by George Anderson

Digitally Controlled Amplifier

Connect Vintage Analog to Modern Digital Tech

The dsPIC30F2023-controlled MiniTron is a high-end vacuum tube stereo amplifier with distortion control, power output, and more. The fully functional amplifier successfully blends its unique circuitry and specialized processing software to precisely match the radically different worlds of high-voltage analog and low-voltage microcontrollers.

When I first became interested in electronics, vacuum tube technology was the only thing available to the average experimenter. (Junk radios and TV sets offered a plentiful supply of free parts.) As a result, I learned to build guitar amps, stereo equipment, and ham radio equipment with vacuum tubes. Later, I learned to use the bipolar transistor, MOSFET, and integrated circuit when they became available. I quickly embraced the digital revolution and even built a music synthesizer in the early 1970s using RTL logic ICs. Then, when the Microchip Technology PIC16C54 appeared, I created all sorts of cool gizmos and a few commercial products and newer Microchip devices.

Since those first crude amplifiers constructed from old TVs in the 1960s, I have been interested in audio technology. I've built most of my stereo equipment—everything from low-powered headphone amps to kilowatt-level monster amps, preamps, guitar amps, and effects. These used bipolar transistors, MOSFETs, ICs, and, yes, vacuum tubes. My audio-related tools and parts—especially the vacuum tube equipment—are segregated from my other electronics. I actually have a separate audio-related workbench that shares only the scope and computer.

Audio electronics technology has evolved a lot in the past 40 years. We now have class G amplifiers, class H amplifiers, and even pure digital (class D) amplifiers with DSPs that process audio in the digital domain and convert it to analog only in the switch-mode output stage. Modern audio equipment offers power output, efficiency, distortion, and size advantages that weren't even dreamed of

Photo 1—This is the finished MiniTron amplifier. I removed the Lexan cover for debugging. I took this photo during a debugging session. I optimized the amplifier's performance with a laptop computer.

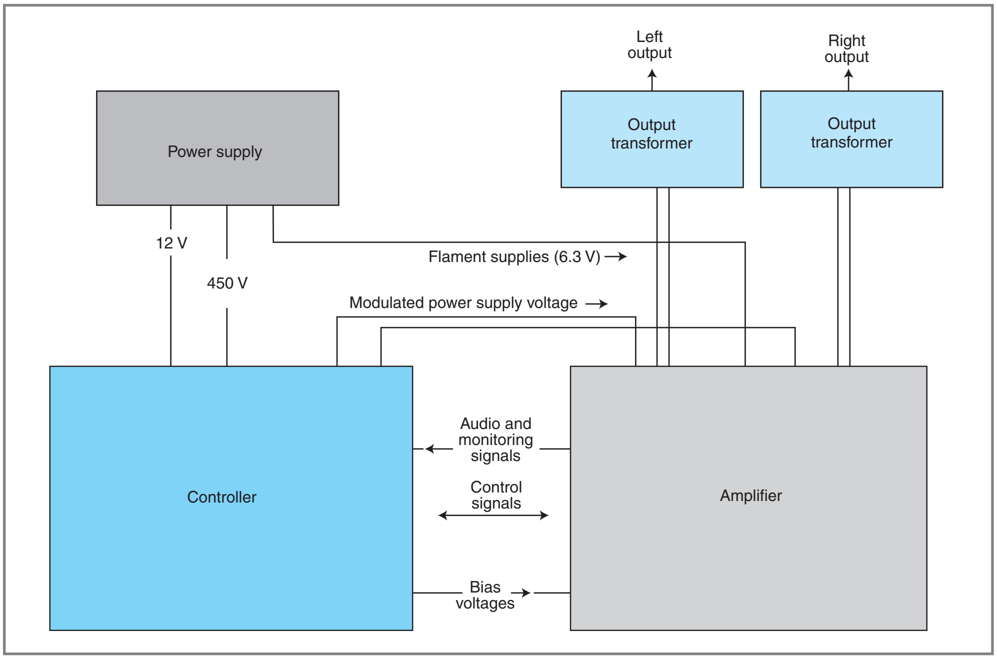

Figure 1—Look at how the controller, vacuum tube amplifier, power supply, and output transformers are interconnected. The individual blocks on this diagram are in the same relative position as their respective subsystems in Photo 1.

only a few years ago. Despite these advantages, there remains a small but growing minority of audiophiles who believe that vacuum tubes offer better sound quality despite poorer measured performance. A vacuum tube purist will tell you that the audio path should not contain any silicon and there should not be any negative feedback used to improve linearity. Often, the preferred design is a simple single-ended class A circuit. I am not going to choose sides. My vacuum tube amplifier designs often use silicon in the signal path and moderate amounts of feedback.

Vacuum tube audio amplifiers are notoriously inefficient. A class A single-ended amplifier may operate at a plate efficiency of 5% or less. Great advances have occurred in the field of efficiency improvement in the solid-state world. Class G audio amplifiers use multiple power supply rails and switch between them based on the instantaneous power demand. Class H audio amplifiers use a variable power supply that tracks the audio signal giving the output devices enough voltage headroom to do their jobs, and no more. The voltage across the output devices stays constant regardless of the power output. This improves efficiency and offers the added benefit of removing certain distortion products. This technique has been applied to other electronic devices, particularly radio transmitters like cellular phones and cellular base stations to reduce energy consumption.

Specialized Microchip Technology dsPIC ICs make modulated supply rails fairly simple, so I recently chose to design a dsPIC-enhanced vacuum tube amplifier. Refer to **Photo 1** to see my first attempt at a digitally controlled amplifier design. I call it "MiniTron." The hardware is intended to be a development platform to learn how to connect the vintage analog world to the modern digital world. I included circuitry for software features that have not yet been implemented. As you can see in **Figure 1**, three main subsystems comprise the design: an amplifier, a controller, and a power supply. Each resides on its own PC board.

In this article, I'll describe my design in detail. You can apply the techniques I'll present to countless other applications. But before I get into the specifics, let's focus for a moment on vacuum tubes.

