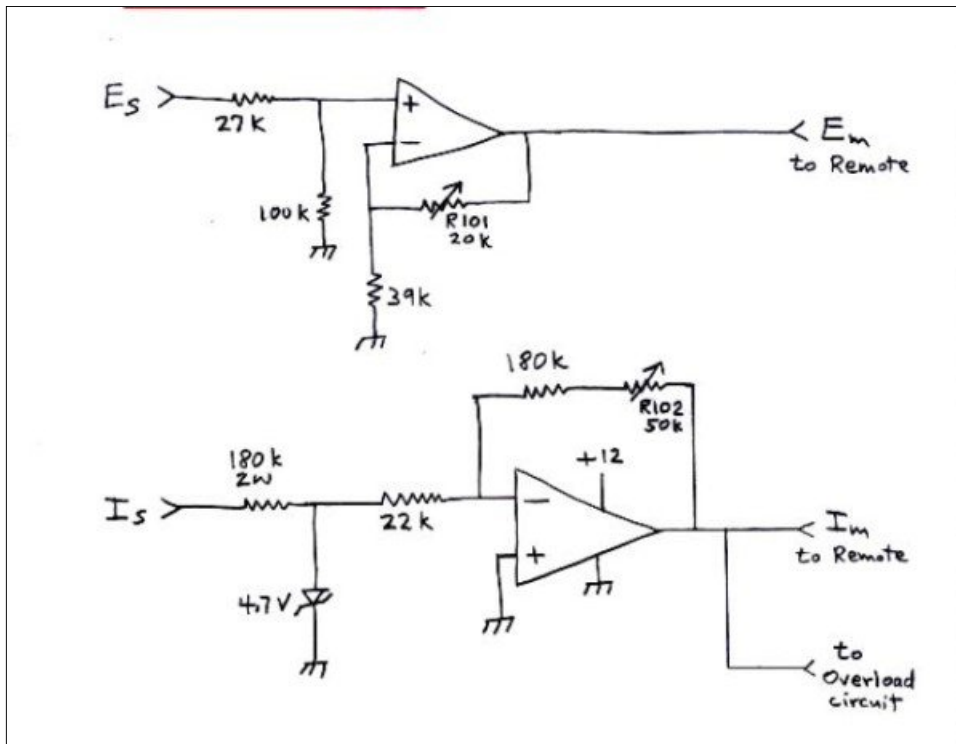
*Other applications of the op amp metering method, including expanded scale metering and differential metering, were used in my 2 meter amplifier; details will be found in **QEX**, May, 1996, 3-12, and November, 1996, 13-20.

Current sensing is accomplished by the usual shunt in the B-minus lead from the bridge rectifier. Here the shunt is 5 ohms. This provides a sense voltage of -5 volts for a maximum current of 1 amp.

For high voltage metering, the multiplier/divider shown below provides a high voltage sense level at a ratio of 1/1000; 5 volts for a full-scale meter reading of 5 kV. We calculate using this 5 volt full-scale level, even though the actual voltage normally used is only 3 kV.



High voltage multiplier components. The resistor with orange and black strips is the 10M multiplier. The green resistor is the lower 10k portion of the voltage divider.



Metering circuits. Even in the event of severe overload, the op amps will protect the meters from burn-out. The sense inputs are E_s from the high voltage multiplier, and I_s from the current shunt. The meter outputs are E_m and I_m .

R101, R102. Multiturn trim pots, Bourns type 260P, surplus.
Suggested: Bourns type 3006P, Mouser #652-3006P-1-203LF and #652-3006P-1-503LF.

For details not shown, please refer to the *Simplified schematic note* on pages 10-11.

Voltage metering. The two resistors, 10M and 10k, in the high voltage multiplier/divider circuit have 10% tolerances, so some range of adjustment in the op amp for voltage metering is needed. The two resistors at input E_s produce a step-down ratio of (approx) 0.8, and the op amp with trimmer provides a gain of 1 to 1.5. The resultant circuit gain is 0.8 to 1.2, a range of +/- 20%. The nominal setting for R101 is 10k.

Current metering. The current sense voltage I_s is negative; it is converted to a corresponding positive level by the op amp. Normally, a negative input cannot be applied to an op amp that has only a positive power rail; the op amp could be destroyed. This op amp, however, is configured in a *virtual ground* circuit. With the non-inverting input at ground, the feedback forces the inverting input also to 0 volts.

