Pax Protection System, Pt. 3

Use with a flat-cable connection, or as a stand-alone for any other amp.

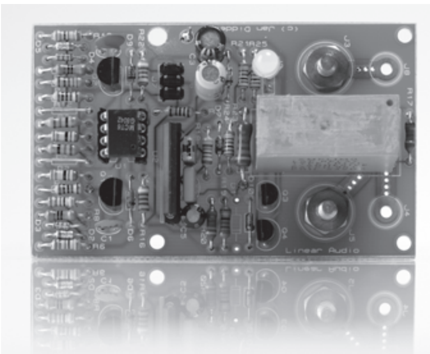

PHOTO 1: The PAX protection system.

In Parts I and II of this series about the paX amplifier, I developed a complete error-correction power amplifier. This article describes the protection system, which, constructed on a separate small circuit board, you can mount directly on the speaker binding posts (**Photo 1**). You can connect the system to the paX amplifier through a six-way flat cable, or use it with almost any amplifier provided you connect the appropriate signals. I will also discuss the Safe Operation Area (SOA) for the output devices and how it is modeled in the protection system.

A good protection system for an audio amplifier has two important tasks: speaker protection and amplifier overload protection. Speaker protection concerns possible excessive DC voltage at the amp output due to either excessive very low frequency signals or a circuit failure inside the amp. (Excessive DC output can also occur if you have a DC coupled power amp and your preamp gives out DC. If you go on a tour of your amp, it would be wise to insert—even temporarily—some input coupling caps.)

There are many convoluted circuits to disconnect the speaker from the amp through a high-power relay in case of significant DC offset at the output. These circuits often do double duty to delay the closing of the relay until after the turn-on transient, as well as immediately opening the relay when power is switched off—to avoid transient on/off thumps in the speaker.

I used a low-cost, but not well-known, IC: the uPC1237 from—among others—NEC. The NTE7100, from NTE Electronics, is pin- and function-compatible. It's an 8-pin Single-In-Line chip with all the functions mentioned above. It can handle two channels for a stereo amp, but I used one chip per channel to make it easier to construct the amp as dual mono.

For the speaker relay I used a little-known device specially designed for this duty and sold by the Dutch company Amplimo. The relay has two parallel internal contacts, one heavy-duty tungsten 100A contact and a smaller gold contact. When the relay closes, the tungsten contact closes first, and is then bridged by the gold contact. The reverse takes place when opening the relay.

CIRCUIT DIAGRAMS

The overall protection system is shown in **Fig. 1**. (The blocks for the Indicator and the Safe Operation Area protection are described later.) The uPC1237 has an internal 3.4V shunt regulator at pin 8, and the supply current is provided by R19 and R20. The relay switching output (pin 6) drives the relay through R18.

Jumper J6 sets the circuit operation. If jumper J6 is placed, the circuit becomes "re-entrant": if there is an error input, the relay falls off, and, after a short delay, is activated again. If, at that point, the error has disappeared, the relay stays activated; if not, it falls off again and the cycle repeats. If J6 is not placed, the relay falls off when an error is present and you must switch the power off and on again to reset the circuit.

DC OFFSET SHUTOFF

Pin 2 of U2 is the DC offset input. AC on the amplifier output signal is removed by R17-C3 and the DC offset is sensed. Although the uPC1237 has only a unipolar supply (the amplifier's VCC+), pin 2 does accept bipolar signals. The calculations are a bit complex because the internal positive and negative thresholds are not equal. It is all explained in the datasheet. With some care you can set the threshold for positive and negative offset to the same value, at 0.6V DC. This value is set by R17.

SWITCH-ON DELAY

You will also see that a sample of the AC from the supply transformer is connected to the uPC via R21 and D8 to C6. This part of the circuit delays the speaker switch-on after a power-up to make sure the amp has stabilized and there are no switch-on thumps. When the power is turned off, this signal will disappear immediately, before the supply capacitors have a chance to discharge. Doing it this way, the speaker relay will be opened before the turn-off thumps occur.

