A Deluxe High Voltage Power Supply
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A half-century ago Larry Kleber K9LKA published one of the most popular construction articles in the history of amateur radio. Appearing first in November 1961 QST and subsequently in eight additions of the ARRL Handbook, plus other ARRL publications, the article featured single-band kilowatt amplifiers that shared a common high voltage power supply. Despite the obvious financial benefits of sharing a power supply – typically the most costly part of a high power linear amplifier – this practice has seldom been imitated, even though amplifier building continues to be extremely popular among "homebrew" devotees.

Sharing a high voltage power supply is harder than it might seem. In K9LKA's original design, 2000V was simultaneously applied to all connected amplifiers, with the filament and screen voltage (the amplifiers used 813 tetrodes with "instant-on" filaments) switched only to the selected amplifier. Today this practice would not only be considered unsafe, but technical advances in amplifier design now necessitate a more sophisticated approach requiring flashover protection, avoidance of metering interaction problems, and so forth.

Despite the obvious convenience of relegating a heavy high voltage power supply to an inconspicuous spot behind an operating desk, this practice has lost favor among commercial linear amplifier manufacturers. Once a staple of commercial designs, as in the venerable R.L. Drake linear amplifiers of the 1970s and 80s, external HV power supplies significantly increase manufacturing costs, in large part because of safety and liability concerns. Safely routing several thousand volts through the rat's nest of cables behind the typical operating desk is a serious and expensive enterprise, and manufacturers are no longer willing to assume the risk of using a single unshielded wire to do the job. (Although used in many commercial designs several decades ago, no manufacturer would today consider using the classic J.W. Millen HV connector, which has no strain relief and uses an unshielded conductor held in place by a single blob of solder.)

Figure 1: The high voltage power supplies, identical except for different voltage ranges, rest on the floor behind an operating table and independently power up to three legal-limit RF power amplifiers.

The high voltage power supplies described here (two power supplies were built, identical except for different output voltages) are intended to overcome these concerns, in effect bringing the benefits, convenience and economy of the fifty-year-old design pioneered by K9LKA into the twenty-first century. The results, shown in Figure 1, are contest-grade power supplies rated for legal limit continuous-duty service in any mode, with substantial "headroom." They sit on the floor behind an operating table, each allowing independent control of one, two, or three remotely located RF decks. For example, one RF deck could be dedicated to 160 meters and another to 6 meters, both popular bands that vintage commercial amplifers seldom cover. High power monoband amplifiers are relatively easy to build and design, with none of the tradeoffs and expenses necessitated by multiband designs. (A ceramic multideck high-power bandswitch, purchased new, can cost more than $500!)

For these power supplies, internal logic circuits handle all the switching and control functions for each RF deck, with vacuum relays designed specifically for DC voltages safely routing high voltage only to the selected amplifier. (Each power supply is intended for single-operator use, in which only one RF deck is on-line at a time.) Simplicity of operation was an important design goal. Thus operation of a power supply requires only two momentary-action pushbutton switches on each RF deck, one that toggles on and off the low voltage circuits (blowers, filaments, etc.) and a second that toggles the RF deck on-line or off-line. The low voltage circuits for each RF deck may be turned on simultaneously, but an interlock circuit permits only one amplifier at a time to be on-line. A power failure resets all the control circuitry to an off state, so that the supply must be manually powered up after the power is restored.

Features

The power supply is remotely operated by each connected RF deck via a 10-conductor shielded cable. The cable provides switched 120 VAC for powering filaments, blowers, and low-voltage circuits, as well as various other connections for power and on-line switching, high voltage metering, plate current trip and reset circuits, indicator lamps, and so forth. The high voltage connection to each RF deck is made through a shielded length of RG6/U coaxial cable, using special high voltage BNC connectors rated at 5000 working volts. For safety purposes, the connectors are designed with reverse polarity pins (i.e., the male pin is in the jack, rather than the plug), with recessed contacts ensuring that the grounded shield is always connected before the center conductor makes or breaks contact. Other than the 240 VAC circuit breakers and a safety "HV Enable" key-operated switch that must be closed to allow the HV circuits to operate, the power supply has no controls or switches.

Three Gigavac G81B vacuum relays (www.gigavac.com) rated for hot-switching DC loads (5A@9KV) transfer the high voltage to the selected RF deck only when that deck is switched on-line. An internal power relay selects primary taps on the plate transformer so that different plate voltages can be automatically assigned to a selected RF deck. Thus, in this power supply, one configuration supplies 4500 VDC to two amplifier ports (intended for RF decks using an 8877 or 3CPX1500a7 triode), and 3700 VDC is assigned to the third port for an amplifier that uses 3CPX800a7 triodes. The second power supply, identical to the first except for the plate transformer and filter capacitor, is designed for lower voltage tubes running 2500-3000 VDC, such as the 3-500Z and the GU-74B.

Circuit Description

A. Chassis Components

As shown in the block diagram of Figure 2, the large chassis components of the power supply (plate transformer, rectifiers, filter capacitor) are interfaced via three connectors to the control logic circuits contained on a single 6.0 in. x 7.5 in. double-sided printed circuit board. Connector pair P100/J200 carries the high voltage from the chassis-mounted components to three HV distribution relays mounted on the controller circuit board.