The required gain in the op amp for current metering is -1, so the nominal setting for R102 is 22k. With the 1% shunt specified in the high voltage circuit, adjustment here is hardly needed, but the trimmer is included in case a different shunt resistor is used.

The 180k resistor and 4.7 volt zener diode at the input I_S to the current metering op amp is for protection in the event of overload. With 3000 volts and the 50 ohm limiting resistor, a dead short would produce a momentary current of nearly 60 amps in the 5 ohm shunt, putting -300 volts at the sense terminal I_S . The zener will clamp this; the resistor is chosen to limit the current in the zener.

Overload circuit

Until recently, high voltage power supplies had never been a problem in my shack. Then one day I decided to try RTTY again after many decades. The FSK signals are 100% duty cycle, but HVPS1 was designed for only 50%. Thus HVPS2 was built, using a heavy-duty transformer. This also allowed the use of WSJT on the moon at full power. All was fine until a ceramic vacuum variable in the 2 meter EME amplifier melted-down, shorting out the high voltage, and knocking out HVPS2.

Forthwith, HVPS3 was built — with overload protection as the main goal. That was a good plan, because there was still more trouble in the 2 meter amp. The bypass capacitor shorted-out. Then the high voltage HN connector arced.* Soon after that, a glass vacuum capacitor melted-down and shorted-out. With each problem, the overload circuit tripped instantly, with no power supply damage. Using the high-pot** I was able to locate all the problems, rebuild the amplifier with wide-spaced air-dielectric capacitors, and get back on the moon. The hardest part was pulling the amp out of the rack and lugging it over to the workbench every day for new repairs and mods. Note for young homebrewers: try not to build your gear so heavy that you cannot lift it when you get old. (By the way, that 2 meter amplifier worked flawlessly on SSB meteor scatter and EME CW for ten years, before it was used for the 100% duty-cycle WSJT work. Well, live and learn!)

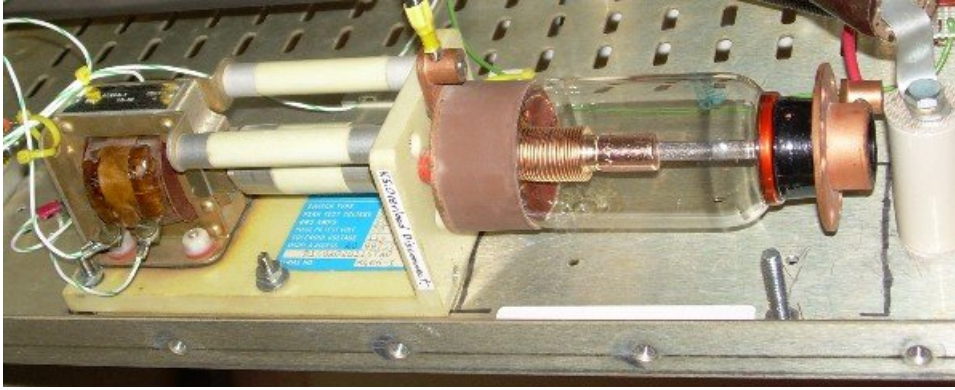
*That was a connector with a short glass insulator. The HN connectors with long teflon insulators are the best.

**"High-voltage breakdown tester", R. L. Measures, AG6K, QEX, August 1988, pp. 5-7. Update: www.somis.org/BVT.html. This tester is also useful for trouble-shooting high voltage power supplies.

Troubles like those mentioned above tend to arrive in droves, and then vanish. There has been no more arcing or tripping of the overload circuits for over a year, except for the occasional *Wrong antenna!* episode. Protection circuits are not intended for daily use; you just want to be sure they are in there when needed.

The value of high voltage overload protection was thus amply demonstrated. Encouraged by the good luck with HVPS3, I used the salvaged components from the blown-up HVPS2 (luckily, this included all the main expensive parts) to build HVPS4 and try a few circuit variations.

The main component needed for overload protection is a good high voltage relay. HVPS3 uses this vacuum relay:



Vacuum overload relay. This Jennings beauty, rated for 50 kilovolts at 50 amperes, was spotted at an Alamogordo hamfest by one happy flea-market hound. It sat on the shelf for 20 years, waiting for this project. The relay is 12 inches long overall. The solenoid is connected to the fat insulator under the two mounting pillars. The insulating material is all teflon. The sound of the solenoid is S9.

HVPS4 uses this open relay:



Open overload relay. The ceramic pillars are 3 inches high. The contacts are spaced 2 inches. The gray swinging bar is made of Micalox, a high voltage insulating material molded of mica and glass powder, noted for its machinability and mechanical strength. The sound of the solenoid is S9+.

