Improved Power MOSFET Protection Circuit

Lessons learned from the Hafler Five Hundred output stage failure analysis.

By Daniel Dufresne

This article describes the failure analysis on a "Hafler Five Hundred" solid-state stereo power amplifier. Following the failure analysis, I list potentially weak points in the original circuit and describe a new output circuit designed to minimize the risks of power device failure. This protection circuit features improved output transistor overvoltage and overcurrent protection; uses new, in production, plastic cased, TO-3P, output devices; and can be adapted to many existing commercial power amplifiers that use similar metal-oxide-semiconductor field-effect transistors (MOSFETs) as output devices. The resulting modified amp meets all the original specifications.

This article also contains information about drop-in replacement device availability for the TO-3 case. This information is useful for the repair of any amp that uses metal-cased lateral MOSFETs in the output stage.

WHAT IS A HAFLER FIVE HUNDRED?

The Five Hundred, also known as the DH-500, was manufactured by the Hafler company between 1980 and 1989[1]. In 1987, Rockford Corporation purchased the Hafler line of products. The DH-500 is a 255W per channel stereo amp. The output transistors are lateral-type MOSFETs, which are sufficiently different from the more common vertical MOSFETs so that they are not directly interchangeable.

The exact types used in the amp are no longer manufactured, so when these transistors fail, you will have difficulty finding replacements, which can be very expensive. Also, the pool of old DH-500s that you can use as a source of scavenged parts is limited. Amplifier owners believe these are very good amps, quite comparable with current in-production models. Check the positive reviews on the web[2] from owners of these fine amps.

PHOTO 1: Failed MOSFET, case cut open with saw, showing vaporized drain bond wire. The square inside is the transistor die. The two small circular areas are the two pins. One is missing the bond wire.

If you just want to repair your amp without doing any modifications, I give information on appropriate drop-in replacement parts and a list of suppliers. But read on still, because just replacing the transistors is not the best or safest long-term solution. Although this article is about the Hafler DH-500, you can apply the information to other Hafler amps, such as the DH-220, and to amps from companies such as Perreaux, Soundcraftsman, and others that use the same lateral type power MOSFETs.

BEFORE WE BEGIN. . .

Article parts. This article includes the following sections:

1. A short description of problem areas with the original circuit leading to potential device failures.
2. A description of the new circuit, designed for improved protection.
3. A protection circuit measurement section showing that the new circuit meets the design goals.
4. A comparison of distortion and other audio measurements—made on the modified amplifier—with the manufacturer's original specifications.

For further repair. I assume your amp is working properly, except, of course, for the defective power transistors. I will not troubleshoot your amp. Those who experience front-end-related problems—beyond their repair capabilities—can contact Musical Concepts/Musical Design[1]. For general repair information and troubleshooting guides, see references 3, 4, and 5.

Schematic and manual. You can find the "Instructions for assembly and operation" manual for free at the Hafler website[6]. Download, save, and print the manual. You will get an Adobe Acrobat® Reader compatible document. The file size is 838KB, 25 pages. I will refer to these instructions as the "manual" from here on. It contains lots of useful information on the original amp such as specifications, circuit description, schematic diagram, component values, and a pictorial diagram.

Total project parts cost for a complete stereo amplifier modification is about $225 and should take four to six hours to complete.

Important safety-related note. Because of the presence of exposed terminals carrying lethal voltages within the amp, this project is not recommended for beginners. Although, if you know which end of the soldering iron to hold and have read and understood your multimeter's manual section on the proper and safe way to measure voltages higher than 40V, you can take on this project.

ORIGINAL CIRCUIT PROBLEMS

The lateral-type power MOSFETs originally used in this amp were made only by Hitachi, Ltd. and are now out of production. The Hafler company is also out of stock on these items. The devices used were specially sorted by Hafler, probably according to the gate threshold voltage value. They are type 2SK176 for the N-channel, and type 2SJ56 for the complementary P-channel. Some of the most important maximum ratings and characteristics are Vds 200V, Id 8A, Pd 125W, Vgs 20V, and TO-3 case.

Often the parts are labeled only with the end of their identification, so just "K176" or "J56" appears on the case, the "2S" being implied. In my amp they bear the Hafler company part number and sorting category "QP113, 2" for the P-channel or "QN113, 4" for the N-channel. Each channel uses three transistors of each polarity.