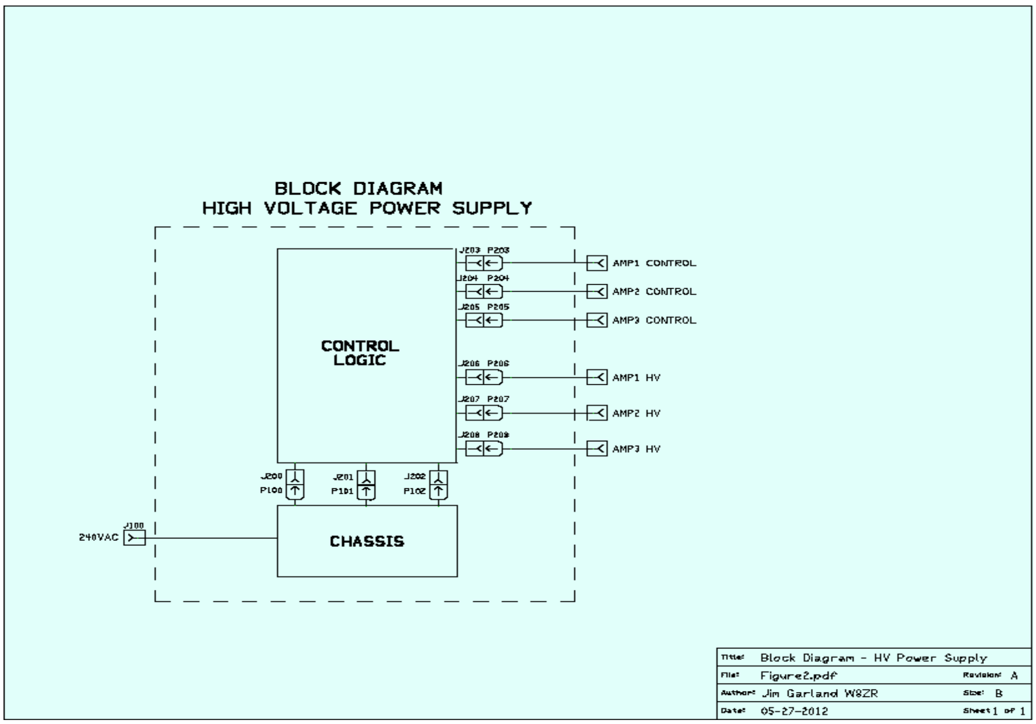

Figure 2: The heart of the power supply is a control logic circuit that arbitrates among three connected RF decks, allowing fully automatic operation.

The interconnecting cable uses 10 KV silicone-insulated test probe wire. Connector pair P101/J201 uses a 12-conductor cable and is used for all the control functions, while P102/J202 interfaces to the eight front panel LED indicators. Additional connector pairs P203/J203 through P208/J208 transfer the control lines and high voltage from the printed circuit board to the front panel control and HV connectors.

Figure 3 is a schematic diagram of the main power supply components. As shown in the diagram, each side of the 240 VAC line is routed through ganged 25A circuit breakers CB100/CB101 to solid state relays K100/K101. When the circuit breakers are closed, 12 VAC is applied by T102 to the control board, whose on-board regulator provides 12 VDC to operate the relays and logic circuits. The “HV Enable” key switch S1 disables the AC relays for servicing or testing purposes, but leaves alive all the other control functions. All 120 VAC components used in the power supply (muffin fan, digital panel meter) and RF decks (blowers, filaments, low voltage power supplies) use either L1 or L2 from the 240 VAC line and the N ("neutral") line.

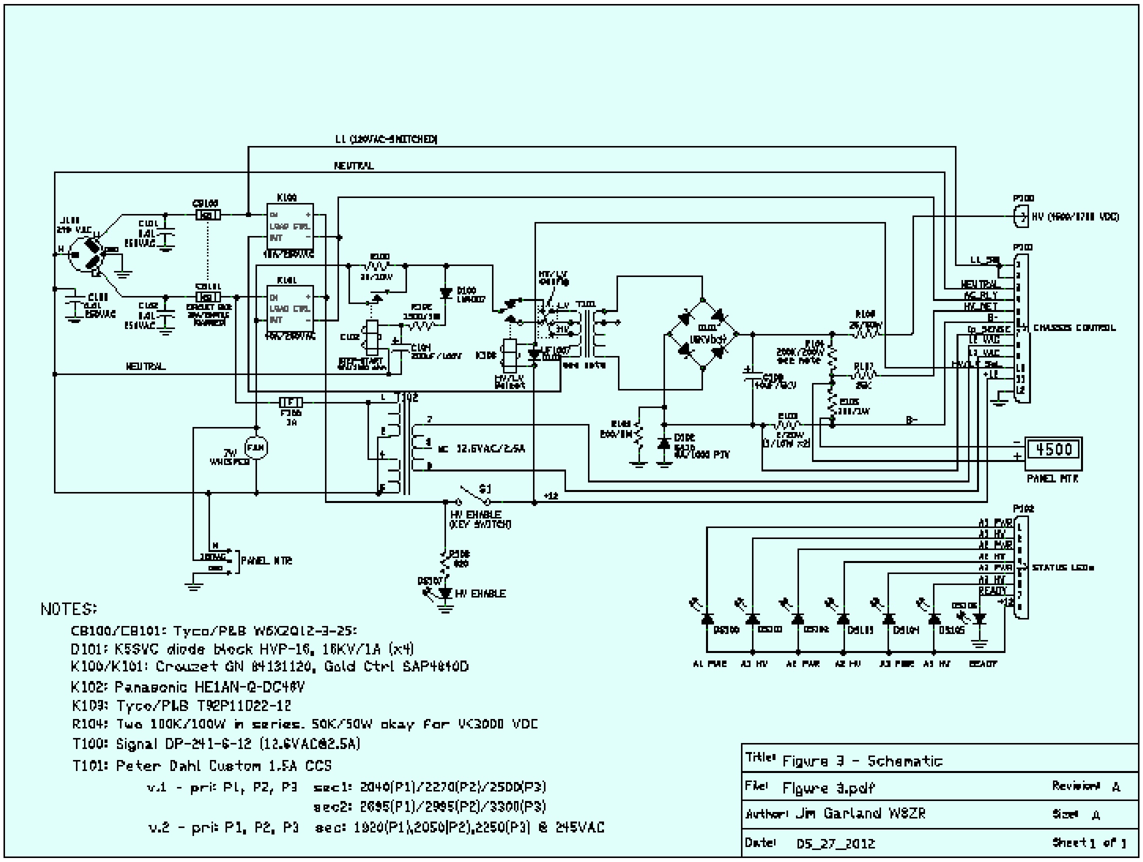

Figure 3: Schematic diagram of the high voltage circuits.The power supply uses a capacitor input filter with a large oil-filled capacitor filtering the rectified output from the full-wave bridge rectifier. An "HV Enable" key-operated safety switch disables the plate transformer by deactivating the solid state power relays.