Although these high voltage relays can often be found on the surplus market, locating one could be a problem. This is a good place for

homebrewing ingenuity; solenoids, ceramic insulators, and contacts from old relays are readily available. A homebrew relay need not be precision-built for the usual industrial relay lifetime of 1,000,000 operations, since we hope not to have that many short circuits. Since I did find two high voltage relays, I missed out on the fun of trying to fabricate one.

The main reason for tripping a relay in the high voltage line, rather than the contactor in the primary circuit, is that the contactor is not able to cleanly break the extremely high primary current in a high voltage arcing situation. Contactors may be severely damaged when attempting to break such heavy currents.

The reason for not relying on a circuit breaker instead of a high voltage overload relay is that breakers have no sharply defined trip levels. A typical breaker will trip in less than one second at five times rated current, but might take more than a minute to trip under a 110% overload. Breakers are essential for preventing damage to wiring and for fire protection, but they do not adequately protect the equipment. The circuit breaker mainly protects against defects in the primary circuit and transformer.

The overload circuit is constructed on the control board; it uses the current indicating output from the metering circuit, and compares this with two preset levels. There is a definite sequence to the overload trip operation:

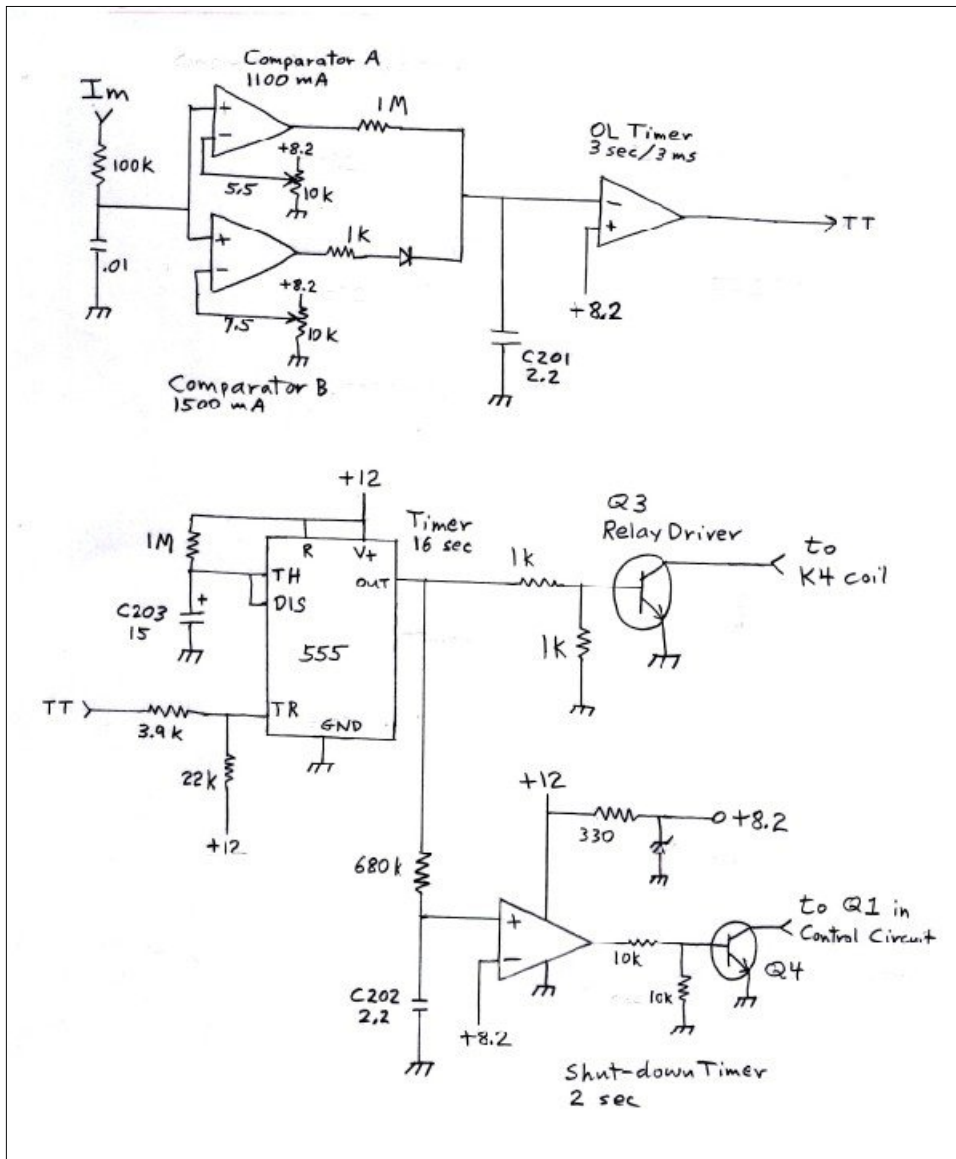
- At 1100 mA, the circuit begins a three-second timing interval, and then triggers into an overload condition. This delay allows for minor tuning adjustments and any possible spikes in the signals to the amplifier. This limit level will also provide some protection in the case of excessive thermal drift in a VHF amp, or operator errors such as *Wrong antenna!*, or *I forgot to tune the amp!* The amplifiers also have plate current overload circuits which operate under these conditions.
- At 1500 mA the overload condition is set instantly, independently of the 1100 mA timer. This is the protection for arcing or other faults in the amplifier or high voltage cables.
- The trip levels are set by trimpots on the control board, and may be varied as desired.
- When the overload condition is set, the overload relay disconnects the high voltage from the amplifier, and other timing circuits are activated automatically.
- First, a timer is set to hold the overload relay open for 16 seconds.
- Then, two seconds after the overload relay opens, the power supply is put into the OFF state, releasing the contactor in the primary circuit. Now the high voltage capacitor will begin to discharge through the bleeder.
- In the OFF state, 120 VAC is still available for the control circuits, the overload timer, and the overload relay. This is true even if the circuit breaker happens to trip.
- After the 14 second discharge interval, the overload relay is de-energized and the contacts will close again. By this time the capacitor will have discharged to a low level. Thus, even if there is a solid, persistent short in the amplifier, the closing current at