SAFE OPERATION AREA

The second task of the protection system is to guard the output devices against excessive low impedance loads and shorts. Michael Kiwanuka has written a very informative article on Safe Operation Protection in audio power amplifiers[1]. My own protection circuit is different, but was inspired by Mike's design and has many things in common with it. **Figure 2** shows the circuit, which receives two types of information from the power amp. The first is the I_c in the output devices through VprotP and VprotN (via connector J7 in **Fig. 1**). This actually is the voltage across the output stage emitter resistors. Second, through the components connected to the supply and Vout, a voltage is developed that represents V_{ce} of the output devices. (Note that the circuit values in **Fig. 2** are illustrative only. This article later explains the circuit in detail and how to calculate the various component values in a specific case.)

The purpose of the SOA protection is

to limit the combinations of V_{ce} and I_c for the power devices to a safe value. Normally, such a protection circuit would be arranged to take away the drive from the output driver transistors to limit the available output current. The protection transistor collector (Q1 or Q2, **Fig. 2**) would normally be connected to the base of the (pre) driver transistor in the output stage. Q1/Q2 turns on when its V_{be} exceeds 0.6V, shunting the driver base signal away. But in my experience, even with a V_{be} of only a few 100mV, the protection transistor starts to influence the driver base signal, resulting in increased distortion.

For this reason I decided to make this an on/off protection circuit: the protection transistors drive the "overload" pin (pin 1) of the uPC1237 through the dual optocoupler U1, an MCT6. If overload occurs, pin 1 of the uPC is set high via R1 (**Fig. 1**) and the uPC opens the speaker relay. I have the uPC set for auto re-entry by jumpering J6. In this mode, the speaker relay will be opened again if the overload is no longer present.

You can argue that the protection system should work by limiting the output in case of overload and not by disconnecting the speakers. I agree that for PA duty this would be preferred, but for home use it is a very minor nuisance, if at all. But doing it this way prevents influencing the music signal by the circuit when there is no need for protection activation.

In using this amp for about a year now, I have never seen the protection system disconnect the speakers, except for one case in which I had a problem with a balanced cable which put a signal with 2.5V DC on the amplifier input. I immediately heard the off cycling of the amplifier, so I switched it off and managed to find the problem. After I solved the problem, all was as it should be. So, for me, this works quite well.

STATUS INDICATOR

Then, last, there is a small bi-stable circuit that takes the relay drive voltage to drive a bi-color LED, which you can place on the front panel. The LED will be one color when the amplifier is in turn-on delay or in protection and another color if the amplifier is operating normally. This circuit is shown in **Fig. 3**. All components shown in **Figs. 1–3** are on the output/protection (o/p) board, shown in **Fig. 4**.

CONSTRUCTION

Before building the o/p board, you should first complete and test the amplifier you want to use. You need the amplifier to test the o/p board, which you can populate first with the DC and delay circuitry around U2. Start with the components shown in **Fig. 1**.

Next, construct the six-wire flat cable as shown in Fig. A in the Construction Guide (audioXpress.com). Be sure to orient the notches in the six-pin headers exactly as shown! (Consult **Fig. 5** for connections to a different amp than the paX.) Connect the two boards with the flat cable, again noting the header notch