Note that it is poor design practice to ground the neutral line to the chassis, since doing so results in unpredictable and potentially dangerous paths for the power line return currents. Modern building codes often mandate a four-wire 240 VAC power cord with an integral ground wire, e.g., for electric dryers, but if your home has the older three-wire (L1, L2, N) configuration, then a separate station ground wire should be connected to the power supply chassis. A threaded 10-32 ground lug is provided on the front panel below the power cord for this purpose. (Note that outside the U.S., many countries with 250 VAC service do not use a neutral line. Builders from those countries must either use 250 VAC fans, filament transformers, etc., or else derive a "virtual" neutral from a center tap on the primary winding of the plate transformer.)

K102, R100, R102, C104 and D100 comprise a step-start circuit which limits the surge current at power-up to 10A until filter capacitor C106 is partially charged. The intrinsic time constant of this circuit is about 0.3 sec, but because D100 picks off its voltage at the downstream side of R100 the actual time delay is closer to 0.8 sec. The plate transformer T101 is custom designed for the power supplies by the P.W. Dahl company (www.harbachelectronics.com) and is a versatile 67 lb (5 KVA) hypersil-wound transformer with three primary taps and two secondary taps. By mixing and matching taps, the higher voltage transformer can provide six RMS voltages ranging from 2000 VAC to 3300 VAC (1920 VAC to 2250 VAC for the lower voltage transformer), each at 1.5A CCS. Relay K103 allows each power supply to select two of these voltages. Four diode blocks, each rated at 1.5A/15kV comprise a bridge rectifier that rectifies the output from the transformer secondary. The rectified DC is filtered by a large 40 μF/5000V oil-filled capacitor, C106 (50 μF/4200V in the lower voltage power supply), which the author had on hand. Bleeder resistor R104 is made up of two 100 KΩ/100W power resistors in series and dissipates about 100W. D102 provides flashover protection to the metering circuits by clamping the B- return current to within 1V of ground in the event of an arc to ground somewhere in the power supply or RF deck, while R109 anchors the B- return to ground in the unlikely event it should become disconnected from its RF deck. R103 is used to sense the power supply current and is connected to an optically isolated overcurrent trip circuit on the control and logic circuit board.

B. Control and Logic Circuits

The functions of the HV power supply control and logic circuitry are:

(1) to allow each amplifier to be independently powered on or off. When an amplifier is turned off, all power to it is removed, including all high voltage, low voltage and control circuits.

(2) to interlock each amplifier, so that only one amplifier can be placed on-line at a time. When an amplifer is brought on-line, any previously selected amplifier is taken off-line, but remains in a standby state. High voltage is applied to an amplifier only when it is on-line.

(3) to implement metering and control functions for each amplifier that are independent of one another. From the perspective of the operator, the shared power supply is essentially invisible.

(4) to control flashover surges, in order to prevent damage to the connected amplifiers.

(5) to enable simple hookup of the connected amplifers. Each amplifier plugs into the power supply with a single control cable and a single HV cable. Any amplifier can be disconnected (unplugged) from the power supply, without affecting the operation of the remaining amplifiers. The AC power and on-line switches of each amplifier are simple momentary action SPST pusbutton switches on the front panel of each amplifier.

(6) to switch automatically primary taps on the HV power transformer, to allow the connected amplifiers to use different plate voltages.

(7) to facilitate easy construction of the HV power supply by mounting all logic, control, and switching circuitry on a single printed circuit board. Thus the construction of the power supply is only moderately more complicated than construction of an ordinary single-amplifier power supply. This means that an amplifier builder can incorporate multiple amplifier capability into a newly built power supply at reasonable effort and cost in order to allow for future needs.

Referring to the circuit diagrams of Figures 4a and 4b (shown at end of article), the three RF amplifier decks are actuated by two momentary action pushbutton switches for each amplifier: one controls AC power (blower, filaments, LV supply) and one controls HV and enables the amplifier to be brought on-line. The buttons are debounced by U201, with C200 setting the maximum debounce time (50 mSec) before the button states stabilize. R200-R205 hold each button line high. These resistors are in parallel with 500K resistors internal to U201 and result in about 2mA of current through each button when it is pressed. Grounding the button line activates the control circuitry.

The active-low button states are inverted by hex inverters U202, and the three AC power buttons are applied to the clock inputs of D flip-flops U204a, U204b, and U205a. Each flip-flop is configured so that it toggles its output states Q and Q' each time its button is pressed. A positive pulse is generated by R206 and C202 at power-on and is applied to the reset line of the three flip-flops, ensuring that they power up with Q=0 and Q'=1. The voltage pulse reaches a maximum of about 10V about 200 msec after power is applied, ensuring a reset after the remainder of the circuitry has had time to wake up. The high state Q'=1 of each flip-flop is passed at power-up via OR gates U203a, U203b and U203c to the reset inputs of U205b, U206a and U206b, thus ensuring that the HV logic is also powered up in a Q=0 state.

The outputs of the six flip-flops have several functions. The Q outputs of U204a, U204b, and U205a are combined by OR-gate U207, whose output actuates the power supply's main power relays. The outputs of all six flip-flops are also applied, via 3-input AND gates U208a, U208b, and U208c, to the 8-port relay driver U209. Each port is grounded when active and can sink a maximum of 500 mA. The purpose of the AND gates is to interlock the power and HV buttons to prevent improper operation. One input of U208a, U208b and U208c is grounded when the overcurrent relay K200 is tripped and shuts off the HV supply of any on-line amplifier. A second input ensures that the HV for any amplifer cannot be turned on unless the AC power to the amplifier has previously been turned on. The third input routes the selected amplifier to the appropriate HV relay driver port.

The HV button flip-flops U205b, U206a and U206b operate in the same manner as the the AC power button flip-flops, except that each HV flip-flop is interlocked to the other two HV flip-flops via the 3-input OR gates U203a, U203b, and U203c. As mentioned previously, one input to each OR gate is used to reset the flip-flops on power-up. A second input resets each HV flip-flip whenever its corresponding AC power relay is turned off. Resetting the flip-flip in this way thus keeps the HV from inadvertently turning on if the AC power relay is subsequently energized after being turned off. In other words, the only way to turn on the HV for a particular amplifier is to actuate its HV button.