REPLACEMENTS

A friend offered to sell me a non-functional DH-500, which I bought for a most reasonable sum, and this is how I started this small project. Inspection revealed that most of the amp's output transistors were defective. The first thing I did was to look for replacements. Exicon and Magnatec now manufacture drop-in replacement devices in the same TO-3 metal case and also in a plastic TO-3P case.

The Exicon numbers are ECF10N20 for the N-channel, and ECF10P20 for the P-channel, both in a TO-3 case and selling for £6.66 UK[7]. The Magnatec parts are BUZ901 for the N-channel, and BUZ906 for the P-channel, all in a TO-3 case. These go for about £8.00 UK[8]. All prices are from May 2006. Although I have not tested these, they look to be drop-in replacements. However, none of the devices are sold matched or sorted.

I decided that before I spent money on this, I better make sure the new transistors would not fail as the old ones did. Yes, parts fail, but in this case too many transistors had failed (8 out of the 12 output transistors were unserviceable). So I decided to see whether I could find

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a failure mode that would explain the type of fault I had observed.

You can analyze the original circuit to determine the cause. For the next part I refer you to the manual for details about parts identification and the schematic. The parts reference identification is from the manual.

FAILURE HISTORY

Someone else had worked on the unit I bought, so I did not know the exact failure history. Here is what I found: All six N-channel output MOSFETs, as well as two of the P-channel, were defective. Because the output devices were already removed and placed in an antistatic bag, I could not say from which channel they came. On the left-channel amp board, bipolar transistor Q13—the negative polarity driver—had its base lead missing (melted?), both diodes D13 and D14 were shorted internally, and resistor R9 was physically broken.

The MOSFETs had all failed open circuit, drain to source, as measured by testing the parasitic diode between the source and drain. I cut open three of the cases (**Photo 1**) and found that on all three units the drain bonding lead was melted completely and the die was partially melted. The only way to melt a bond wire is to apply too much current for too long.

GATE TO SOURCE VOLTAGE LIMITING

In the original circuit, the output MOSFETs are protected only by a unipolar gate voltage limiter. The circuit is made out of a series-connected signal diode and a zener diode: D11, D12, D13, and D14. Some designers believe that with power MOSFETs "no complex power limiting or protection circuitry is needed"[9]. Others think that for MOSFETs, limiting the Vgs voltage value will limit the drain current to a safe value. Neither idea is supported by facts, at least it is not so for all devices or all operating conditions.

Before proceeding further, you should read the manual, which gives a good description of the amplifier circuit. I used the simplified schematic in **Fig. 1**