VACUUM TUBE THEORY

Vacuum tubes work on the principle of thermionic emission. Electrons are emitted from a hot cathode and travel through a vacuum toward a positively charged electrode, the plate. Charged wire structures between the two electrodes have the ability to regulate the current flow by altering the electric field in a manner somewhat similar to the gate in a MOSFET. Most vacuum tubes function like depletion-mode MOSFETs. The current flow through the device is large and uncontrolled unless a negative "bias" voltage is applied to the control grid. The application of plate voltage without "negative bias" voltage results in a large, often destructive, current flow.

Keep this basic information about vacuum tubes in mind as you read the rest of this article. Now, back to my project.

POWER SUPPLY

The amplifier's power supply is a simple unregulated design (see **Figure 2**). It uses conventional rectification and filtering to provide voltage sources for the design. The filament supplies are 6.3-V AC connected directly to the tubes. The 10-V supply feeds a 5-V regulator and a MOSFET driver on the controller board. The –150-V supply is connected to the bias generator on the controller board. The high voltage is routed directly to the amplifier board to supply the first two stages and to the agile buck converter on the controller board.

AMPLIFIER

The amplifier is a class H design using modulated supply rails. The audio path is purely vacuum tube (no feedback paths exist), and the circuitry is a single-ended class A design (current flows for the entire audio cycle).

Refer to **Figure 3**. Each vacuum tube section is represented by a circle with three elements inside it. The cathode is

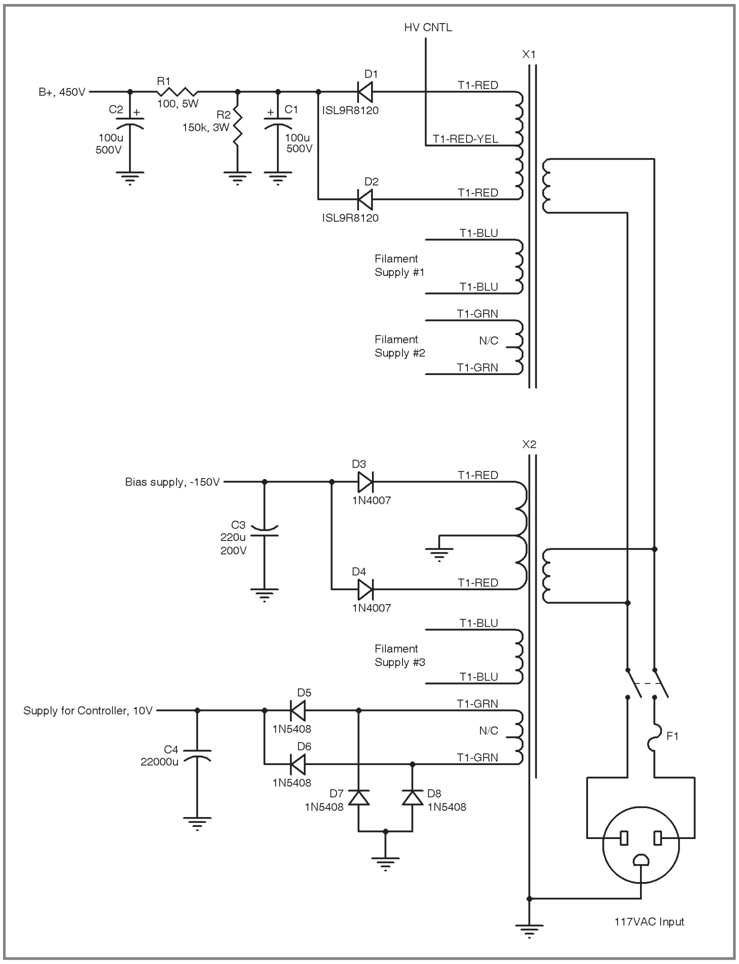

Figure 2—The MiniTron uses a conventional linear power supply built with toroidal transformers that is housed in a die cast aluminum box. An SMPS is planned.

the element across the bottom. It functions like the source in a MOSFET. The cathode has a heating element. It is often shown separately from the device itself in a manner like the power and ground pins on digital logic ICs. It is connected across a power supply for "heater power" or "filament power." The grid is the middle element represented as a series of dashes (usually three or four), functioning like the gate in a MOSFET. The plate is the upper element corresponding to the drain in a MOSFET. There are only electron tubes (N channel devices). There are no positron tubes (P channel devices). Many tubes have two or more sections in a common glass envelope. They are shown as individual tubes on the schematic in a manner similar to a quad NAND gate. Sometimes the sections are identical (the output tubes in this design); sometimes they are not (the input and driver sections). It isn't always possible to determine this from the schematic alone.

There are three gain stages. The first two are conventional using the two sections of a dual vacuum tube triode. Both stages are common cathode (like common emitter) voltage amplifiers. The first stage uses an LED in series with the tubes cathode. It functions as a low-voltage (1.8-V) Zener diode, fixing the bias of the stage. The second stage uses a CCS IC as the plate load. Both of these "modern tricks" serve to lower the distortion of the amplifier. These two stages provide all of the voltage gain. The third stage is rather unique. It is a cathode follower which functions in a manner similar to a MOSFET source follower. It provides no voltage gain (a small loss), but it provides a large current gain. Cathode follower output stages are rare in audio amplifiers because of the extreme drive voltage requirements. The tube used is a dual triode with identical sections. Both sections are wired in parallel, except for the provision to adjust the bias independently for each section. These are both adjusted by the controller. A cathode follower typically has a high PSRR so that the power supply can vary without affecting the output, as long as there is sufficient headroom for the signal being processed. It is desirable to operate the third stage with a constant voltage across it, having the tube's current varied by the signal. Since the cathode of the tube is the output and the plate is the voltage supply pin, the plate voltage must be varied in step with the signal voltage. This is the function of the agile switch-mode power supply (SMPS) converter.

The amplifier has two identical channels. Each channel has three bias voltage inputs to control the tube parameters. There are current-sense resistors in series with the output transformers and a resistive tap from the driver tube. These are used to measure the tube's plate voltage and sample the audio for the agile SMPS. There is also a temperature sensor mounted in the area of highest heat found on the first prototype PCB. These signals are routed via a ribbon cable to the controller PC board.