The third input of the OR gates turns off the HV of any selected amplifier whenever the HV button for another amplifier is pressed. Thus, only the most recently selected amplifier is ever on-line. This function is implemented by means of a pulse caused the positive edge of the HV flip-flop's Q output transition, in conjunction with the RC differentiator connected to the Q output. This pulse is used to reset (turn off) any previously selected HV flip-flops. Diodes D205, D206, and D207 protect the input of the OR gates by clamping to ground the negative pulse caused by a negative-going transition of the flip-flop. If desired, the user can replace capacitors C211, C212, and C213 with wire jumpers. Doing so would then disable the automatic switch-off function and require the HV of a selected amplifier to be manually switched off before the HV of any other amplifier could be selected.

The overcurrent protection circuit monitors the voltage developed across a 2 ohm resistor in series with the B- return of the HV power supply (shown in Figure 2). When this voltage indicates excessive current, the optoisolater turns on Q200, latching K200 in a closed position. R212 sets the current trip threshold, and diodes D201-D204 protect the peripheral circuitry from the momentary current surge caused by flashover in the HV supply.

Mechanical and Assembly Details

Figures 5 and 6 show interior views of the power supply. As shown in Figure 6, the front panel removes and tilts out of the way to enable easy access to components, should servicing ever be required. The power supply enclosure measures 12"W x 10"H x 21.5"D (the second power supply is only 20"D) and is fabricated around a frame made from 1/2 inch square aluminum stock. Figure 7 shows the frame detail at the corners. The bottom plate is made from 3/16" aluminum plate, while the front, rear, and top panels are fabricated from 1/8" aluminum plate. The side panels are 1/16" aluminum. An aluminum subpanel (Figures 8 and 9) divides the power supply into two compartments. The front compartment houses the control logic and switching circuitry, with the printed circuit board (Figure 10), step-start components, and 12.6 VAC low voltage transformer mounted on the front side of the subpanel.

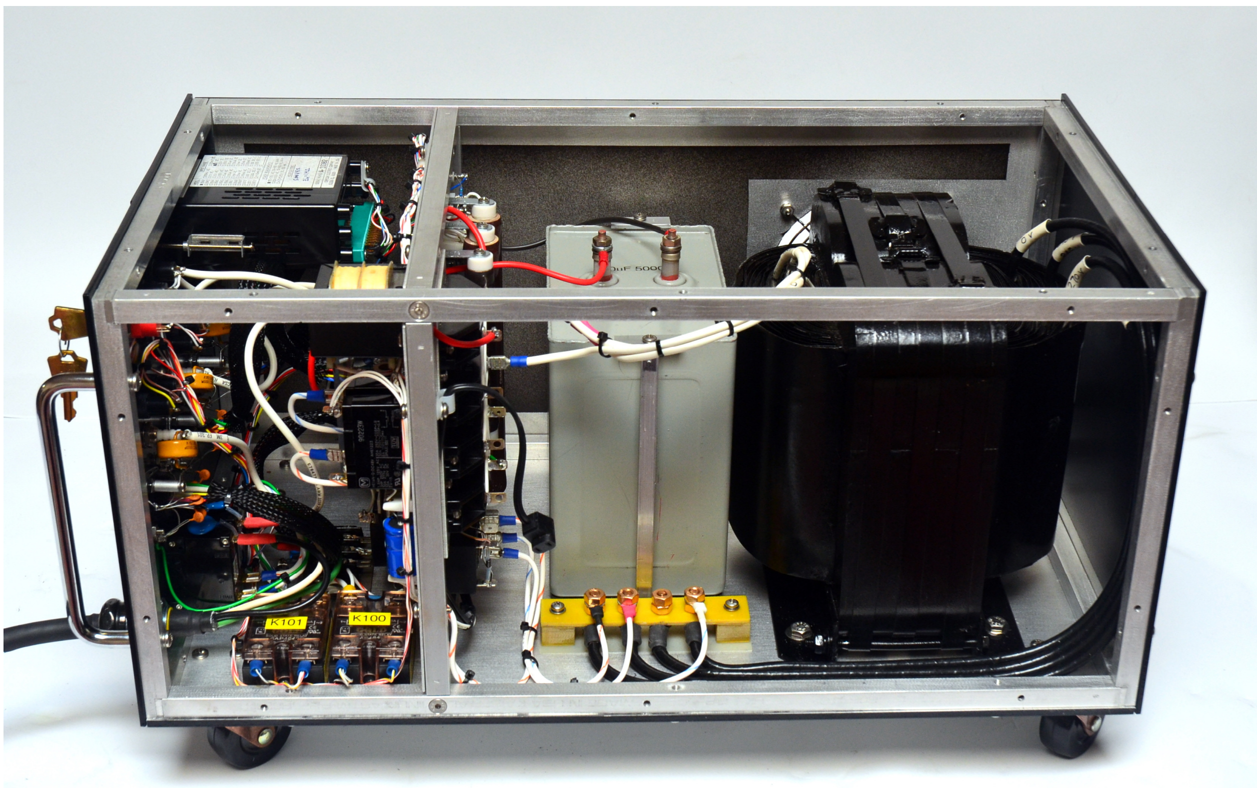

Figure 5: The 67 lb plate transformer, filter capacitor and bleeder resistors mount behind a subpanel that isolates the high voltage components from the control circuitry.

The printed circuit board was designed using Circad 98, a commercial schematic capture and PCB layout package (www.holophase.com) that the author has used for many projects. "Gerber" files for the completed layout were then uploaded to Advanced Circuits (www.4pcb.com), which manufactures high quality printed circuit boards in small quantities at very reasonable cost. Figure 11 shows a breadboard lashup used to debug the logic circuitry before committing the design to a printed circuit board. The small plastic enclosure with the LEDs and momentary-action lever switches simulate three remote RF decks. Interested readers can view a short video demonstration of the breadboard logic circuitry at www.youtube.com/w8zr/HVPS.