the overload relay contacts will be minimal.

- After this complete sequence, the operator may try to restart the power supply.

There is a terminal at the remote jack on the power supply panel to signal an overload condition to the remote unit, for another lamp or LED, but I don't use it. The overload relay is loud enough to indicate what is happening.

What happens to the tetrode amplifiers, with their delicate screen grids, when the high voltage is suddenly cut off? The amps have screen grid overload protection circuits, and also sensing circuits which put them in standby when high voltage is absent.



Overload circuit. When the circuit trips, Q3 activates the overload relay, and Q4 shuts down the power supply. The 555 timer holds the overload relay open long enough for the high voltage capacitor to discharge through the bleeder.

C201, C202. 2.2 μ F. Suggested: Metallized polyester film (polyethylene teraphthalate), Mouser #581-BQ054D0225K. Tantalum

electrolytic capacitors may be substituted if pre-tested for low leakage.

C203. 15 μF , tantalum electrolytic; pre-tested for low leakage.

R101, R102. Multiturn trimpots, Bourns type 260P, surplus.

Suggested: Bourns type 3006P, Mouser #652-3006P-1-103LF.

Timer, 555. Bypass the V_+ terminal with 0.22 μF monolithic ceramic and 2.2 μF tantalum electrolytic. Bypass the control voltage terminal with 0.01 μF disc.

For details not shown, please refer to the *Simplified schematic note* on pages 10-11.

Comparator A will trip the overload timer in 3 seconds; comparator B will trip it instantly. The signal diode at the output of comparator B prevents it from interfering with the timing initiated by comparator A. A current of 1 amp produces a 5 volt metering level at the terminal labeled I_m . This determines the 5.5 volt and 7.5 volt reference levels for the comparators, corresponding to the 1100 mA and 1500 mA trip points.

The overload timer triggers the 555, K4 closes, power is applied to the K5 coil, the high voltage contacts of K5 open, and the 16 second delay interval begins. At the same time, the 555 starts the shut-down timer. After 2 seconds, Q4 switches Q1 off, and K1 is released; this releases K2 and removes primary voltage from the high voltage transformer T2, shutting down the high voltage. After the 14 second discharge interval, the 555 times-out and the overload relay is released.

The 100k/.01 RC filter at the I_m input is intended to reject short power-line transients.

Some high voltage overload relays have 24 VDC coils; this would permit K4 to be deleted, and K5 could be driven directly by Q3.

