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By Dr. Gregory L. Charvat (United States)

Vacuum Tube Home Theater System (Part 2)

Vacuum Tube Power Amps

Details about vacuum tube power amps in the "Frankenstein" system

Initially developed in college during my undergraduate years, the home theater system earned the name "Frankenstein," because it was the largest audio system in the dormitory (see **Photo 1**). It is a 7' tall vacuum tube home theater system mounted into a military surplus equipment rack from World War II that is enameled in black crinkle paint and topped with an menacing back-lit sign that reads "DANGER POWER ON."

Developing a vacuum tube home theater system is expensive because modern movie tracks are six channels (front R/L, rear R/L, front center, and subwoofer) requiring six power amplifiers. Power levels must be sufficiently high so clipping does not occur during loud explosions in war movies or other action sequences. *audioXpress* readers may agree that powerful tube-audio amplifiers are not inexpensive.

In the first portion of this series, I covered the system's architecture and circuit-level details. Now, I'll detail the power amplifier designs that provide relatively high-peak power for movies.

PHILOSOPHY

Fortunately, action movie sound tracks are generally quiet during dialog and plot development, with the occasional loud action-filled scenes. Vacuum tube power amplifiers are ideally suited for these scenes.

Tubes are capable of handling significantly more instantaneous power than their rated average power. This is the reason why tubes are used in radar systems requiring high-peak power supporting low-duty cycle pulses. [1] In radar systems, this peak power can reach several orders of magnitude greater than the average power rating for the tube.

A tube-power amplifier was developed using the radar design philosophy. The RMS power capability of this amplifier exceeds the specification for the output tubes because the amplifier is meant to run at maximum power for only short periods of time, leaving the higher RMS power available for loud action scenes.

This design pushes EL34s to the limit, providing 80-W RMS per channel for the front and rear speakers and 52-W RMS for the subwoofer in a mode somewhere between Class AB and B. EL34s in Class AB mode are capable of providing 40-W RMS of power. Therefore, this design can only supply its maximum power for a finite amount of time before overheating occurs.

SYSTEM BLOCK DIAGRAM

The Frankenstein supports two modes: high-fidelity stereo and home theater. The analog outputs from a surround-sound processor and a McIntosh C-24 high-fidelity stereo preamplifier are fed into an audio switch matrix inside the audio transfer switch and surround pre-amplifier. In high-fidelity mode, the C-24's output is routed to the power amplifiers. In surround-sound mode the output from the surround processor is routed to the power amplifiers. Refer to the first article in this series for details as well as a block diagram and call-out diagram.[2]

There are five power amplifiers, audio input to each is sourced from the audio transfer switch and sur-

Photo 1: The Frankenstein, a vacuum tube home theater system

plifiers are built into the quad-power amplifier, driving the front and rear speakers. The mono-block power amplifier drives the subwoofer. There is no center-channel amplifier, but the connections are builtin to add one.

The amplifier architecture is a negative feedback, high-fidelity amplifier include a differential amplifier, a loop compensator, a phase splitter, and a push/pull output (see **Figure 1**).

THE MONO BLOCK POWER AMP

The mono block power amplifier's power supply provides 535 VDC for the push/pull output, 400 VDC for the phase splitter, regulated 120 VDC for the differential amplifier, and 6.3 VAC for the filaments (see **Figure 2**). Higher plate voltage could be used for the push/pull output circuit, resulting in greater peak output power. However, voltages above 600 VDC require special high-voltage wires, complicating the implementation of the design. In addition, the quiescent bias current of the tubes would have to be reduced, resulting in greater THD by pushing the bias points of the tubes further away from Class AB.

Each stage of the power supply is isolated to eliminate the power supply as a path of unintended feedback. The high-voltage output of T1 is rectified by V5, a 5U4GB. A pair