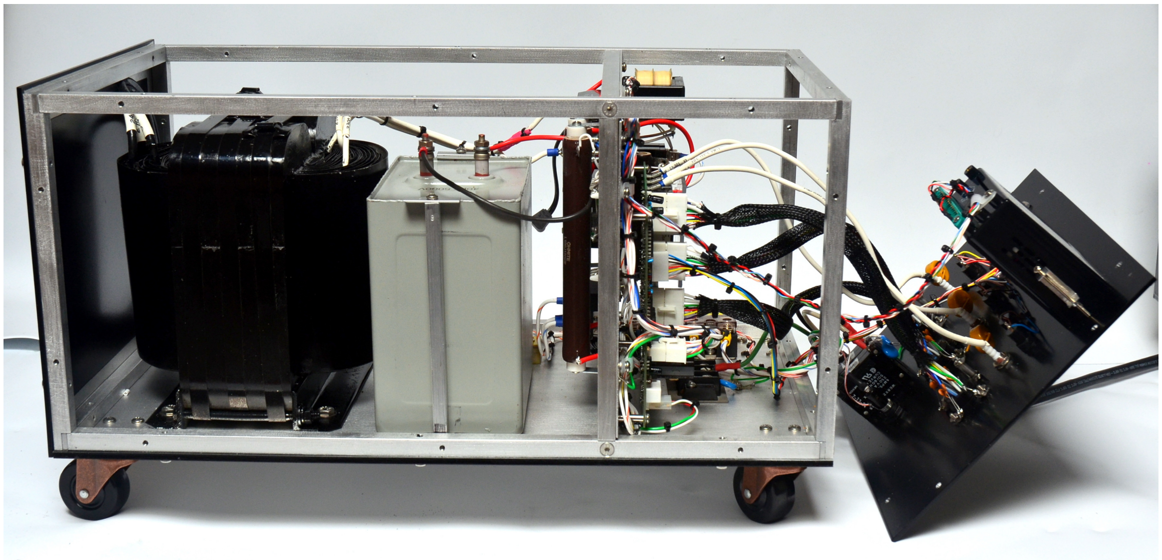

Figure 6: The front panel detaches and tilts forward for servicing and access to the logic and control circuitry.

All point-to-point wiring in the power supply uses silicone insulated high voltage wire or color-coded PTFE (Teflon) insulated wire. PTFE is a very durable insulator and has excellent heat resistance and dielectric strength. The wire is costly, but can frequently be found at bargain-basement prices at hamfests and on-line auction and swap sites.

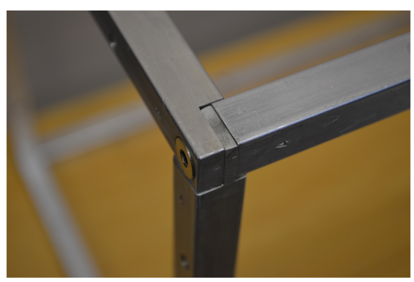

Figure 7: The rectangular frame is constructed from 1/2 in. square aluminum stock. A single 10-32 flathead screw secures the three interlocking pieces that form each corner.

The HV diode blocks are heatsinked to a 4.5 in. x 5.75 in. x 0.125 in. aluminum plate, which is mounted on 0.5 in. metal standoffs on the rear side of the subpanel. The rear subpanel also holds the bleeder resistors, HV/LV–select relay, and miscellaneous other components, some of which are mounted on silver/ceramic terminal strips scavenged from old Tektronix oscilloscopes. “Pem” type threaded fasteners are used instead of nuts in order to facilitate component removal. All other hardware is stainless steel, using pan-head phillips screws. A 4.75 in. “whisper” muffin fan mounted on the right side of the enclosure silently exhausts warm air drawn through a ventilation cutout on the opposite side. The large oil-filled capacitor sits on a rubber pad and is secured to the base plate by clamps fabricated by 3/8” square aluminum stock.

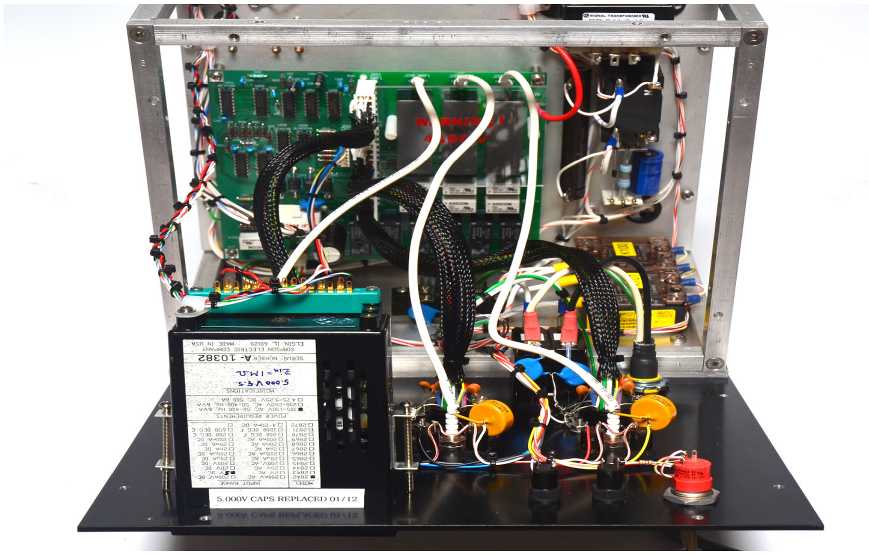

Figure 8: The front side of the subpanel houses the controller printed circuit board, the low voltage transformer, and the step-start circuits.

The enclosure panels are powder coated with a smooth black satin finish. The front panel is similarly finished, and was custom made by Front Panel Express (www.frontpanelexpress.com) from a CAD file supplied by the author. The panel lettering and other markings are engraved and backfilled with red and yellow paint (white paint for the lower voltage supply). Each power supply sits on two inch casters and weighs about 90 lbs.

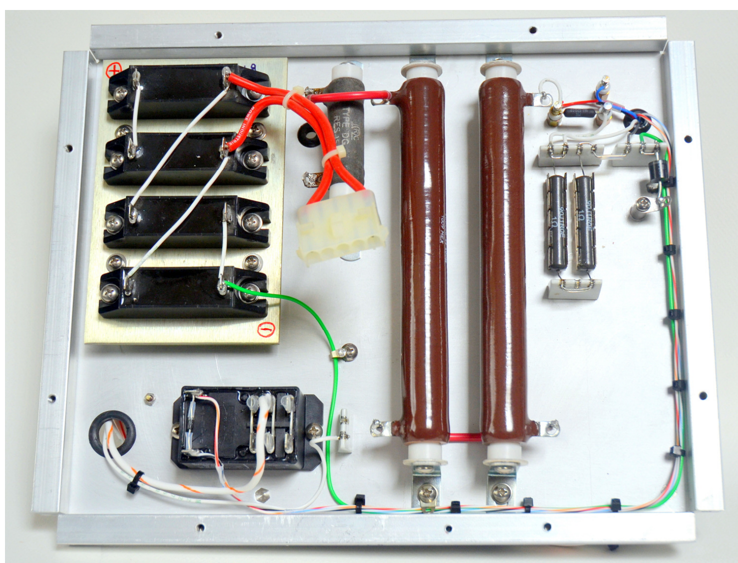

Figure 9: The bleeder resistors, metering components and HV– select relay mount on the rear of the subpanel. PTFE spacers insulate the bleeder resistors from the chassis, while the HV diode blocks are heatsinked to a 1/8 in. aluminum plate.