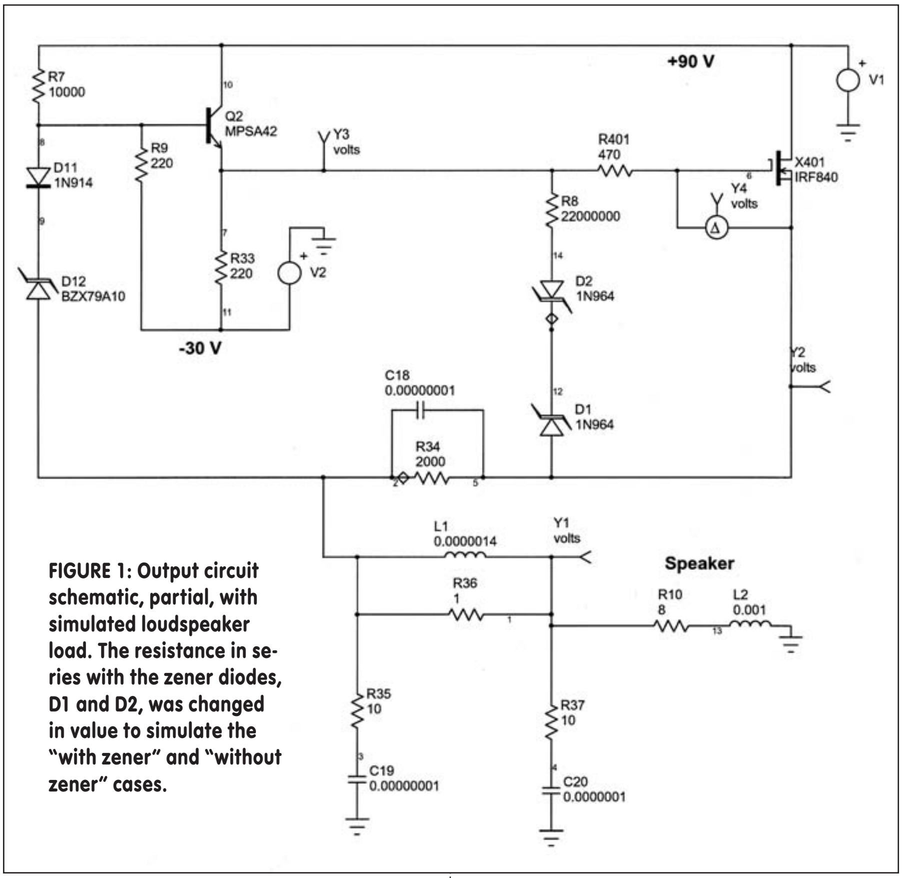

FIGURE 1: Output circuit schematic, partial, with simulated loudspeaker load. The resistance in series with the zener diodes, D1 and D2, was changed in value to simulate the "with zener" and "without zener" cases.

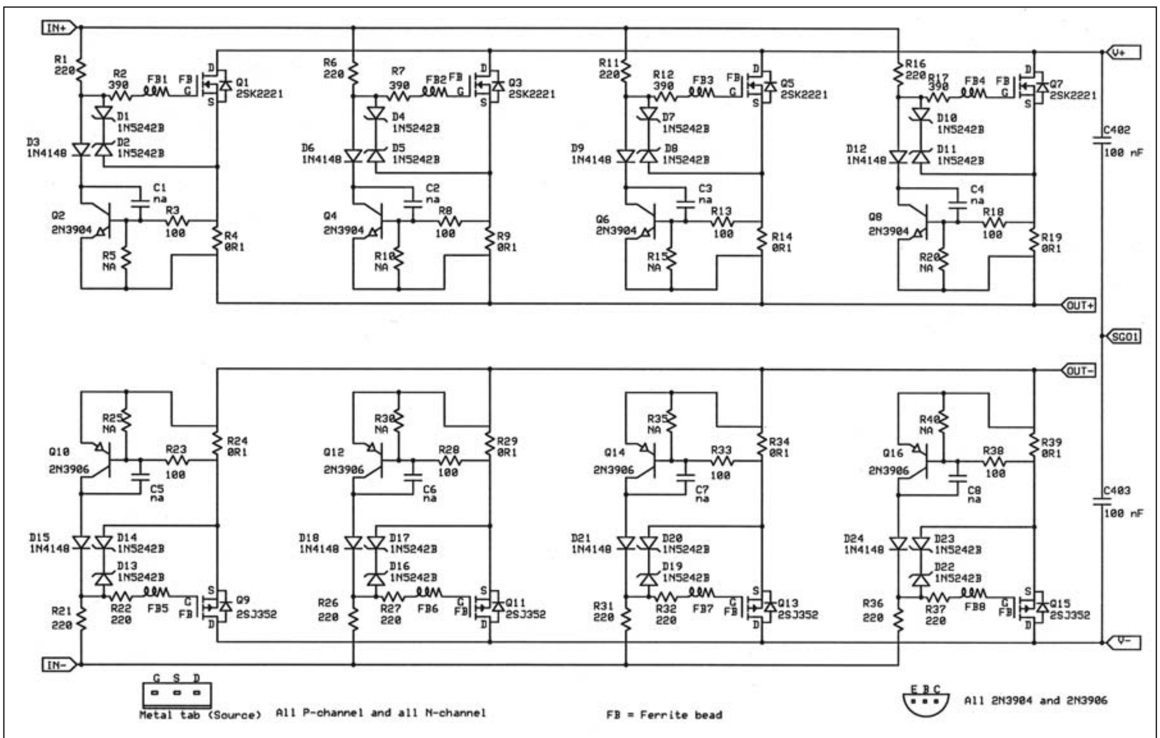

FIGURE 4: New output assembly schematic, showing all eight sub-circuits, four with N-channel and four with P-channel MOSFETs.

for circuit simulation. It shows the schematic of a section of the output circuit with a loudspeaker load.