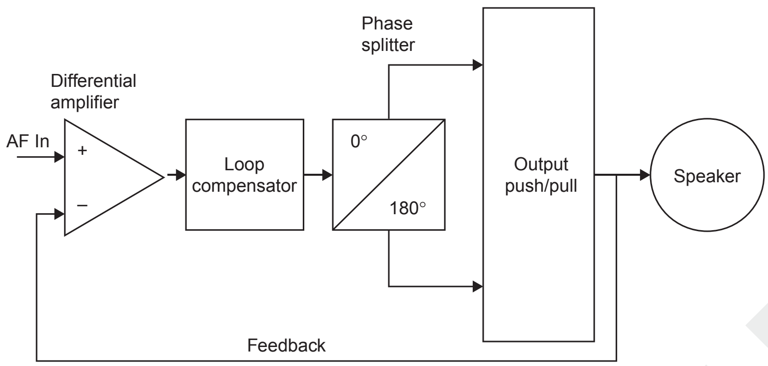

Figure 1: An amplifier block diagram

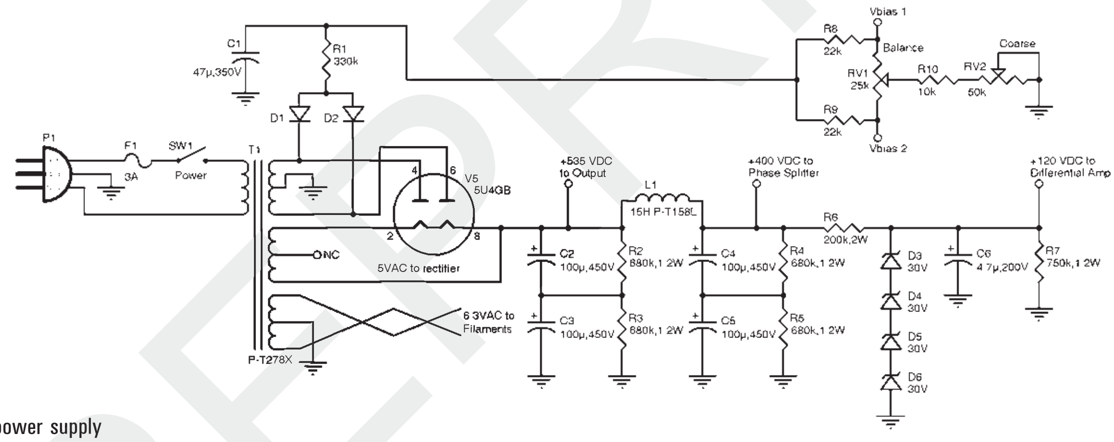

Figure 2: A power supply

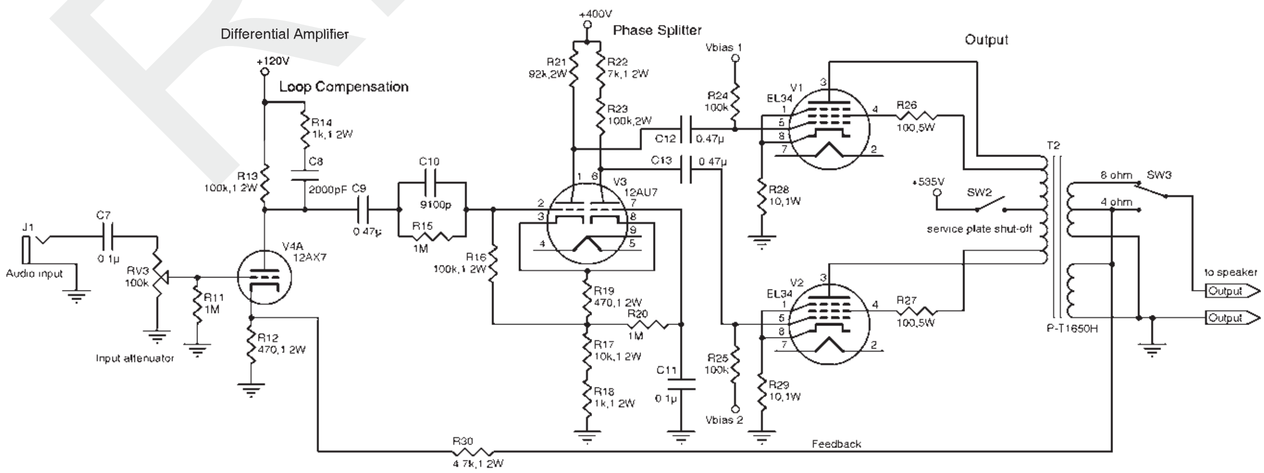

Figure 3: A complete amplifier

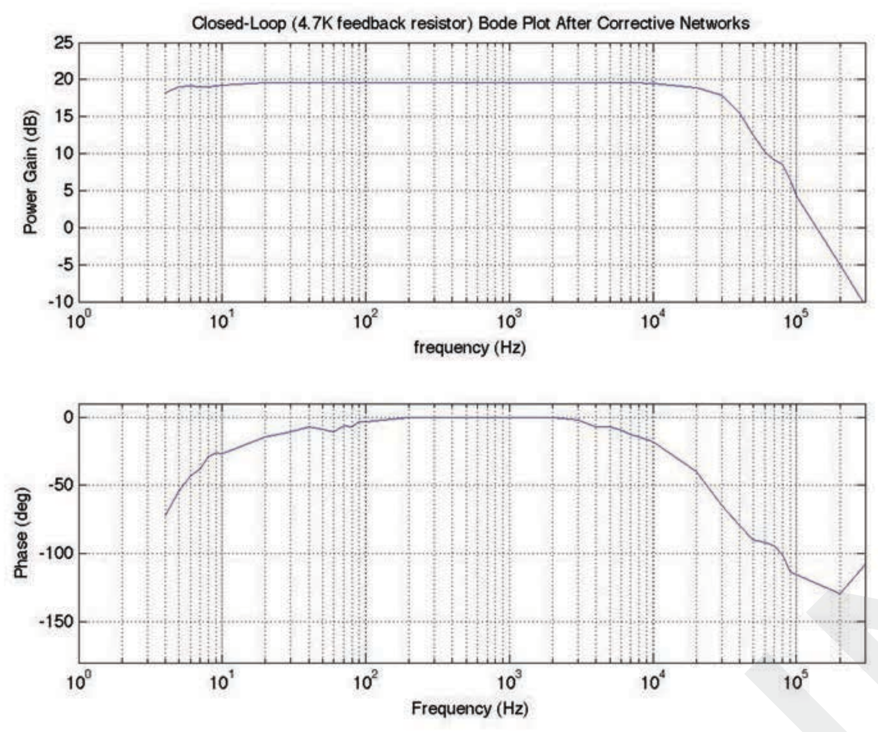

Figure 4: A mono-block power amplifier bode plot


Photo 2: A mono-block power amplifier

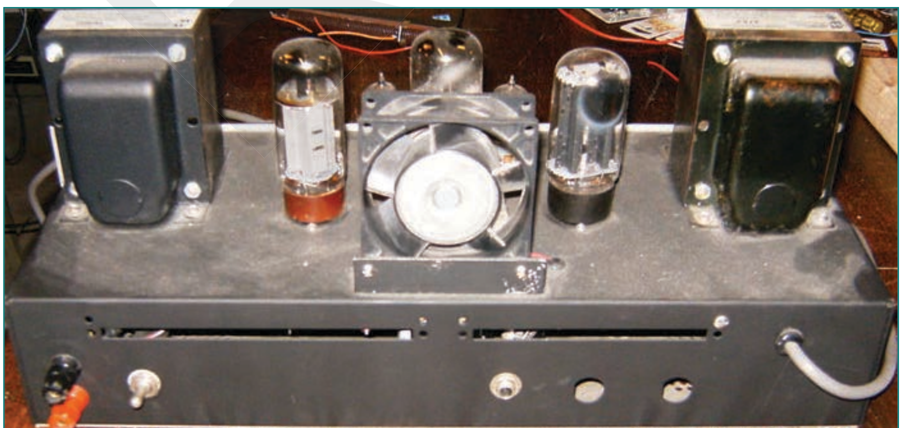
Photo 3: A rear view of the mono-block power amplifier

of 100-µF, 450-VDC capacitors (C2 and C3) filter the 535 VDC. A 15-H choke (L1) and two 100-µF, 450-VDC capacitors (C4 and C5) isolate the phase splitter from the output. A solid state 120-VDC Zener diode voltage regulator (D3–D6) isolates the differential amplifier from the phase splitter.

The output circuit uses a Hammond P-T1650H output transformer (T2) and a pair of EL34s in a push/pull configuration (V1 and V2 in **Figure 3**). A toggle switch on the secondary provides a convenient way to select speaker impedance. A toggle switch on the primary enables the plate voltage to be shut off during servicing. Direct grid bias is fed into the control grid g1 for both V1 and V2. Bias is set to approximately 37.5 mA through each tube by adjusting RV1 and RV2.