The most tedious part of construction was fabricating the frame for the aluminum enclosure. In order for the frame to be square, tolerances for the individual pieces had to be maintained to within 0.015 in. After the frame was completed, sixty precisely spaced holes had to be drilled and tapped into it for attaching the six panels. Obviously, other builders will likely have more sense than the author and will spare themselves this ordeal by building the power supply into a commercial enclosure!

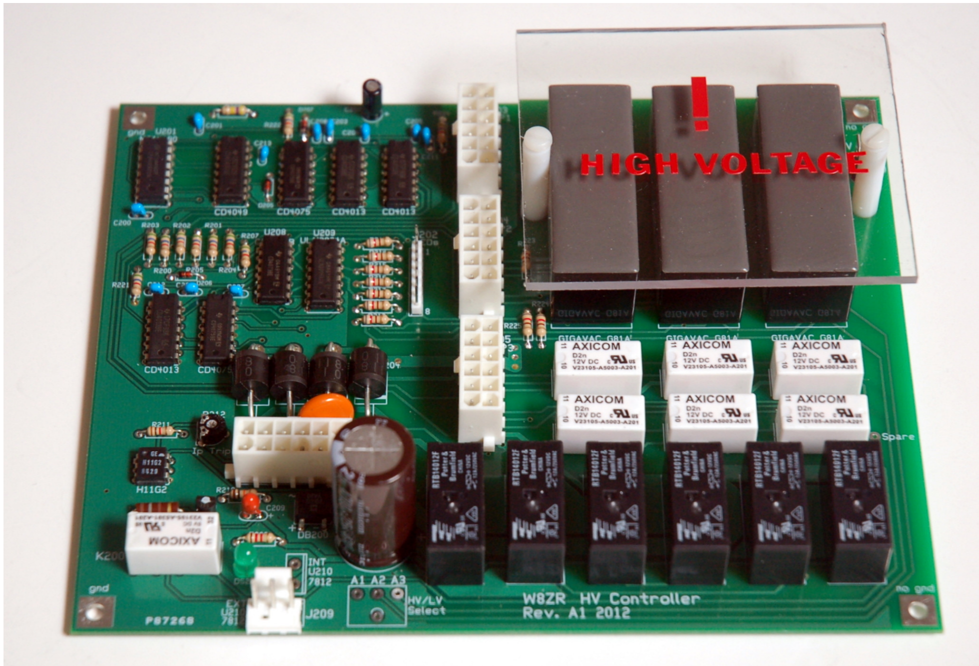

Figure 10: The double-sided printed circuit board houses the logic and control functions, the over-current protection circuit, and the control relays. A plastic shield covers the Gigavac HV relays to keep nearby wires and cables at a safe distance.

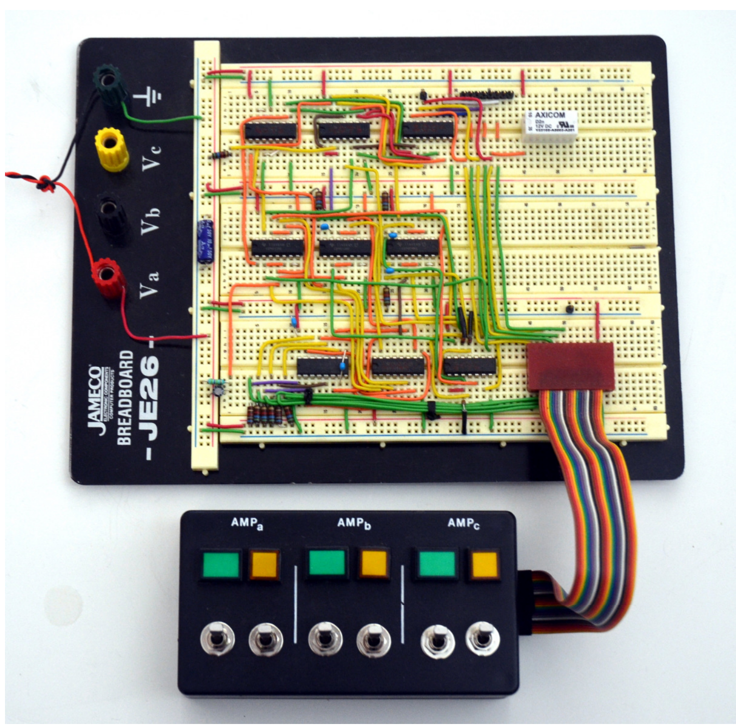

Figure 11: The logic and control circuitry was tested and debugged with this breadboard mockup, before laying out the printed circuit board.

There are many reasons why amateurs enjoy building their own equipment. Saving money, experimenting with new circuits, learning new skills, and experiencing the satisfaction that comes from creating something innovative and useful have always motivated amateur radio homebrewers. For some, including the author, there is also a strong esthetic pleasure that comes from designing and building a unique piece of equipment that cuts no corners, and cannot be purchased commercially. But all builders, no matter how skilled or experienced, quickly learn that there is no design that cannot be improved upon and no level of workmanship that cannot be executed more carefully. Because perfection always remains out of reach, every new project thus represents an irresistible challenge to improve one's skills and advance the state of the art. That spirit of innovation has infused amateur radio since its earliest days, more than a century ago, and is still alive and well today.