Suppose that at a particular instant, the amp generates –28V at the output. The load is a loudspeaker—a full-range type—but it could also be just a subwoofer with a series inductance or a bi-amplified loudspeaker system. I modeled this load with an equivalent series circuit made of an 8Ω resistor and 1mH inductor, which are quite typical values[10].

In this example the load current is –3.5A, and at this precise instant, the 2A speaker fuse opens. When it does, the energy stored in the circuit inductance generates a positive voltage. Circuit simulations show that you can generate 100V or more this way. This voltage is coupled through the various circuit components and appears across the gate-to-source terminals of the N-channel MOSFETs, Q401, Q402, and Q403 (I used only one transistor in the simulated circuit).

Figure 2 shows SPICE (Simulation Program with Integrated Circuit Emphasis) simulation results for the original circuit and the new circuit, showing the gate-to-source voltage versus time, for a load current of –3.5A at the time the (simulated) fuse blew. The bottom curve shows the –100V peak across the gate-to-source terminals of the MOSFET for the original circuit. Such an overvoltage is likely to lead to instant failure in the MOSFETs and other components, similar to the ones I observed in the amp. The top curve shows that the new circuit limits the overvoltage to about

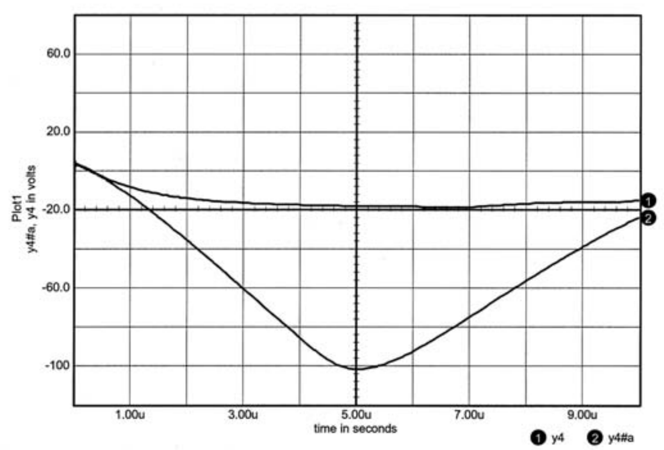

FIGURE 2: SPICE simulation results for the original circuit and the new circuit, showing the gate-to-source voltage for MOSFET X401 vs. time. At the start, the current is –3.5A in a series-connected load, made of one 1mH inductor and an 8Ω resistor. Starts at the simulated fuse blowing. For the original circuit, curve 2, the gate voltage peak is at 5μs and at about –100V. With the added zener diodes, curve 1, the voltage reaches 18V.

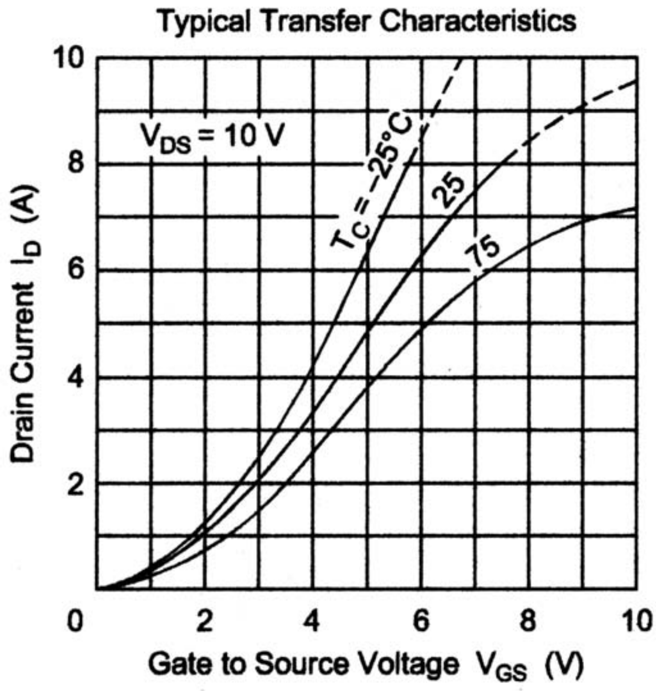

FIGURE 3: Typical transfer characteristics, drain current versus gate-to-source voltage, for the Renesas Technology Corp. 2SK2220, 2SK2221, with temperature of –25° C, +25° C, and +75° C. To the best of my knowledge, this data is identical for the original 2SK176 device. Source: Renesas Technology Corp., used by permission.