To initially set the bias, start by setting RV2 to a maximum value of 50 KΩ and RV1 to half of its value, 12.5 Ω. Then, slowly reduce RV2 while measuring the current through V1 and V2. As RV2 is increased, adjust RV1 so the same current is flowing through both tubes. Set the bias so both tubes are drawing 37.5 mA quiescent current. The bias should be periodically checked to compensate for tube aging.

This bias point is a compromise between suggested biasing for Class B (generally accepted 25–30 mA) and Class AB (60 mA) providing some reduction in crossover distortion compared to Class B.[3]

The phase splitter consists of a 12AU7 dual triode (V3), where V3a amplifies then outputs a phase-inverted waveform to g1 of V1. Similarly, V3b feeds its output to V2. However, V3b is coupled to the output of V3a through a common set of cathode resistors, producing a non-inverted output (see **Figure 3**).[4] Consequently, the two outputs from V3 are 180° out of phase. The magnitude of both outputs must be equalized by adding resistance in series with R23, where R22 was added to equalize the gain.

The audio input is fed in through J1 and through the potentiometer RV3 into the grid of a dual-triode

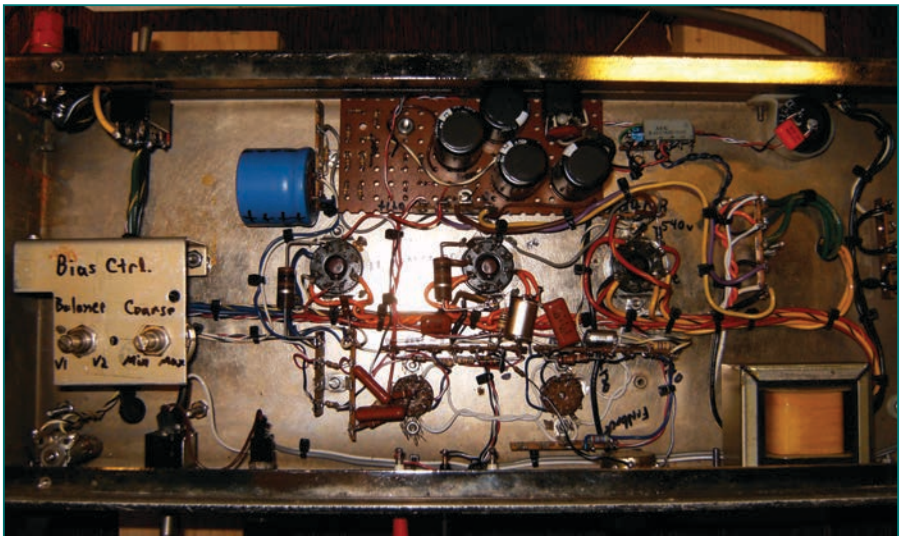

Photo 4: An inside, bottom view of the mono-block power amplifier

12AX7 (V4a). V4a amplifies the audio input and feeds it into the phase splitter while it simultaneously closes the negative feedback loop R30, which is in series with V4a's cathode and the secondary of T2. V4a is a differential amplifier, amplifying the difference between the input audio signal and the output of the amplifier.

The loop compensation circuit is part of the differential amplifier, which includes of R14, R15, C8, and C10. Prior to the installation of these components, the open-loop transfer function was measured by removing R30 and acquiring the bode plot from 4 Hz to 300 kHz. Results showed that the uncompensated amplifier crossed 180° of phase with significant open loop gain at both a low and a high frequency, resulting in oscillation at one or the other if the loop was closed. A compensation network was developed by using a method for both high- and low-frequency poles in tube feedback control systems.[5] The procedure is summarized in the *Radio Designer's Handbook*.[6] This loop compensator enables the amplifier to be unconditionally stable when the feedback loop is closed. Operating in a closed loop is desirable because it reduces THD, flattens the frequency response, and increases the effective bandwidth of the amplifier.