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Sidebar

High Voltage Safety Considerations

We are all so besieged these days with verbose safety warnings on mostly harmless consumer goods that it is easy to forget that some things really are dangerous. High voltage power supplies definitely fall into this category, especially since many amateurs are accustomed to solid state circuits and seldom encounter any d.c. voltage higher than 12V. *This power supply produces voltages that are highly lethal.* So *please* take to heart the following ten precautions. Furthermore, don't expect to learn from your mistakes, because if you don't exercise proper precautions the first time, you're unlikely ever to have a second chance.

1. Don't let your reach exceed your grasp. This is not a project for beginners. You should not attempt to build this power supply unless you're a seasoned builder who has experience with high voltage circuitry.

2. Young amateurs should not attempt this project. Working with high voltages requires the maturity and patience that comes with age and experience.

3. Never work around high voltage when you are tired, stressed, or in a hurry.

4. Never work around high voltage after drinking alcohol. Even one beer or glass of wine can impair your judgment and make you careless.

5. Before working on a high voltage power supply, always follow these three steps: *Unplug* (the AC power cord), *discharge* (the filter capacitors) and *verify* (that the output voltage is truly zero). Time-honored practice is to use a "chicken stick" (a wooden dowel or PVC tube, with one end attached to a grounded wire) to make sure filter capacitors are completely discharged.

6. When working on a high voltage power supply, remember that a dangerous time is after the power supply has just been turned off, but before the filter capacitors have fully discharged. A 50 µF capacitor charged to 4000 V holds a potentially deadly 400 Joules of energy. Even with bleeder resistors, it can take a minute or more to discharge fully.

7. When removing a recently discharged filter capacitor from a power supply, tie the two terminals together with wire. Large high voltage capacitors can self-charge to dangerous levels if the terminals are left floating.

8. Don't stake your life on the expectation that bleeder resistors, fuses, circuit breakers, relays, and switches are always going to do their job. Even though modern components are very reliable, it is safe practice always to assume the worst.

9. Don't build this power supply if you don't understand how the circuit works. High power amplifiers and power supplies are not "plug-and-play" projects with step-by-step instructions. Builders must be knowledgeable enough to improvise, make component substitutions, and implement design changes.

10. With high voltage projects, it doesn’t pay to be “penny wise and pound foolish.” Use high quality components throughout and save your forty-year-old junk box parts for projects where safety and reliability are not paramount requirements.

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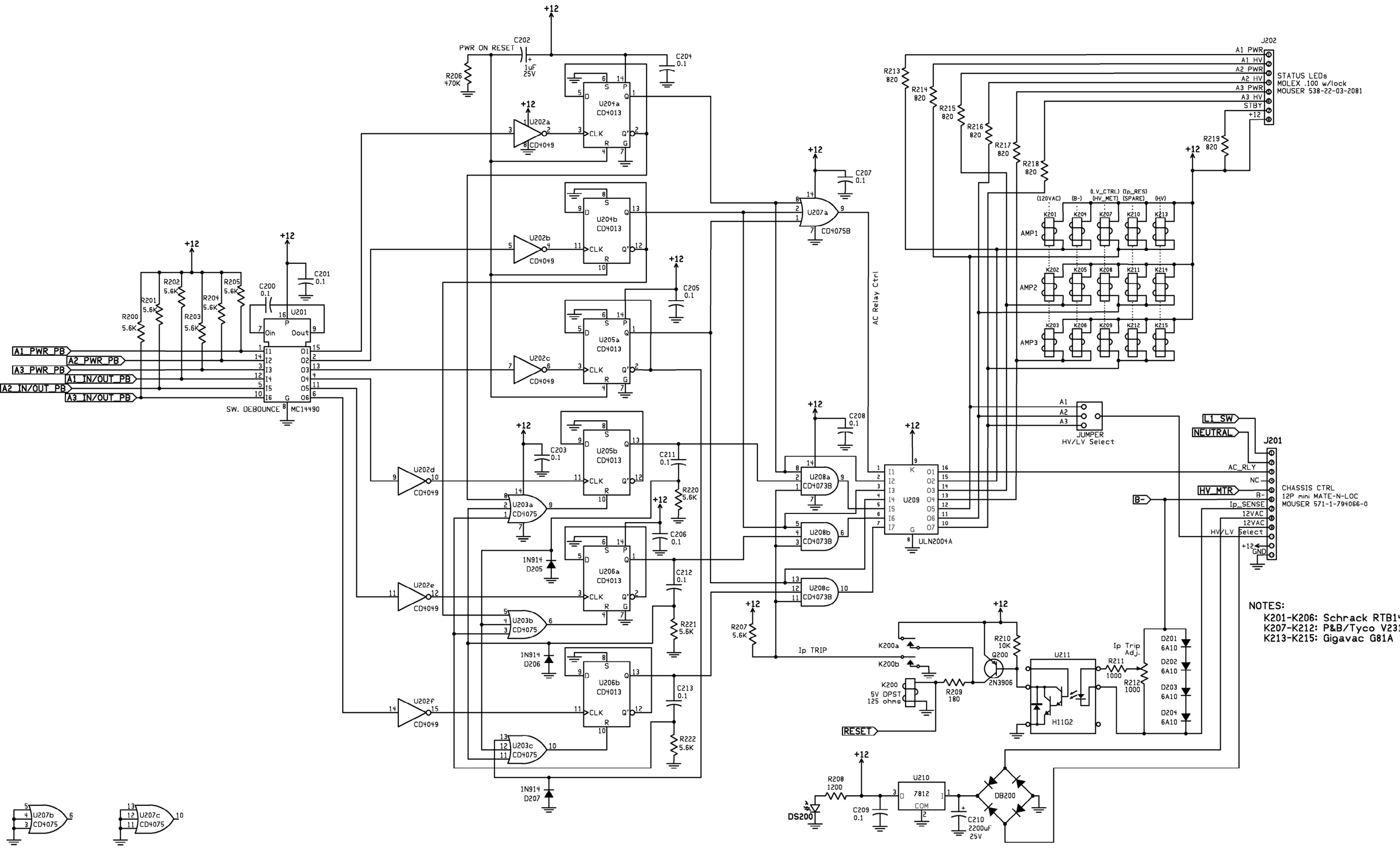
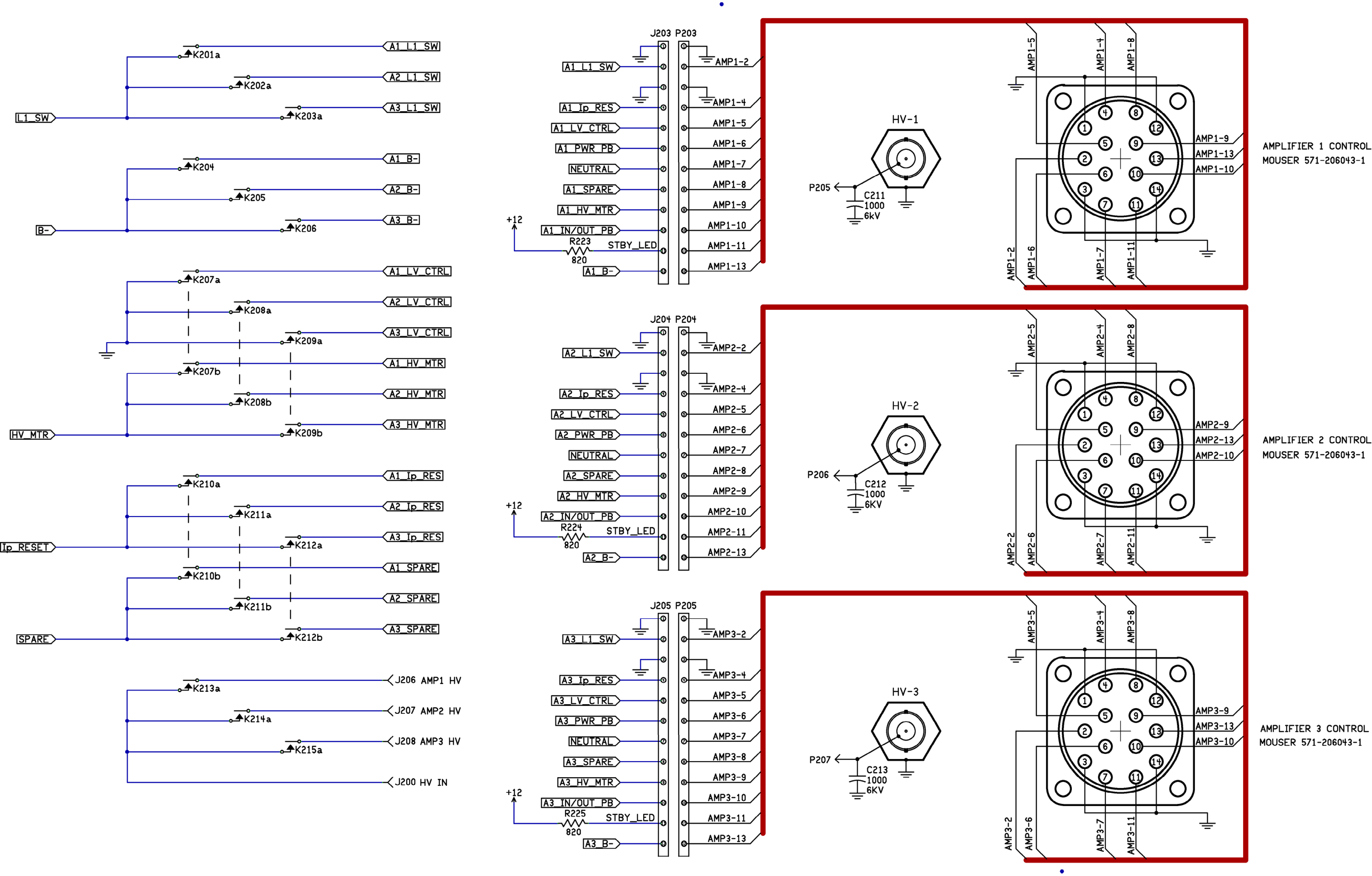
FIGURE 4a