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18V peak. You will need to add a proper gate-to-source overvoltage protection feature, as part of the new output circuit, to limit future failures due to this phenomenon.

LIMITING THE DRAIN CURRENT

Typical 2SK176 device drain current, Id, versus gate-to-source voltage, Vgs, curves are identical to the 2SK2221 curves (**Fig. 3**). These show that limiting Vgs to 10V does not limit the drain current to a value that is always less than the device maximum-rated value of 8A. At +75° C the current is about 7.3A for a Vgs of 10V. But for anything other than a typical device, operated at a lower temperature, there is a risk of failure, as the current is typically 9.5A at +25°C at the same Vgs value of 10V. The 9.5A current value is above the maximum 8A rating for this device and will lead to failure.

Because the transistor manufacturer does not give limits on these curves—just typical device data—you cannot tell how much above the maximum the current can go for all devices under all operating conditions. Also of note is the fact that these curves cover only a single Vds value.

To verify this I ran tests on one of the remaining original transistors, a 2SJ56. With the drain-to-source voltage held at 50V, I needed only 5.92V gate-to-source to get a drain current of 8A. I ran the test with a 10ms pulse to limit dissipation. So the original circuit is also lacking proper current protection and this needs to be addressed in the new circuit.

OVERVOLTAGE DRAIN TO SOURCE

The main filter capacitor voltage is directly related to the supply-line voltage. If the supply-line voltage fluctuates, so does the capacitor voltage and also the voltage applied across the MOSFETs from drain to source. The line supply voltage value can be 6% high—from the nominal value—all the time and still be within acceptable distribution voltage limits.

Data11, 12 shows the expected supply voltage variations for various surge duration. Figure 5 from reference 12 (not shown here), in fact, goes to higher and higher voltages for shorter and shorter times. The curve stops at close to 375% of the nominal supply-line voltage at 0.001 time, in supply-line cycles. If not limited, this overvoltage will couple to the output devices. In short, the MOSFETs are exposed to drain-to-source overvoltage conditions and need some transient voltage protection.

So the problems to address are:

1) The original lateral MOSFETs are no longer available.

2) The original circuit does not protect the gate against all damaging overvoltage events.

3) The original circuit does not limit the drain current to a safe value for all operating conditions for all MOSFETs.

4) The supply voltage is not limited and protected against overvoltage transients.

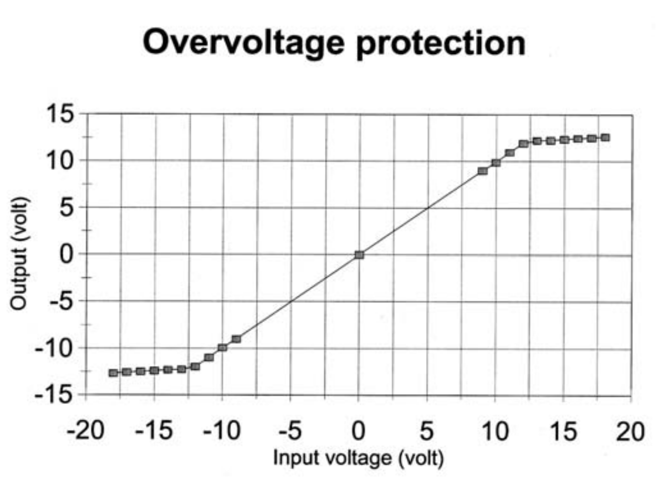

FIGURE 5: Gate-to-source voltage versus input voltage, for the new circuit, showing symmetrical voltage limiting action. These measurements were made with a pulsed test signal, see text.