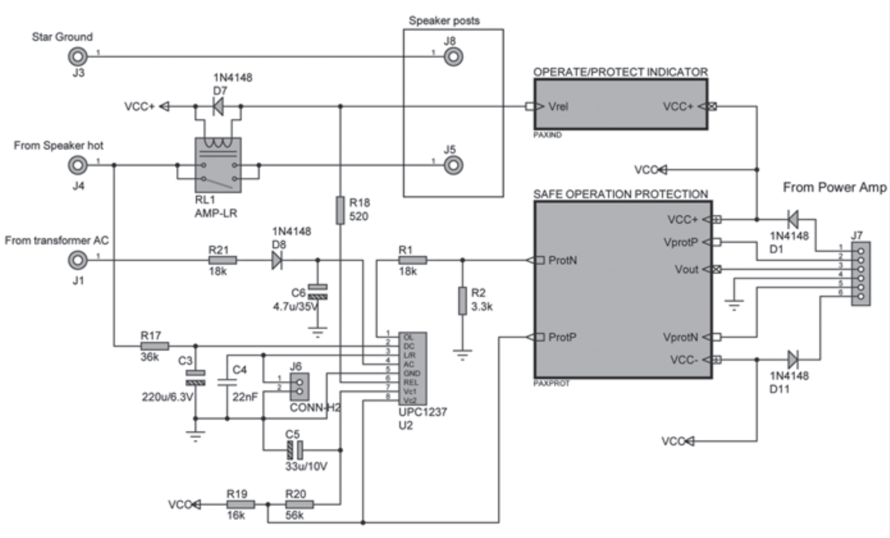

FIGURE 1: Overall protection system.

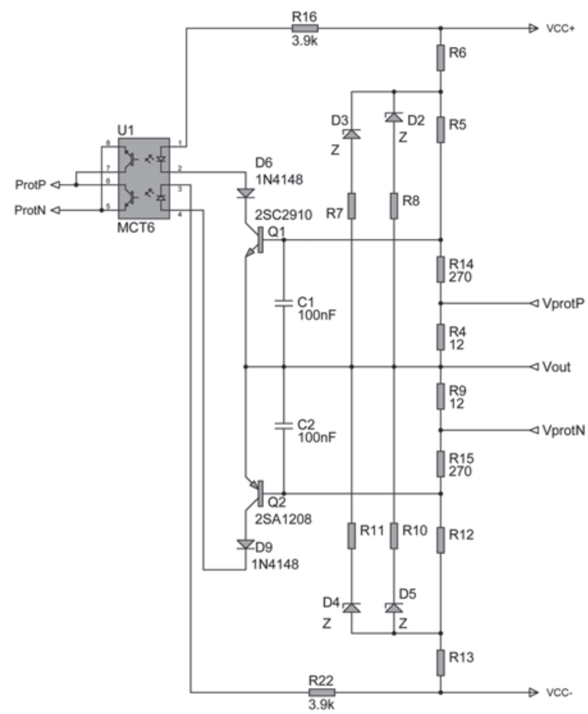

FIGURE 2: Safe Area Protection circuit.

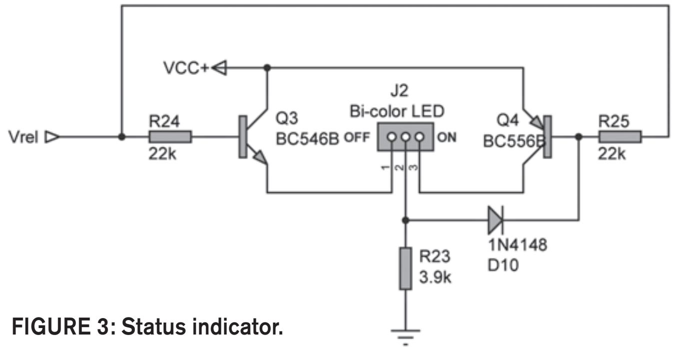

FIGURE 3: Status indicator.

position as indicated on the PCB silkscreen. Also connect one side of the power transformer secondary (the AC point) to the protection board at J1 as shown. Don't connect a speaker yet, nor the speaker wire from the amp to the protection circuit.

When you now switch on the amplifier, you should hear the relay pull in after a few seconds delay. If you find it too fast, you can increase C6 for a longer delay. If you switch off the amp, the relay should immediately open.

Next check the DC offset protection. Temporarily connect a resistor of 100kΩ from the positive or the negative supply to the speaker input point on the protection board (J4). The relay should fall off. Check this with both J6 set and removed to verify correct operation. Then, install all components for the status indicator in **Fig. 3**.

The PCB has labels "ON" and "OFF" at J2. That indicates which pin will be active at which status. If you use a red/green LED, you would connect the RED pin to J2/OFF and the GREEN pin to J2/ON. You may choose to repeat one of the tests described above to verify the correct operation of the status indicator.