Photo 2, **Photo 3**, and **Photo 4** show the mono-block power amplifier. A bode plot of its closed-loop transfer function shows that it has excellent closed-loop bandwidth characteristics spanning 4 Hz to 30 kHz (see **Figure 4**). The maximum RMS output power was measured at 52 W. THD was measured at 0.675% at 1 kHz. These characteristics combined with the low-end cut-

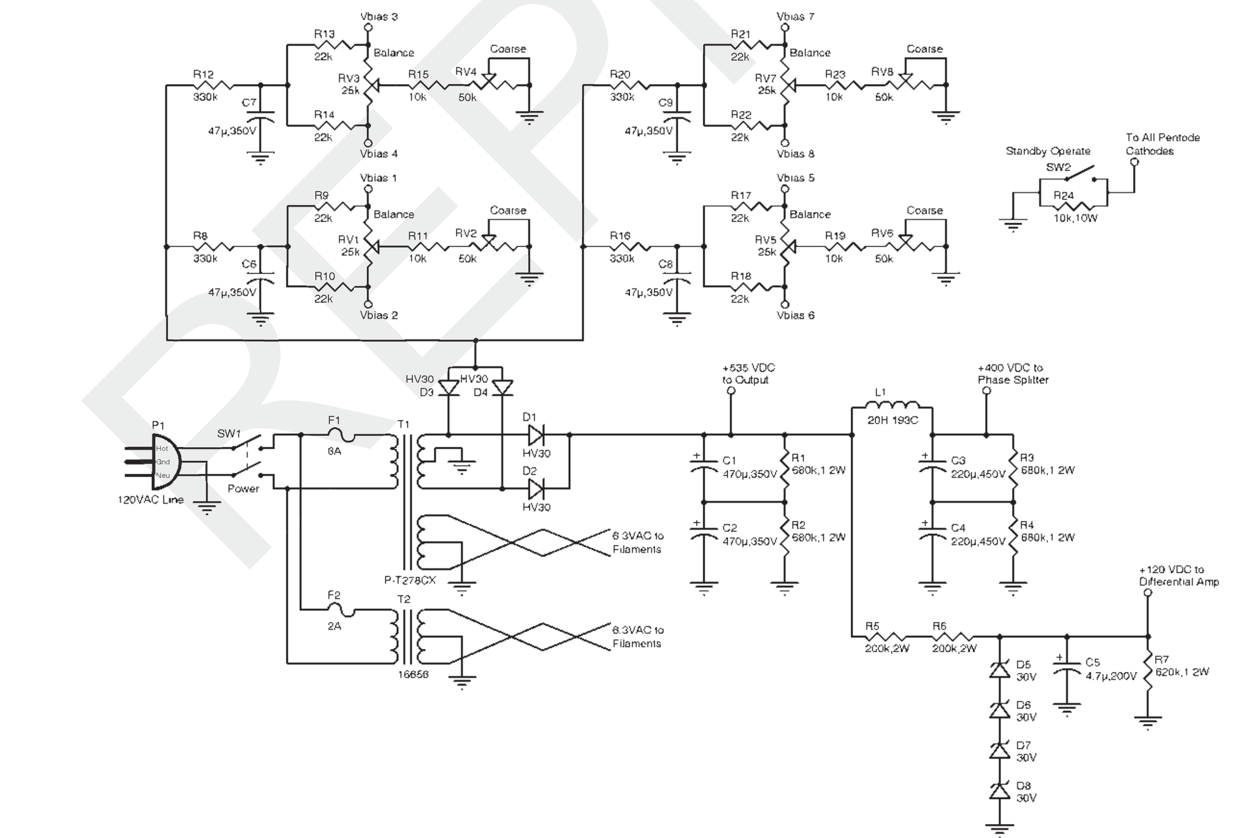

Figure 5: A quad-power amplifier power supply

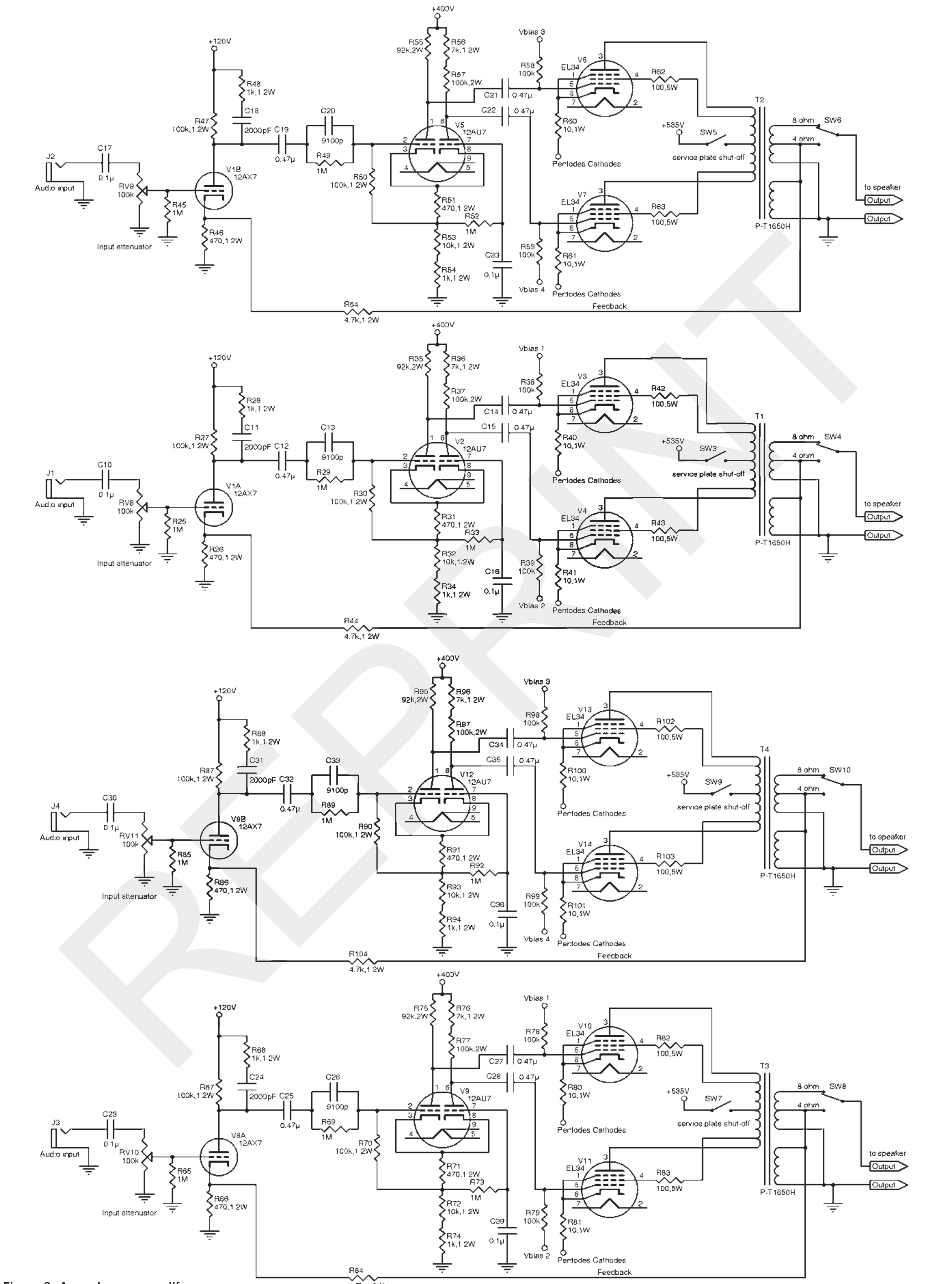

Figure 6: A quad-power amplifer

Photo 5: A mono-block power amplifier

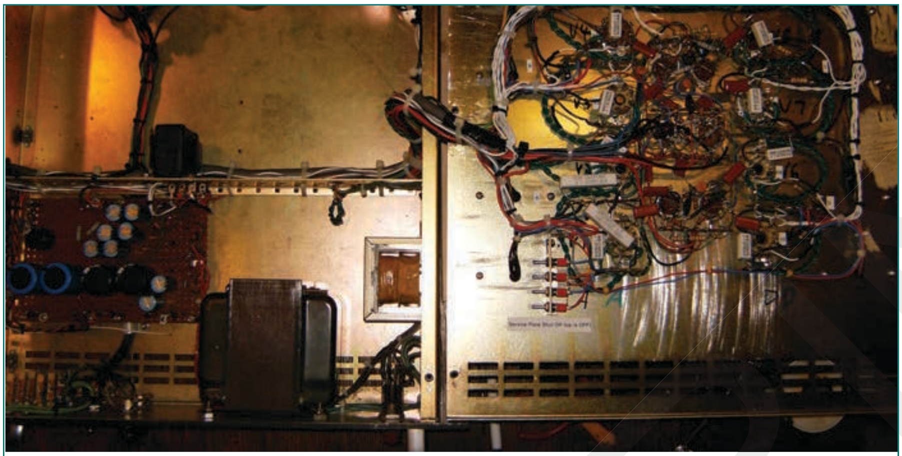

Photo 6: A rear view of the mono-block power amplifier

off frequency of 4 Hz shows that this amplifier is well suited for driving a subwoofer.