NEW MOSFETS AND NEW CIRCUIT

The first hurdle is to find appropriate, new, in production, complementary lateral power MOSFETs. The new circuit uses devices made by Renesas Technology Corp., which Hitachi, Ltd. and Mitsubishi Electric Corp. formed in 2003. This means the new device manufacturer is the same one as for the original devices.

The N-channel is the 2SK2221 and the complementary P-channel is the 2SJ352. These devices have the following maximum ratings and characteristics: Vds 200V, Id 8A, Pd 100W, Vgs 20V, and thermal resistance 1.25°C/W[13]. Download and save the data for the 2SK2220/2SK2221 and the 2SJ351/2SJ352 devices.

The new devices are housed in a type TO-3P(N) plastic case, 15.6mm by 19.9mm (approximately 0.6″ by 0.8″), which is not compatible with the original mounting hardware. So I must address the mechanical changes needed to accommodate the new case configuration.

The new transistors' drain current, Id, versus gate-to-source voltage, Vgs, curves are identical to the original transistors (**Fig. 3**). This means they are functionally equivalent. They are rated a bit lower in thermal dissipation, so use eight per channel instead of the original six.

You will also get a somewhat lower thermal resistance between the heatsink and the ambient than the original configuration. This is because you are using a bigger total enclosed surface area to mount the eight transistors than the original six transistors surface area[14]. This is true even if the contact area was bigger for the TO3 devices. As an added bonus, using eight transistors instead of the original six increases the stage transconductance from about 3S to 4S and the rated current by 33%.

Refer to **Fig. 4** for the new Output Module assembly schematic. The circuit is made up of both N-channel and the P-channel MOSFETs. There are four parallel-connected sub-circuits per polarity. The new assembly holds all eight sub-circuits. It has all the output stage components of a single amplifier channel, making for simpler and faster assembly.

NORMAL OPERATION

I will describe just one sub-circuit, because the others are identical. Refer to the top left section of **Fig. 4** for the schematic of the sub-circuit for MOSFET Q1 for the positive polarity current.

In normal operation the input signal, coming from the positive driver transistor on PC-19, is applied to resistor R1, then to resistor R2 and the ferrite bead FB1, and finally to the gate of Q1. Transistor Q1 is the power MOSFET. The drain current from the supply flows through Q1 then through R4, which is the current measurement resistor, and finally to the amplifier output terminal. The negative polarity is handled in a complementary fashion by Q9 and associated parts. In normal operation this is all that matters; you can ignore all the other parts.

DRAIN OVERCURRENT PROTECTION

When the current flowing in Q1's drain is such that the voltage across R4 rises to 0.6V or so, transistor Q2 turns on and its collector current increases significantly in value. The collector current flows through diode D3 and resistor R1. This increased current through R1 lowers the voltage applied to the gate of Q1 relative to the input voltage, limiting the current out of Q1's source terminal. More voltage at the input of the circuit will make a bit more current flow through Q1. Q2 will turn on harder and shunt away a bit more current, in turn lowering the gate voltage a bit more in relation to the voltage on the other side of R1.

So the current in Q1 can flow up to a certain value, determined by circuit component values, but not much more. Resistor R3 limits the current into Q2 base; without it too much current could flow into the base and destroy the transistor. Diode D3 protects Q2 against reverse voltage at the collector. You can use capacitor C1—should you need it—to ensure stability during overload[15]. Capacitor C1 and the others, in the same position, are not installed on the board.

Because of the low resistance value of R4, it is important to connect it as if it were a Kelvin-type resistor. Otherwise, the lead resistance and circuit wiring resistance will change the current-limiting value. This means you must separate the voltage sensing connections from the current connections.

It sounds complicated, but is quite simple to do. Make the current flow connections through the resistor leads near the ends. Make the connections that go to Q2—the voltage sense transistor—close to the resistor body. You now

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have a Kelvin connection, in reference to Lord Kelvin, Sir William Thomson, 1824-1902[16].

GATE-TO-SOURCE OVERVOLTAGE PROTECTION

Diodes D1 and D2 are the gate-to-source overvoltage protection devices and are connected almost directly between the gate and source of Q1. The two zeners are identical and are each rated at 500mW. A 500mW zener is capable of 200mA in the forward direction[17].