Remote Heads

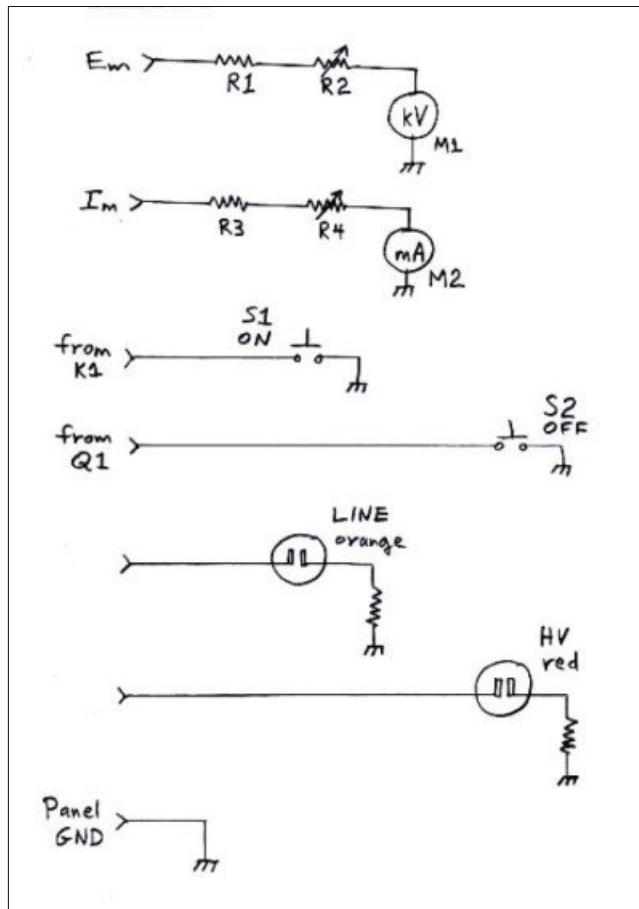
These power supplies are big and heavy, not the sort of things to put up on the operating bench next to the laptop. With the remote heads shown in the photos below, the power supplies can be put under or behind the bench. The remote units are quite simple; two meters, two momentary push-button switches for ON/OFF, and two neon lamps to indicate LINE voltage available and HV enabled. Neon lamps almost never burn out, and shine nicely when installed with fluted lenses.



Remote head for HVPS3



Remote head for HVPS4



Remote head circuit. The meters have no direct connection to the high voltage circuits; the lines E_m and I_m are driven by op amps at nominal 5 volt levels, corresponding to 5 kV and 1 A.

Components for HVPS4 remote unit:

M1. Simpson type 1227, 0-1 mA. Originally 5 ADC, shunt removed, label changed to kV.

M2. Simpson type 1227, 0-1 mA. Originally 30 VDC, multiplier removed, label changed to mA, scale numbering changed to 0-1500.

R1, R2. For a 5 kV full-scale reading with the 1 mA meter movement, the nominal total value is 5k; suggested values are 2.2k fixed and 5k trimpot. Other values will be used for a different full-scale reading or for a meter with a different range; meters up to 10 mA may be used.

R3, R4. For a 1500 mA full-scale reading, the nominal total value is 7.5k; suggested values are 4.7k fixed and 5k trimpot.

Neon lamps. NE51; the resistors are 180k, 2 watt.

Neon lamp holders. Surplus.

S1, S2. Momentary push-button switches. Switchcraft, surplus. Suggested: Mouser #612-PS1024AL-RED and #612-PS1024AL-BLK.

Multiturn trimpots. Suggested: Bourns type 3006P, Mouser #652-3006P-1-502LF.

For details not shown, please refer to the *Simplified schematic note* on pages 10-11.

The remote head is adjusted at the test bench, using no other portions of the power supply. Apply 5 VDC to each meter line and adjust for the proper reading. The control board will be adjusted for metering outputs E_m and I_m of 5 VDC to indicate 5 kV and 1000 mA.