The last part deals with the SOA protection components. Put all remaining parts on the protection board. Connect the flat cable, and connect the speaker output from the amplifier (amplifier J3 to o/p board J4), as well as the star ground wire (o/p J3 to supply star ground).

Switch on the amplifier and verify that it works normally. Then, to simulate an overload situation, connect a resistor of 10kΩ between the positive supply and the node Q1(base)/R14/R5/C1 and verify that the relay falls off. Do the same with the negative supply and the node Q2(base)/R12/R15/C2.

Note: If you don't mount the o/p board directly on the speaker output posts, you can connect the speaker return wire directly from the output post to the supply star ground without going through the o/p board. The speaker "hot" connection then goes from the o/p board J8 to the output post.

STAND-ALONE!

This article focuses on using this o/p board with my paX amplifier. But you can use it with any amplifier, provided you adjust the SOA circuit values as re-

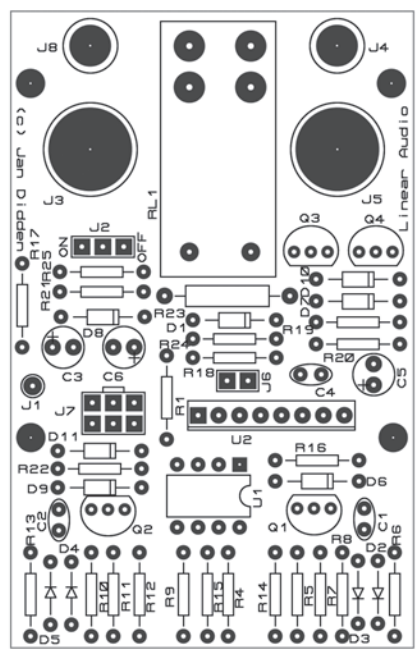

FIGURE 4: Component placement of the double-sided PCB for the o/p board.

quired, as described in the sidebar. **Figure 5** shows the connections that you need to make from your amplifier to the o/p board through J7. *aX*

REFERENCE

1. Michael Kiwanuka: Transparent V-I Protection in Audio Power Amplifiers, *Electronics World*, Oct. 2002.

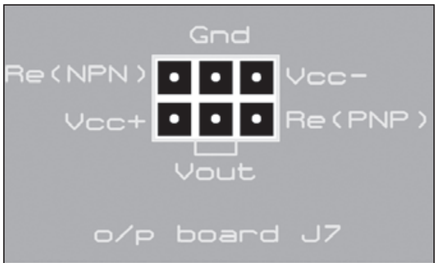

FIGURE 5: Connecting the o/p board to other amplifiers.

Components List Resistors

(0.25W metal film)
R1 = 18kΩ
R2 = 3k3Ω
R4, R9 = 12Ω
R5, R12 = 9k1Ω*
R6, R13 = 9k1Ω*
R7, R11 = 630Ω*
R8, R10 = 780Ω*
R14, R15 = 270Ω
R16, R22 = 3kΩ9
R17 = 36kΩ
R18 = 520Ω
R19 = 16kΩ
R20 = 56kΩ
R21 = 18kΩ
R24, R25 = 22kΩ
R23 = 3.9kΩ 1W

Capacitors

C1, C2 = 100nF ceramic
C3 = 220µF 6.3V
C4 = 22nF ceramic
C5 = 33µF 10V
C6 = 4.7µF 25V

Semiconductors

D1, D6-D11 = 1N4148
D2, D5 = zener diode 18V 0.5W*
D3,D4 = zener diode 15V 0.5W*
J2 = Dual color LED
Q1 = 2SC2910
Q2 = 2SA1208
Q3 = BC546B
Q4 = BC556B
U1 = MCT6 (Fairchild)
U2 = UPC1237 (NEC) or NTE7100 (NTE Electronics)
*: These are nominal values. See sidebar for calculations and adaptions to other amplifiers.