THE CONTROLLER

Figure 4 is a simple depiction of the controller. **Figures 5** through **8** detail the aspects of the controller's circuitry: floating buck converters, the analog I/O, the bias generator, and the connections to the microprocessor.

There are three dsPIC ICs from the Microchip Technology "30F" family that are designed for use in intelligent switch-mode power supplies. I used the dsPIC30F2023, as you can see in Figure 8. The unique SMPS resources in these ICs do most of the hard stuff usually required for an SMPS design. This leaves ample processing power available for other activities and opens the door for all sorts of new digital implementations of power control circuitry that was previously an analog-only domain. In fact, I have the amplifier running with no code at all in the main loop of the software. The interrupt service routine can run the ADC and the SMPS by itself. The simple software is based on an example on Microchip's web site, although they probably never intended for such an application. This project design has the hardware capabilities for full closed-loop converter operation; however, closed-loop operation has not been tested. Closed-loop operation should not have any advantages in this application.

In addition to the agile SMPS the hardware is designed to allow development of advanced control features of the vacuum tube amplifier. This platform is currently being used to develop algorithms and software for use in future digitally controlled vacuum tube amplifier products.

AGILE SMPS CONVERTER

The controller's main function is the agile SMPS. It is the project's "enabling technology" and reason for its existence. The agile SMPS is used to vary the supply voltage on the output tube in track with the audio signal, thereby keeping the voltage across the output tube constant. The plate voltage relative to the cathode stays at a low value (100 V in this design). The absolute plate voltage is constantly moving with the audio signal, swinging from 420 to –250 V (actual measured values). The plate voltage in a conventional design would need to be fixed at 420 V to afford the same headroom and power output capabilities. From this it can be seen that the power dissipated in the output tube is reduced by a factor of about four. The power dissipation is usually the limiting factor in a vacuum tube amplifier, so these techniques can be used to increase the power output for a given amplifier size and cost.

Audio is tapped from the second stage in the tube amplifier and routed to an op-amp for easy gain and offset adjustments in the early development cycle. These can be done in software, so the op-amp will likely be eliminated in later designs. The op-amp gain and level shifters are shown in Figure 4 and located in the center of the analog I/O schematic (see Figure 6). The DC offset potentiometer controls the DC output voltage from the agile converter, which sets the tube voltage. The op-amps feed an A/D pair on the dsPIC30F2023 chip. The ADC's are triggered by the PWM module, and an interrupt service routine simply takes the A/D values and transfers them to the PWM modules duty cycle registers. Math such as scaling or offset can be added here.

Two PWM outputs control two unique floating MOSFET driver circuits that are each capable of driving a high-side MOSFET switch operating at any voltage from 2,500 to –2,500 V. You can see this in Figure 4