QUAD-POWER AMPLIFIER

The quad-power amplifier consists of four mono-block power amplifiers integrated into one chassis, using the same power supply. Diodes D1 and D2 were used for full-wave rectification (see **Figure 5**). For this reason a Standby/Operate switch, SW2, is connected between the cathodes of the EL34s and ground with a 10-Ω, 10-W resistor in parallel. This enables the cathodes of all pentodes to be lifted off ground during warm-up, protecting them against long-term cathode stripping. SW2 is left open for approximately 10–15 s while the tubes warm up then it is closed. A future design iteration might include the use of a vacuum tube rectifier in place of D1 and D2, which would eliminate the necessity for SW2.

The differential amplifiers, including 12AX7s (V1 and V8), are shared between two amplifiers while the rest

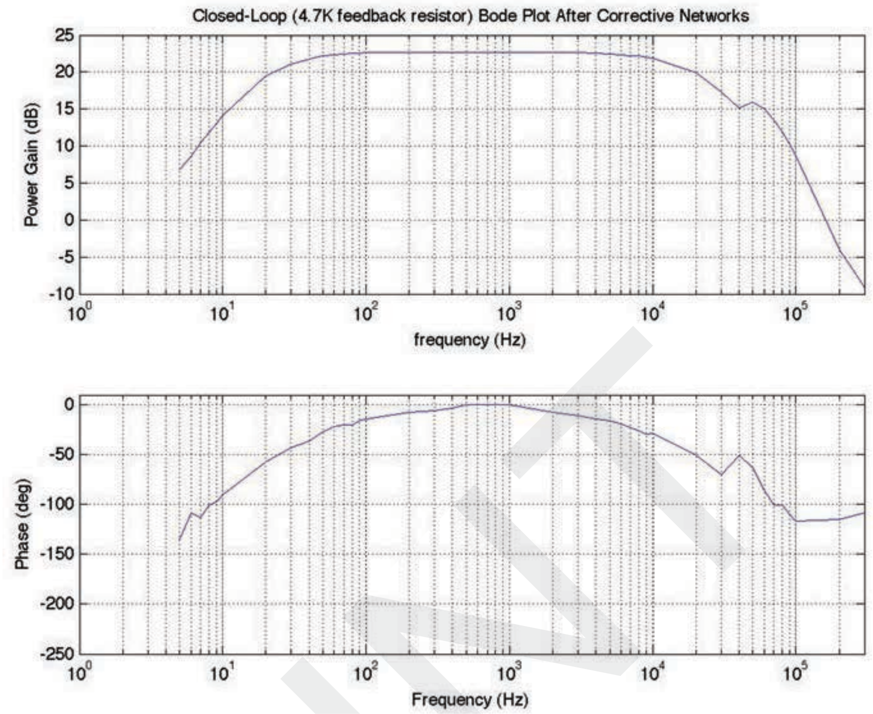

Figure 7: A bode plot of one amplifier inside of the quad power amplifier

of the amplifiers in the schematic are identical to the mono-block power amplifier (see **Figure 6**).

The quad-power amplifier is shown in **Photo 5** and **Photo 6**. The closed-loop bandwidth supports a full acoustical range of 22 Hz to 20 kHz (see **Figure 7)**. The output power was measured at 80-W RMS. Although the output pentodes are biased at 37.5 mA, the THD was measured at 0.45% at 1 kHz. These characteristics are excellent for powering the front and rear speakers of a home theater system.

HIT PLAY

I described the complete implementation of a vacuum-tube home theater using tubes throughout the analog signal chain. Special power amplifiers were developed that push the EL34 to the edge of their output power capability so loud action scenes can be experienced while producing less than 0.68% THD. Use this as a framework for your home theater audio project by either replicating these designs or substituting your components. It's time to build a monster home theater system. *aX*

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