NOTES:
K201-K206: Schrack RTB14012F
K207-K212: P&B/Tyco V23105
K213-K215: Gigavac G81A

FIGURE 4B



L1_SW
K201a
K202a
K203a
A1_L1_SW
A2_L1_SW
A3_L1_SW
B-
K204
K205
K206
A1_B-
A2_B-
A3_B-
K207a
K208a
K209a
A1_LV_CTRL
A2_LV_CTRL
A3_LV_CTRL
HV_MTR
K207b
K208b
K209b
A1_HV_MTR
A2_HV_MTR
A3_HV_MTR
Ip_RESET
K210a
K211a
K212a
A1_Ip_RES
A2_Ip_RES
A3_Ip_RES
SPARE
K210b
K211b
K212b
A1_SPARE
A2_SPARE
A3_SPARE
K213a
K214a
K215a
J206 AMP1 HV
J207 AMP2 HV
J208 AMP3 HV
J200 HV IN
J203 P203
A1_Ip_RES
A1_LV_CTRL
A1_PWR_PB
NEUTRAL
A1_SPARE
A1_HV_MTR
A1_IN/OUT_PB
+12
R223
820
STBY_LED
A1_B-
AMP1-2
AMP1-4
AMP1-5
AMP1-6
AMP1-7
AMP1-8
AMP1-9
AMP1-10
AMP1-11
AMP1-13
HV-1
P205
C211
1000
6kV
AMP1-9
AMP1-13
AMP1-10
AMPLIFIER 1 CONTROL
MOUSER 571-206043-1
J204 P204
A2_L1_SW
A2_Ip_RES
A2_LV_CTRL
A2_PWR_PB
A2_SPARE
A2_HV_MTR
A2_IN/OUT_PB
R224
A2_B-
AMP2-2
AMP2-4
AMP2-5
AMP2-6
AMP2-7
AMP2-8
AMP2-9
AMP2-10
AMP2-11
AMP2-13
HV-2
P206
C212
6KV
AMPLIFIER 2 CONTROL
MOUSER 571-206043-1
J205 P205
A3_L1_SW
A3_Ip_RES
A3_LV_CTRL
A3_PWR_PB
A3_SPARE
A3_HV_MTR
A3_IN/OUT_PB
R225
A3_B-
AMP3-2
AMP3-4
AMP3-5
AMP3-6
AMP3-7
AMP3-8
AMP3-9
AMP3-10
AMP3-11
AMP3-13
HV-3
P207
C213
6KV
AMPLIFIER 3 CONTROL
MOUSER 571-206043-1