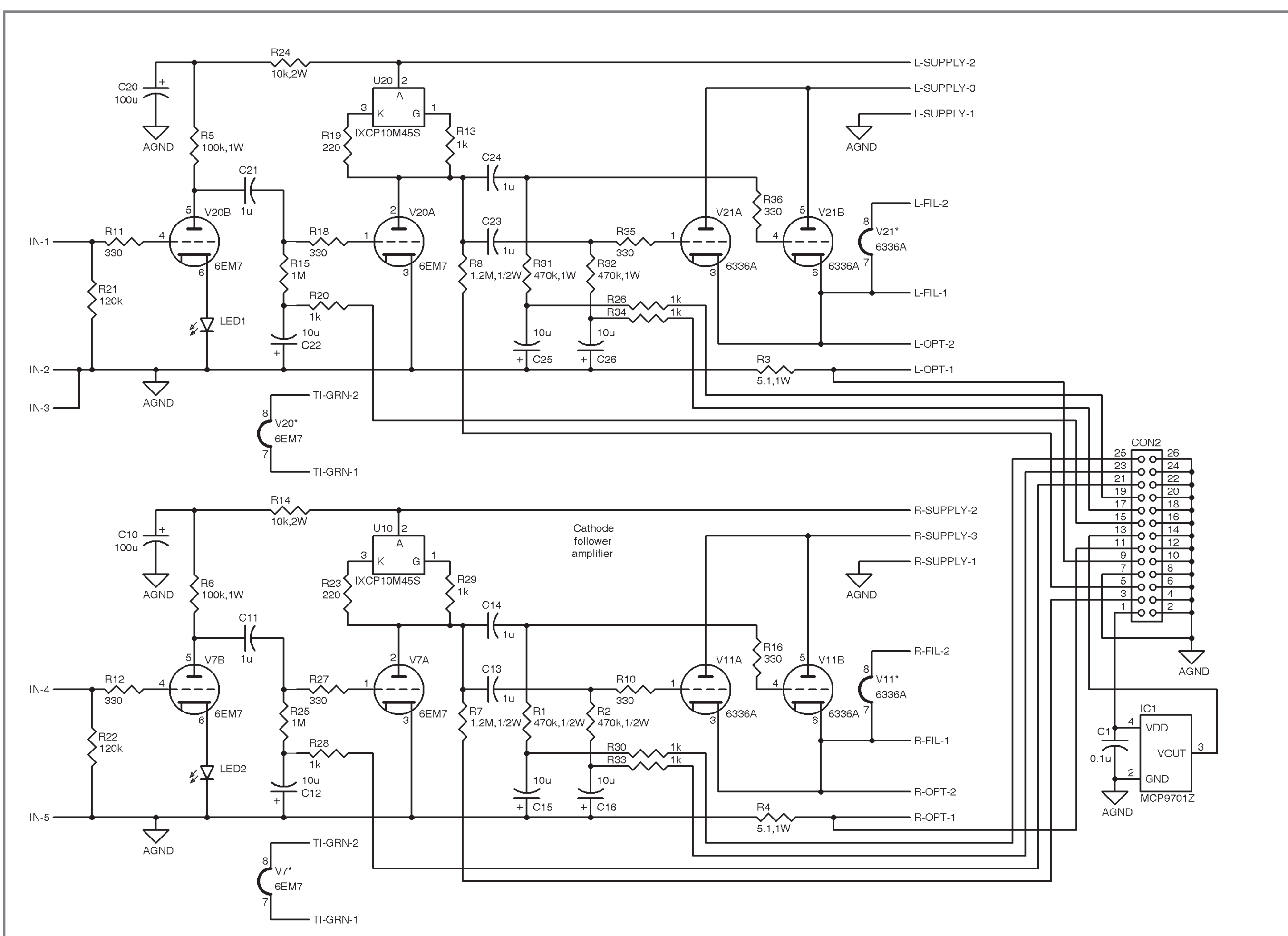

Figure 3—The amplifier is a class H design with modulated supply rails. The audio path is purely vacuum tube, no feedback paths exist, and the circuitry is a single ended class A design (current flows for the entire audio cycle). There are three gain stages.

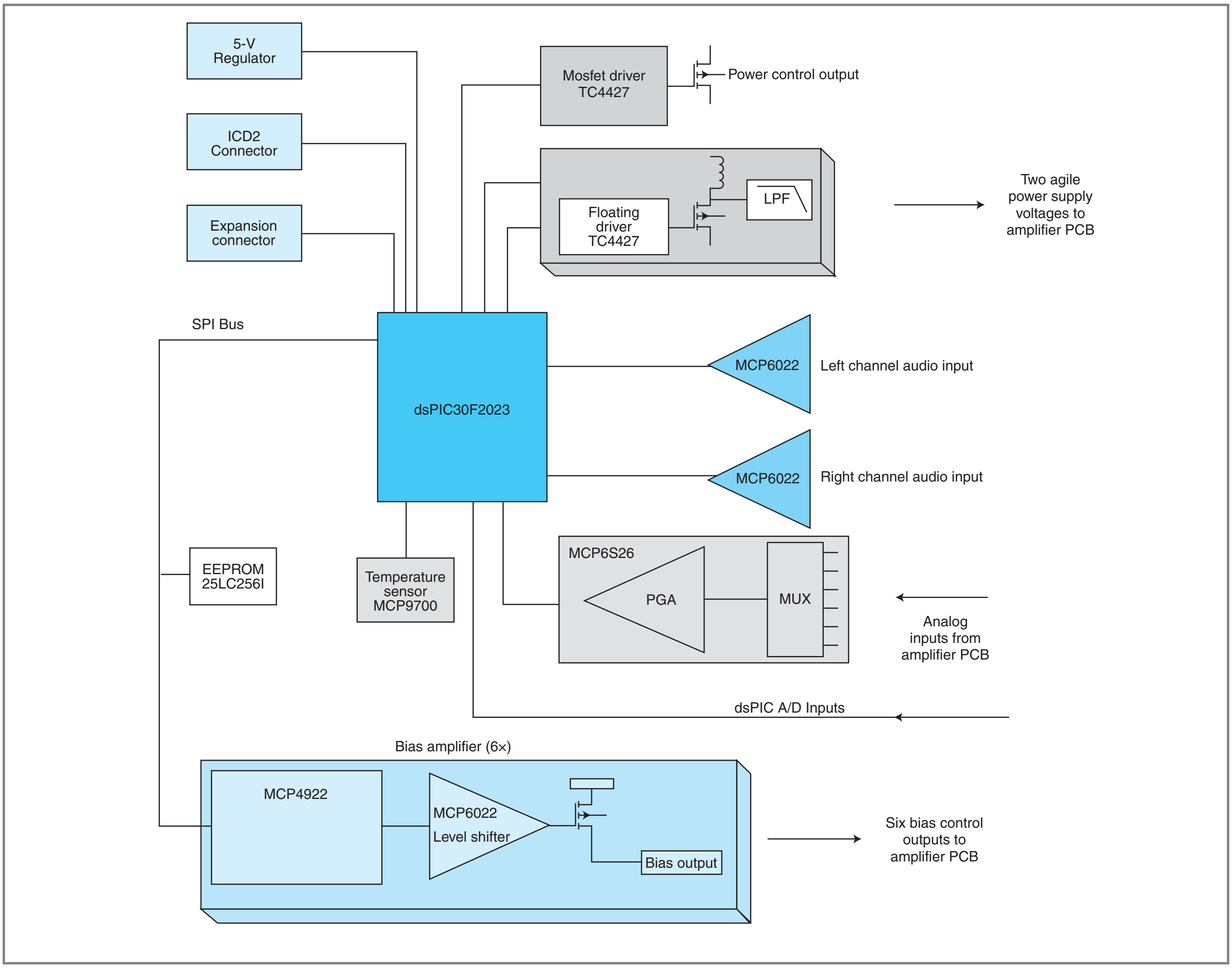

Figure 4—These are the individual controller elements.

and the floating buck converter schematic (see Figure 5).

I determined early in the design cycle that the converter's output voltage could be "pulled" below ground potential by the large reactive load presented by the output transformer and loudspeaker in the vacuum tube amplifier circuit. The source of the switch FET operates in the range of 500 to –400 V. A typical high-side driver IC, such as an International Rectifier IR2213, will fail catastrophically when its output goes negative. I devised the floating driver circuit for this situation.

An isolated DC-to-DC converter module is used to generate a floating 12-V supply. It has a 3,000-V isolation rating. This floating 12-V supply powers a Microchip Technology TC4427A low-side MOSFET driver IC. The ground-referenced PWM signal from the dsPIC30F2023is applied to the input side of an Avago magnetic isolator IC, which has separate input and output circuits and carries a 2,500-V isolation rating. The input side is powered from the main 5-V supply. The output side is powered by a 7805-type regulator off of the floating 12-V supply. The 12-V supply floats at the source potential of the switch FET. The low internal capacitance of the magnetic isolator and the DC-DC converter enables the floating supply to experience 1,000-V swings at a 1-MHz rate without issue. This enables a common low-side MOSFET driver to drive an N-channel MOSFET in a high-side switch application. The agile SMPS output is ground referenced in this application, but it does not need to be. The driver can operate in a totally floating arrangement if the circuit design dictates it.