Miscellaneous

J6 = header 2 × 1 pin
J7 = 2 × 3 pin DIL flatcable header
RL1 = Amplimo -LS relay
DIL socket 2 × 4
SIL socket 1 × 8 pin
(See www.pilghamaudio.com for kits)

CALCULATING AND SETTING UP THE PROTECTION SYSTEM

The amplifier protection circuitry uses Safe Operation Area (SOA) protection. In this section, I address the specific design equations and how to develop the circuit values for the SOA part.

Figure A shows the various curves that you need to develop the SOA protection for two pairs of output devices. I_c (A) is on the vertical scale, V_{ce} (V) is on the horizontal scale. When V_{ce} is zero, it means that V_{out} is equal to V_{supply}. In practice, there will always be a few volts V_{ce} remaining at maximum output, but I will disregard that for the moment.

Curve B shows the safe combinations of DC I_c and V_{ce} for two parallel STD03 Sanken Darlingtons used in the paX amplifier. Curve C shows this for loads lasting no longer than 100ms. This means that combinations of I_c and V_{ce} that fall below and to the left of the curve are safe, but as soon as the curve is crossed, the protection system should activate. Because music is impulsive and not DC, you could argue that protection for curve C would be sufficient. If you use curve B you have an additional safety factor, but you are not using the amplifier to its maximum capability for music reproduction. I will, therefore, use some intermediate values.

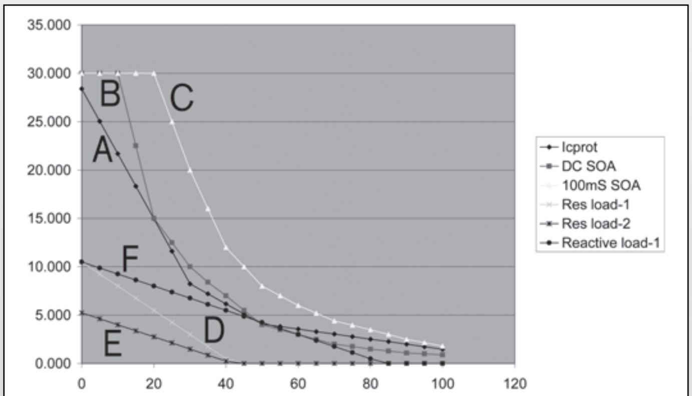

FIGURE A: SOA, load lines, and protection locus. See text for explanations.

Figure A also shows some load lines, which are combinations of I_c and V_{ce} required to drive a (resistive) load, assuming ±44V supplies. The lowest one, E, is an 8Ω load; Curve D is 4Ω. For example, in the 4Ω case, you see that when V_{ce} = 0, the output voltage is the supply voltage (44V in this case) and thus I_{out} in 4Ω is 11A. Curve F is also for a 4Ω load, but now with a maximum reactive component of 90° phase shift. This is a particularly mean load.

With V_{ce} = 60V, V_{out} is actually -16V negative, but I_c is still positive (about 3A). That means that the upper transistor (N device), with a 60V V_{ce}, sources current even with a negative V_{out}! Under these circumstances (which can happen easily with real speaker/crossover loads), quite high V_{ce} to I_c combinations can occur although the device dissipation is very much limited as shown in the SOA cure. For instance, in this example, at V_{ce} = 60V and I_c = 3A, allowed dissipation (per device!) is 90W, although the datasheet calls this a 160W device.

So, you can put in a simple current limiter that follows, say, the 4Ω complex load line. But then you cannot use the large safe area, especially at low V_{ce} and I_c between 10A and 30A, which may come in handy with speaker loads that have low resistive impedance dips. It is clear from **Fig. A** that a simple current limiter is not enough.

You want to "model" the Curve B DC or Curve C 100mS in the circuit with some nonlinear circuit elements, and my target SOA protection curve is labeled A. You can see that at higher V_{ce} I allow more dissipation than the DC curve. The reason is that these high V_{ce} excursions only take place with reactive loads and therefore are by definition not DC loads but short-term. The target curve has three inflexion points at V_{ce} = 30V and V_{ce} = 50V.