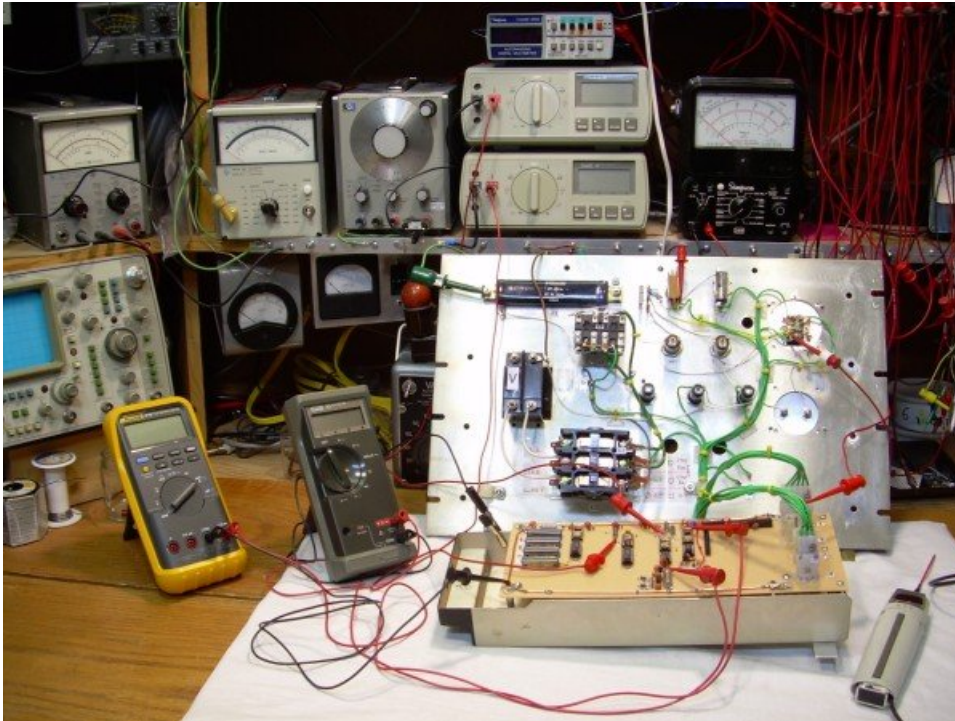
The meter multipliers in the remotes are formed in two parts, in order to protect the meters from severe maladjustment.

Any length cable may be used to connect the remote head to the power supply. With the #24 wire in the shielded cable used here, a rough calculation shows that wire resistance is negligible for cables under 500 feet.

Test and adjustment

Testing is best done circuit-by-circuit as construction proceeds. The more preliminary testing, the better the chances for final success.

Modular construction allows the panel and control circuits to be checked-out before installation in the main cabinet. This allows convenient adjustment at the test bench, and permits tests and repairs to be conducted with no high voltage present.



Test bench. This photo shows the panel and control chassis connected for test and adjustment. On the bench are six digital meters — which meter is used the most? None of the above! It is the trusty old Simpson 260 that is the favorite.

The white cloth with soft carpeting underneath helps keep things in place, is comfortable to work on, and makes it easy to find #2 lock washers and MMICs. The Variac (with switch) behind the panel is used for all bench testing. The two meters to the left of the red warning lamp read line volts and amps; the ammeter enclosure includes a fast-acting circuit breaker.

Now the metering circuits are given a second adjustment. (The first

adjustment was setting the trimpot resistances with an ohmmeter before installation, according to calculations.) The second adjustment (and first test) is made on the test bench by applying simulated sense voltages E_S and I_S of +5 V and -5 V, and adjusting for +5 V at each of the metering outputs E_M and I_M .

The third adjustments are made after the panel and control chassis are installed in the cabinet, but before the primary cable between contactor K2 and high voltage transformer T2 is attached. Only the 120 VAC line cord is plugged-in, not the 240 VAC cord; no high voltage will result. For the third voltmeter adjustment, a relatively low voltage from the test bench is carefully applied to the HV capacitor, and the E trimpot is adjusted for a DMM reading at E_M of 1/1000-th of the applied voltage. The op amps are linear, so full voltage is not required for adjustment; I use 400 V from an old Heathkit test power supply. The capacitor is then allowed to discharge while monitoring the voltage, and a temporary ground strap is applied to the high voltage capacitor; see section *Safety*.

The third milliammeter adjustment is also made with no high voltage present; a negative test current from the test bench is applied to the shunt. I used 250 mA and verified the calibration at 800 mA; these are the idle and peak currents for my 4CX1000A amplifiers.

Next is the setting of the overload limit points. The 1100 mA and 1500 mA thresholds are represented by 5.5 and 7.5 volts at the meter point I_M . Adjust the trimpots for these reference voltages at the corresponding op-amp (or trimpot) terminals. Then apply a gradually increasing voltage at the point I_M . Check to see that the circuit trips at the proper levels. Check the timing by monitoring the various outputs; I use a 50-year-old antique stopwatch, but that's only for fun — the timing is not at all critical.



Control board trimpots. The four trimpots are conveniently located at the top of the control board; they calibrate the meter circuits and set the overload trip points.

Construction

Procedure. The power supplies were built while keeping in mind these two homebrewing rules:

1. Build it so that it will never need repairs.
2. Build it so that it will be easy to service when it does need repairs.