The rest of the SMPS converter is textbook buck converter stuff, but the requirements are a bit unique. The output voltage must operate over a wide range. Operation into the usual resistive test load differs from the operation in the amplifier due to the aforementioned reactive load. The inductor value (L3) was determined empirically. The output capacitor (C13) was also determined through iterative testing, as was the output filter network (L2, C18, C14). The filter must allow the converter to be modulated at an audio rate. This modulation should be flat up to

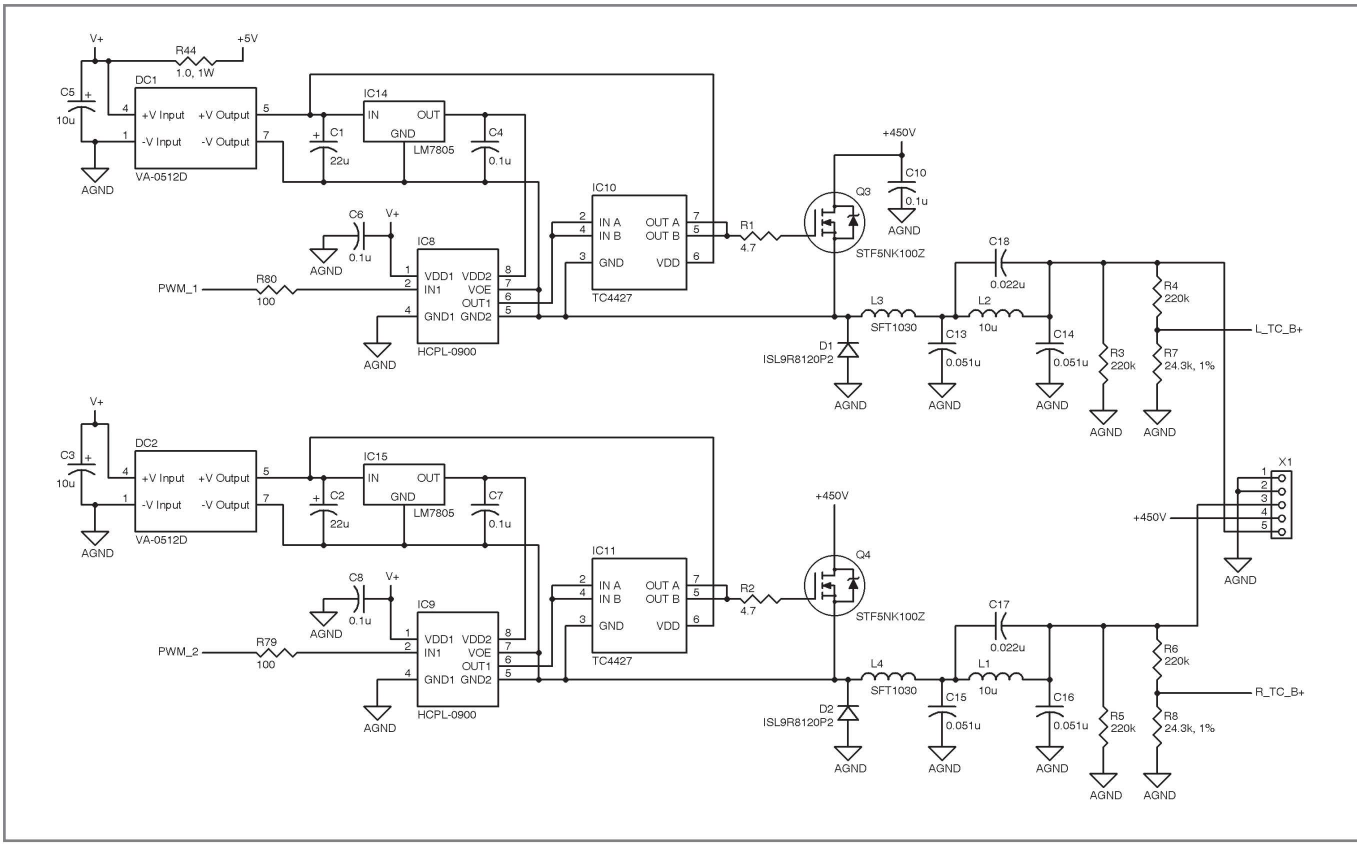

Figure 5—The floating buck converters allow a low-voltage output from the dsPIC to control a floating high-voltage supply. There is one for each stereo channel. It can't get much simpler than this.

20 kHz with minimal phase shift. The filter should attenuate the switch frequency by at least 35 dB to avoid intermodulation effects in the amplifier. There is a resistive voltage divider at each output. This is routed to an on chip A/D input pair to enable closed-loop operation if desired.

AMP SUPERVISION & CONTROL

There is ample processing power available for amplifier monitoring and control. There is hardware designed into this amplifier for the development of supervisory and control features. A MOSFET and driver circuit is included to control the high-voltage supply. It can be used to enable or disable the HV, or ramp it up slowly using PWM if desired. This feature has not been tested or connected yet. This is shown in Figure 4 and in the lower-left portion of the analog I/O schematic (see Figure 6).

Tubes require a negative bias voltage to control the current flow. The negative bias voltages are derived from the –150-V_{SOURCE} in the bias generator circuit shown in Figure 4 and in the bias generator schematic (see Figure 7). Each bias voltage is controlled from a D/A output, which is level-shifted from 0 to 5 V to 0 to –150 V using an op-amp and a MOSFET. In the current software, the bias voltages are hard coded to a predetermined value.

The unused A/D inputs monitor several operating voltages in the amplifier. Any input that may be subjected to high voltages is protected with Zener diodes and capacitors. Sufficient series resistance is included to limit rise times. The microprocessor does not have enough A/D inputs to monitor all of the desired signals. A Microchip Technology MCP6S26 PGA/multiplexer is used to switch between the infrequently scanned inputs under SPI control. The total power supply current signal, the SMPS temperature, and the tracking converter output voltage signals are routed to the four on-chip comparators. Any of these can be used to generate an interrupt that may be used to shut down the system if potentially damaging conditions exist. These monitoring functions are shown in Figure 4 and in the analog I/O schematic (see Figure 6).