The way I implemented this is shown in **Fig. B**, which is the positive half of the full circuit given in **Fig. 2** about the protection circuit. (Again, part values are illustrative only; you can calculate the exact values for your amp later. The negative part works similarly, so I will not discuss it.)

There are four distinct points on the target curve (A). The first and last points are defined by V_{ce} = 0 and I_c = 0, respectively. The other breakpoints are at V_{ce} = 30V and V_{ce} = 50V. These two breakpoints are caused by diodes D3 (for 30V) and D2 (for 50V). Remember: all currents are for two parallel devices! At each breakpoint, the diode(s) start to conduct and shunt current away from R5, so that Q1 conducts later.

To calculate the component values for this rather involved circuit, start with the simple part: if V_{ce} = 0, the maximum allowed I_c is 28A for two output pairs. Also at this point, V_{out} = VCC so there is no current coming from R6/R5. The voltage to turn on Q1 comes exclusively from the voltage drop across the output devices' emitter resistors, through Rs. You need to ensure that at 28A the voltage at Q1b is approximately 0.6V. Although there are two emitter resistors (0.22Ω) and two Rs resistors (100Ω) in the circuit, they are in effect parallel, so from now on use Re = 0.11Ω and Rs = 50Ω. With 28A through the parallel value of Re, V_{re} = 3.1V, which is attenuated through Rs and R4: 12/(50 + 12) × 3.1 = 0.6V, which is close enough.

Now it gets interesting. Move to the breakpoint where V_{ce} = 30V. The allowed I_c is about 8A (curve A). Set R14 to 270Ω and then calculate the rest. Disregard D2/R8 and D3/R7 for the moment; you just need to be sure later that that was justified (that the diodes don't conduct at up to V_{ce} = 30V).

V_{ce} = 30V and allowed $I_{c\ max}$ = 8A gives an effective Vs of Vs = R4/(Rs + R4) × (Re × I_c), which, with the given values, is 0.17V. You need V_b = 0.6V, so the current from R5 should generate the remaining 0.43V across R14. So this current needs to be I_{R5} = 0.43/270, or 1.6mA, which also flows through R6, of course. With a V_{ce} of 30V (disregard the small V_{ce} loss across Re), that would make R5 + R6 = (30 - 0.6)/1.6 = 18.4kΩ. It doesn't really matter how you split up the total value (it does matter for the other values, of course, but not for the functioning), so make them equal and round them off: R5 = 9kΩ and R6 = 9kΩ.

At this breakpoint (V_{ce} = 30V), diode D3 should be on the verge of conduction, so D3 should be a zener equal to the value of Vm. Because you have 1.6mA through R6, Vm = 30 - (1.6 × 9) = 15.6V, making D3 a nominally 15.6V zener.

Now move to the next point, 50V/5A. Analogous to the 30V point, D2 should be on the verge of conducting so you can disregard both it and R8 for now.

As before, calculate the contribution of I_c at Vs: Vs = 12/(12 + 50) × (0.11 × 5), which is 106mV, so the V_{ce}-derived current from R5 and R6 should add 0.6 - 0.106 = 0.494V at Vb; therefore, I_{R14} = 0.494/270 = 1.8mA. This 1.8mA also flows through R5 and R6, so Vm = 0.6 + (1.8 × 9) = 16.8V. This, of course, means that D2 should be a nominally 16.8V zener.

Still at the V_{ce} = 50V point, with Vm = 16.8V and D3 a 15.6V zener as calculated, you have 1.2V across R7. The voltage across R6 now is V_{R6} = 50 - 16.8 = 33.2V, so I_{R6} = 33.2/9k = 3.7mA. Because 1.8mA flows through R5, 1.9mA must flow through R7 with 1.2V (Vm - 15.6V from D3) across R7, so R7 = 632Ω.