Try as I may, in over 60 years of homebrewing I have never fully achieved these goals, but any special effort expended in the attempt has always been worthwhile. Rule number 2 implies that the enclosure be large enough to avoid crowding, and to allow space for additions and modifications. For nearly every piece of gear in the shack, I have often wished that I had used an enclosure twice as big. Miniaturization can be the basis for an interesting avocation, but is not always the best method for an ordinary ham shack. Even with the large enclosures for these power supplies, it is surprising how soon you can run out of space when trying to keep everything at least one inch away from the high voltage.

Ample enclosure space is especially important when, as is often the case, a project is mainly a learning experience — trying new circuits and understanding their operation. When a project does not work right off the bat, and circuit changes are needed, that can be a valuable experience from a learning point of view. Later modifications need not imply defects in an original design, but merely new ideas, newly available components, or new requirements.

Component selection. As for the first rule, one has to balance the ham radio traditions of low-budget projects, surplus sources, flea markets, and used components, with the goal of highest reliability. Posted above the workbench is a reminder from the early, classic days of ham radio, a large copy of the following proclamation found in an old transmitter service manual:

This radio equipment has been constructed of materials considered to be the best obtainable for the purpose.
— Collins Radio Company

This does not always mean buying a new component; I would rather use an old, rusty, hermetically-sealed, mil-spec, WW2-surplus transformer, than a shiny new import built to questionable standards. On the other hand, bitter experience has taught me the folly of using old electrolytics, or any second-rate components. Project work usually

proceeds so slowly that the *per diem* cost is quite low, making ham radio homebrewing a relatively inexpensive hobby. Considering the work expended in homebrewing, using high quality components is economical in the long run. Bargains, of course, can be great fun; all the Simpson meters in the photos here, and all the meters in the homebrew station, were found at flea-markets.

Project scheduling. Time should never be a factor. Weekend projects are fun, but a major project could take a year. My homebrew transceiver took three years to design and build. No amount of time taken in diligent care and effort is wasted. It takes only one bad connection to ruin an all-out contest effort, or spoil an attempt to work a new DXpedition.

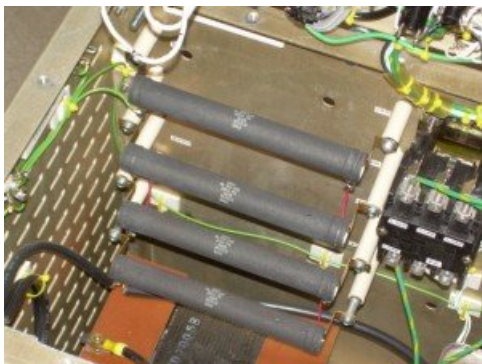
Wires. Some of the wires used for high voltage are rated at 15,000 volts, intended for neon signs; others are rated at 25,000 volts, intended for CRT anode connections. Some crimp connectors are used, since the insulation crimps can provide good strain relief, but each crimp connector in the power supply is soldered after crimping.

Connectors. Molex, .093 inch. Mouser #538-03-09-2057 and similar types listed on the Mouser online catalog page. Suggested for the control board: snap-in types, mounted on an aluminum plate.

High voltage cable. For connection between the power supply and amplifier; type RG-214 coax jumper cable with HN connectors. The double shield of the coax keeps the high voltage safely inside the cable. Insulation failure may result in a short, but would not cause exposed high voltage. The uniqueness of the connector prevents dangerous mix-up; it will not fit the UHF or N connector on the amplifier. These cables, factory-assembled, are often seen on the surplus market.

Insulation. The large resistors in the high voltage circuit are mounted on 2 inch ceramic insulators. Screws of minimal length are used, so as not to create a short internal path.

Cooling. The exhaust fans are small 120 volt types, from surplus dealers. The fan in HVPS4 is at the top of the cabinet rear wall, near the bleeder resistors. In HVPS3, the four bleeder resistors are mounted one above the other, offset horizontally 1/2 inch from one another with insulators of increasing length, as seen below; this permits good air circulation.



Four-part bleeder in HVPS3.

The exhaust fan is on the panel, directly above the resistors.

Safety

More important than DXing, contesting, or ragchewing is the need for safety in the hamshack. This is especially true for the high voltage power supply. Among the factors to keep in mind are the following:

- Limited access to the hamshack.
- Secure covers and fittings for all gear.
- Effective grounding of all items to a common ground bus.
- Proper procedures for working on high voltage equipment.
- High quality shorting stick, called a *crowbar*.
- High voltage alertness.