An EEPROM is included for storing start-up parameters, data logging, and keeping track of operating points over time (see Figure 8). An expansion connector is provided for connecting additional hardware. It is expected that this will be used for a keypad/display module.

SOURCE CODE

I outlined a serious feature set for the amplifier design. It requires a major software development effort supported by several experiments to develop the algorithms needed for a full-featured amplifier. This effort is underway.

The code I'll present here is for a fully functioning amplifier. I have been listening to it for a few weeks and I have made basic performance measurements. All of the bias voltages were determined experimentally and hard coded as initial conditions for the appropriate variables. The gain and DC offset values for the SMPS are set via the trim potentiometers. The amplifier works very well and meets my original goals: it demonstrates enhanced performance over a conventional design, it provides a platform for feature development, and it enables hardware improvement.

Note that the main loop for the code is completely empty at this time. Once set up, the SMPS and ADC modules that are critical for the amplifiers function are interrupt-driven. There is ample room for feature development as long as the performance of the ISR is not impacted.

PC BOARDS

I designed two unique PC boards for this project. I will design a third for the SMPS to replace the current linear power supply. The linear supply is built on perf board, so it doesn't use a true PC board.

The density of the amplifier PC board is very low, there are few through holes, and the trace size is large. The PC board is well within the capabilities of home fabrication, so I made one myself.

The controller PC board has two main sections (which I laid out independently). The high-voltage section (the right side of board) operates with voltages approaching 500 V. The HV section is kept completely isolated from the logic section. It has a "moat" of ground around it, and all connections into this section are made with leaded resistors, except ground. A mixture of leaded and surface-mount components is used in the HV section. In many cases, surface-mount components do not have the required voltage or current ratings. The logic section of the PC board is pretty conventional. Surface-mount components are used in most cases. This board is beyond the capabilities of home fabrication, so I sent it to a quick-turn PC board house.

CHASSIS/CABINET

This project is intended to be a development platform, but I also intend to bring it to listening sessions and possibly an audio show or two. I need a functional chassis to support the circuitry and protect onlookers from the deadly voltage, but still allow easy access to the electronics for development purposes. I also must be able to replace or

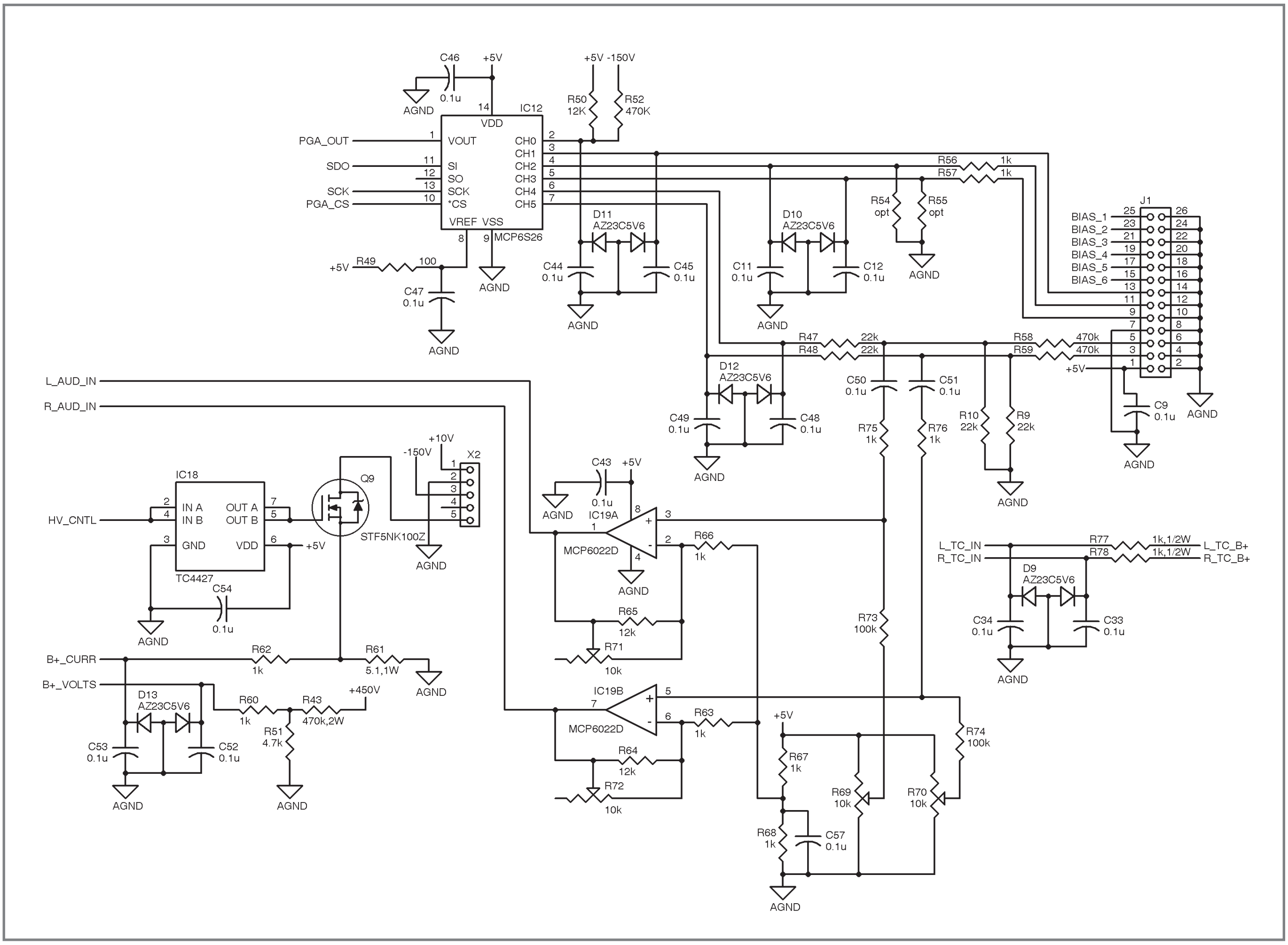

Figure 6—This is the analog I/O. IC12 is used to multiplex one A/D input for several voltage readings. IC19 provides buffered audio. IC18 is a switch for enabling the high voltage.