Moving on now to 100V/2A, it becomes pretty boring: I_c = 2A, so the contribution from Re to Vs is Vs = 12/(12 + 50) × (0.11 × 2), which is only 43mV, and the remaining V_{be} = 0.6 - 0.043 = 0.557V must be generated by the current through R5 and R14, so I_{R14} = 0.557/270 = 2mA. This current also flows through R5, so Vm = (2 × 9) + 0.6 = 18.6V.

The current through R6 is: I_{R6} = (100 - 18.6)/9 = 9mA, so the excess of 9mA - 2mA = 7mA needs to be shunted away through D2/R8 and D3/R7. $V_{R7} = V_m - V_{D3}$ = (18.6 - 15.6) = 3V with R7 at 632Ω, so I_{R7} = 4.7mA, which sets I_{R8} to 7 - 4.7 = 2.3mA. Thus, V_{R8} = 18.6 - 16.8 = 1.8V, so R8 = 783Ω.

Phew! There you have it, but it would be nice if there was some way to verify this before committing solder (and parts). I have disregarded several considerations, such as the loss of V_{Re} for V_{ce}, the base current for Q, and some roundings in the calculations. I have developed a spreadsheet to try to double-check all this (available on www.linear-audio.nl and www.audioxpress.com). It works backwards from what I just did: using the component values in the circuit, it calculates at each V_{ce} the Vb contribution from the current through R5, and then finds the I_c that would add just enough voltage across Re to make V_{be} = 0.6V.

Plotting those pairs of V_{ce} and I_c, then, should give the actual SOA curve (A) I wanted in the first place. You see that the spreadsheet shows reasonable correspondence to our values, but there are some deviations. The reason is that once I had the spreadsheet, I "played" with the component values to get the best fit to the SOA curve, or to get "nice" values for parts. I used a Vcc of 44V and a Vce(min) of 2V in the spreadsheet. Also, manipulating the R5 and R6 ratio lets you home in on standard zener values.

The way to do that is to use Excel's solver to find the ratio of R5 to R6 that results in, say, D3 = 15V. Some more playing, then, gets you to a value close to a standard value for D2 as well. In the spreadsheet version on the website, I used the solver to adjust the R5/R6 ratio (cell B12) for a D3 (cell J3) value of 15V and just by luck the D2 value came out to 18V, both standard zener values. The R5/R6 ratio is now 0.51 instead of 0.5. Just try it, you can't break anything, but don't mess with the formulas unless you know exactly what you're doing!

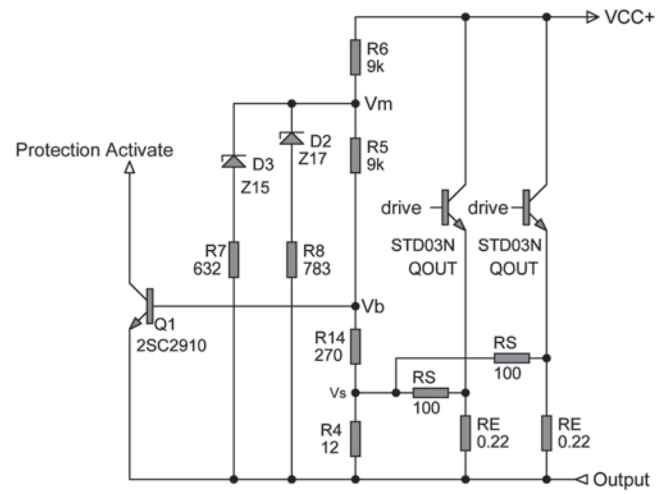

FIGURE B: Positive half of the SOA protection circuit.

I developed the spreadsheet for this particular application and did a fair amount of checking, but I cannot guarantee that it is without errors. Remember that this spreadsheet gives you an approximation of the real hardware only, but since I stayed on the safe side with the protection curve (A), small deviations won't cause disaster. If you find any errors, please let me know and I will update it, giving credit where it is due, of course.

It is not easy to test the accuracy of such a protection system in the real world, and mistakes could be expensive. So this spreadsheet that double-checks the calculation of the values and then works backwards to verify them is important gaining confidence with this circuit. ■