Grounding

The power supply is fitted with a heavy 1/4 inch ground post at the rear of the cabinet; a heavy lead runs from the post to the station ground bus. The station ground bus is tied securely to ground rods and to the power line ground at the service entrance. Do not rely on the ground wire in the line cord.

Procedure

One often sees the warning "Switch to Safety". This is good advice, but it may not be sufficient. I am only content when the plug is pulled. Here is a procedure for high voltage work:

- Check the ground lead running from the ground post at the rear of the power supply to the test bench ground bus.
- Check the heavy lead running from the test bench ground bus to the station ground bus.
- Do not rely on the ground lead in the line cord, since you are going to pull the plug.
- Turn off the power supply while watching the voltmeter, carefully observing the capacitor discharge to zero. Then immediately ...
- PULL THE PLUG ON THE LINE CORD AT THE OUTLET.
- Inspect the shorting stick for defects.
- Keep one hand behind the back.
- Clip the ground lead of the shorting stick to a convenient ground post (installed when the power supply is built).
- Touch all high voltage points with the shorting stick.

- Touch both capacitor terminals simultaneously with the hook on the shorting stick; this will cover a possible open shunt situation.
- Hook the shorting stick into a wire loop on the positive capacitor terminal (installed when the power supply is built).
- Connect a shorting jumper to the capacitor terminals. Use a 12 inch (30 cm) jumper made with heavy braid, two copper clips, and no hidden connections. Connect the ground end first.
- Disconnect the transformer primary leads from the contactor.
- Proceed with tests and repairs.

Situations will vary, and the procedure will be adapted accordingly. To me, the *most crucial steps* are watching the voltmeter — this confirms the condition of the bleeder — and pulling the plug. HVPS1, built in 1961, goes so far as to have a circuit which senses bleeder current and lights an indicator light on the remote panel to confirm proper bleeder operation.

Some builders use a shorting stick with a resistor to discharge capacitors. This can sometimes be a good idea, but with the *watch the voltmeter to monitor the capacitor discharge* method, the resistor is not necessary; the shorting stick is more reliable without it.

Since full metering is included in the remote head, no testing with probes or test leads is required with full power applied.

Crowbars

Shorting sticks are called *crowbars*, perhaps in reference to actual crowbars formerly used at high power broadcast stations. A crucial factor is the quality of the crowbar.



Crowbars. The crowbar on the left was put together in 1961. An 18-inch (45 cm) wooden handle from an auto windshield ice scraper, a length of silver-plated 5/32 inch (4 mm) hard copper wire formed into a hook, 2 feet (60 cm) of tinned copper braid, an aluminum strap formed into a clamp, a bolt and nut, and a solid copper clip.* Easy! The braid is soldered to the clip and to the hook. No screws, no lugs, no crimping, nothing in the ground circuit to come loose.

The beautiful crowbar on the right arrived recently with a load of surplus gear. It has a lovely handle, the hook is nicely threaded into the handle and secured with a nut, there is a lug and nut for the wire, and the lug was crimped onto the wire. I used it a few times, but then the wire broke off, hanging only by the crimped insulation. The break was hidden inside the connector. How safe is that? I went back to using my ugly old homebrew crowbar, with all connections visible.

*Suggested: Mueller #BU-85C, Mouser #548-85C.

High voltage alertness

Fatigue can be a mortal enemy if allowed to infiltrate the workshop. Don't do high voltage work when you are too tired to think clearly!

There is also another alertness issue: Does one glass of beer at dinner rule out evening work in my shop? No, but it does limit the work to equipment that runs on no more than 13.6 volts.

Conclusion

Although it is one of the more low-tech components of a modern high-power ham station, the high voltage power supply can still cause serious trouble if the design is not given careful attention. The supplies described here include the essential features of overload protection, meter protection, and remote control. The circuits work smoothly and have been tested in service for several years. These methods can be used for any power supply; they will help to provide safe and trouble-free high voltage in the hamshack.

About the author

Mark Mandelkern, K5AM, was first licensed as W9ECV in 1948. His homebrew station in New Mexico is described at www.zianet.com/k5am/.

Mark's main ham operating activity is 6 meter DX, with 137 countries confirmed. He also enjoys HF DXing and contesting, with DXCC confirmed on ten bands and a number of top-ten contest awards.

Mandelkern is emeritus professor of mathematics at New Mexico State University.



K5AM home page: www.zianet.com/k5am