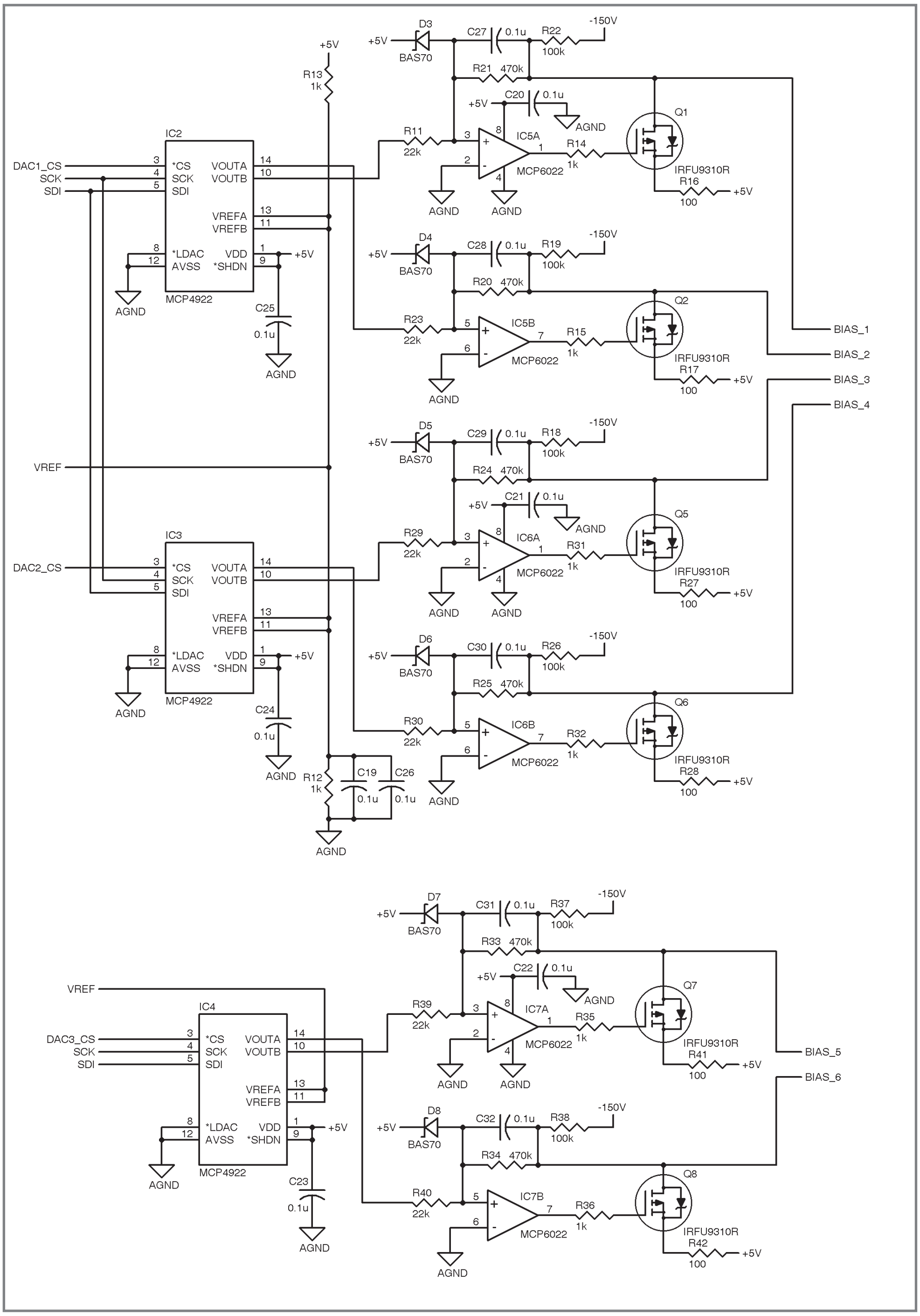

Figure 7—There are six identical bias generators. These are negative voltage supplies under DAC control. The current drain from each supply is only a few microamps.

upgrade the components or PC boards as required. Plus, I can "show off" all of the unique circuitry, not hide it under a chassis.

I mounted all of the components on top of a piece of aluminum diamond plate that slides into a groove in a wood box. The rear panel of the box is removable to allow chassis plate removal. I cut another groove for a piece of clear Lexan 1.5" above the chassis plate. This allows the PC boards to remain covered yet visible. I can remove the Lexan for experiments.

PERFORMANCE TESTING

As I write this article, the amplifier project has been operational for about a month. I haven't had the time to tweak the design or develop any new software. I made some quick measurements, but detailed testing must wait for now.

Maximum power output at 5% distortion is 38.3 W. The power at 1% distortion is 24.6 W. Distortion at 10 W is 0.33%. In contrast, similar measurements on a conventional amplifier (one of my designs) of similar size and weight generated different results. Maximum power output at 5% distortion is 9 W. The power at 1% distortion is 4.7 W. Distortion at 1 W is 0.78%. Clearly, these techniques allow for more undistorted power output and far lower distortion at the power levels found in most listening.

Does this project meet my original design goals? Yes, and it does so in a big way.

I wanted a development platform for writing code. I got it. I was expecting to double the power output of a conventional amplifier of equal size. I found much more. This technology can be applied conservatively to generate triple the power output. I have not made any efficiency measurements yet, but it looks like similar sized gains have occurred. The distortion levels have dropped to levels not usually seen in vacuum tube amplifiers, especially in the 0 to 2 W range, where most listening takes place. Many vacuum tube proponents claim that it is this distortion that gives a vacuum tube amplifier its special "tube sound." I've listened to this amplifier for a total of about 10 hours, and I can say that the "tube sound" is still in there!

At first, you might think this design is not cost-effective because the cost adder for the agile SMPS/controller is about $150. But when you step back and realize that it can be used to double or triple an amplifier's power output and figure out what it would take

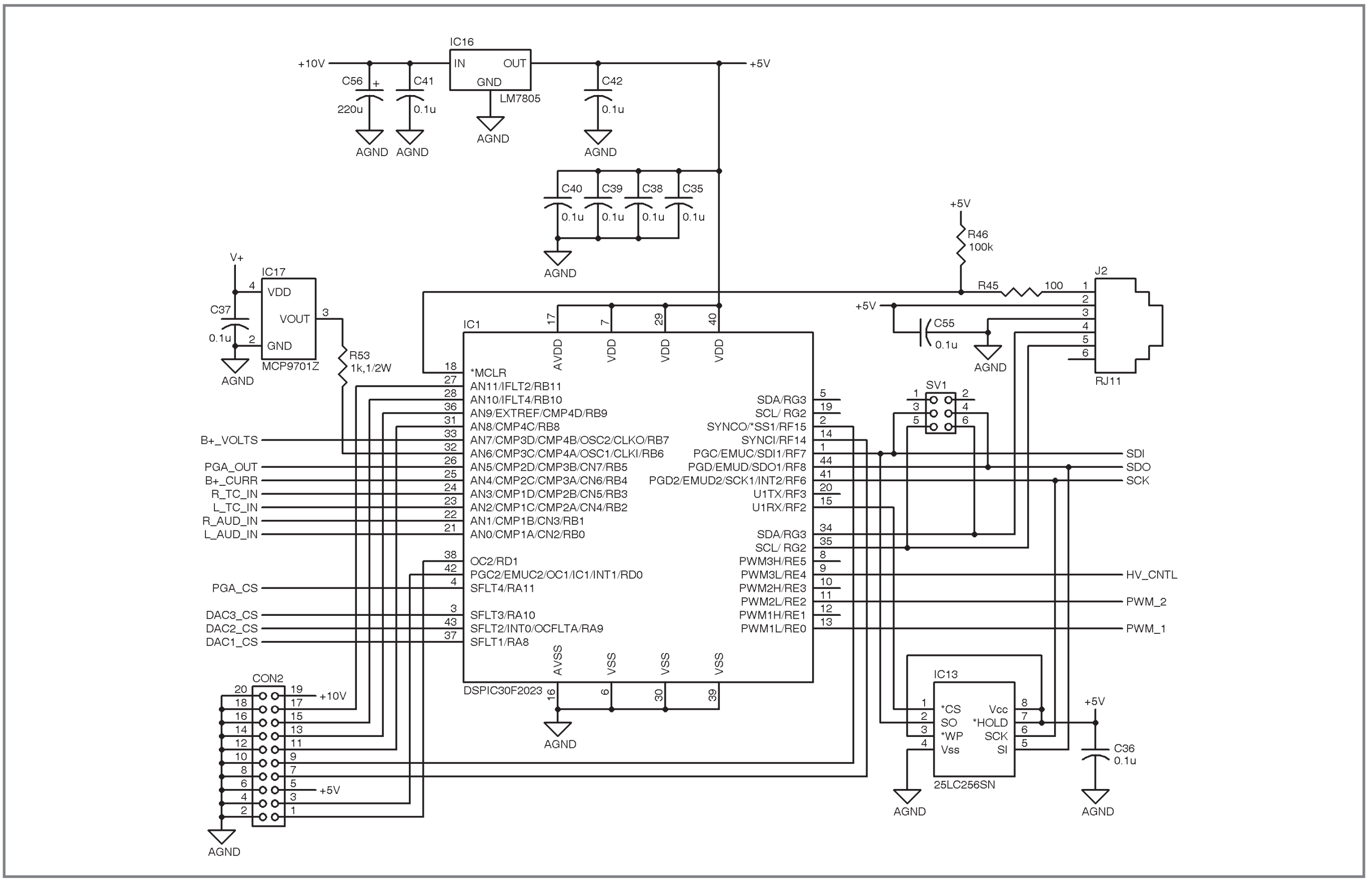

Figure 8—The circuitry includes a dsPIC30F2023, EEPROM, voltage regulator, and temperature sensor. A jack for the ICD2 is included for program development and testing.

to double the power output by traditional means, you realize that adding the controller is an overall cost savings.

This project is a high-end stereo amplifier. Most people have some sort of music reproduction or home theater equipment. Few people have (or even want) high-end equipment due to its high cost. This project is one step in direction of reducing the cost of high-end equipment. You can apply this technology to solid-state amplifiers and vacuum tube amplifiers for the musical instrument market.

WHAT'S NEXT?

My amplifier is back on the workbench. I'm using this project to develop the software for many of the features I outlined earlier in this article. There will be the inevitable hardware upgrades as well because Microchip has released a second generation of dsPIC processors made specifically for SMPSs. There are also some new ICs from Analog Devices that reduce the floating MOSFET driver to a single chip.

I plan to continue taking this design down the road toward possible production. I will likely do this in stages, with the SMPS to replace the analog power supply coming first. I may also develop a vacuum tube guitar amplifier using the same technology. These techniques can go a long way to improve the reliability of vacuum tube guitar amplifiers while enabling all sorts of new and unique distortion profiles.

George Anderson (tech@tubelab.com) worked at Motorola for 36 years as an RF engineer focused on cell phones and two-way radios. He holds a BS in computer engineering from Nova Southeastern University (graduated at age 40) and an MSEE from Florida Atlantic University (graduated at age 46). George's technical interests range from ham radio to various microprocessor-related technologies.

PROJECT FILES

To download the code, go to ftp://ftp.circuitcellar.com/pub/Circuit_Cellar/2009/231.

SOURCES

dsPIC30F2023 DSC, MCP6S26 PGA/multiplexer, PIC16C54 Microcontroller, TC4427A MOSFET driver IC
Microchip Technology, Inc. | www.microchip.com