With all four circuits in operation, the driver will need to source more than 800mA to destroy the zener diodes. This limits the maximum voltage applied to the gate to a safe value. Resistors R1, R2, and ferrite bead FB1 take care of any oscillation tendencies and protect the zeners (see the sidebar "MOSFET Oscillation" and references 18 and 19). You can remove the ferrite bead if you increase the gate resistor R2, but you better be prepared to hunt down oscillations in the 1MHz to 100MHz range.

Resistor R1 also serves as a troubleshooting aid. Use resistor R5 if you are not able to locate the 0.1Ω resistor or you prefer a higher valued current-sensing resistor. Using higher values for the current-sensing resistors makes them do double duty by also ensuring better current sharing between the various paralleled transistors, also known as ballasting. If you use higher values of R4, the current limit will be lower than 7A, unless you can shunt the increased voltage away. This is the function of resistor R5.

The input capacitance value, Ciss, is different between the P-channel and the N-channel transistors. I selected the total gate resistor value so the N-channel and the P-channel have the same input RC time constant. This way both positive and negative slew rates would be better matched at the output stage. Low values of non-symmetrical slew rates are an audible source of distortion and much less preferred than symmetrical slew rates[20].

Capacitors C401 and C402 were part of the original circuit and are reused in the same configuration.

MOSFET MATCHING

In the unlikely case that due to individual differences only one transistor conducts all the quiescent current, that device will dissipate about 34W, still within its rating. I think that matching results in lower harmonic and intermodulation distortion levels, plus a monotonous distortion level change with signal level. None of this has been proven; it is just a theory. But the measurements at the end of this article look funny, and this is the only way I can think of to explain it.

Limiter Circuit Measurements. I performed some measurements of the

TABLE1: PARTS LIST.

Reference	Description
R1, 6, 11, 16, 21, 26, 31, 36	resistor 220Ω 0.5W 5%
R2, 7, 12, 17	resistor 390Ω 0.5W 5%
R22, 27, 32, 37	resistor 220Ω 0.5W 5%
R3, 8, 13, 18, 23, 28, 33, 38	resistor 100Ω 0.25W 5%
R4, 9, 14, 19, 24, 29, 34, 39	resistor 0.1Ω 5W 10%
R5, 10, 15, 20, 25, 30, 35, 40	resistor, value to be determined, 0.25W 5%
Q1, 3, 5, 7	2SK2221, transistor, lateral MOSFET N-channel 200V 8A 100W
Q9, 11, 13, 15	2SJ352, transistor, lateral MOSFET P-channel 200V 8A 100W
Q2, 4, 6, 8	2N3904 transistor, bipolar, NPN 40V 100mA
Q10, 12, 14, 16	2N3906 transistor, bipolar, PNP 40V 100mA
D1-2, 4-5, 7-8, 10-11, 13-14, 16-17, 19-20, 22-23	1N5242B diode, zener, 12V 5% 0.5W, DO-35
D3, 6, 9, 12, 15, 18, 21, 24	1N4148 or 1N914 diode, signal, 100V 200mA
FB1-8	Ferrite bead, 2.5 turns, AWG 24
C1-8	capacitor 10nF 50V plastic film MKT (not used)
C402, C403	capacitor 100nF 100V plastic film screw, 4-40, pan head, Philips, 0.25″ (4) fiber washer, #4, 0.050″ thick (4) screw, 8-32, pan head, Philips, 0.75″ (4) flat washer, #8, steel (4) lock washer, #8, steel (4) nut, #8-32, steel (4) spacer, threaded, male female 4-40, 0.735″, male thread 0.250″ brass or steel (4) thermal conductive pad, 0.8″ × 1″ (8) insulated spacer, non threaded, outside diameter 0.25″ maximum, inside for #8 screw, 0.200″ thick (4) insulated spacer, non threaded, outside diameter 0.2″ maximum, inside 0.042″, 0.250″ thick (16) vector board or PWB (1)

TABLE 2: TVS, DIODES, AND BLEEDER RESISTORS.

Description	Manufacturers
TVS diode, unidirectional, 1500W peak pulse rating, breakdown voltage of 130V, 1N6298 or 1.5KE130 (4)	Vishay Semiconductors, Littlefuse
Resistor, 10kΩ 5%, 3W (2)	any
Closed ring lugs to fit capacitor and resistor lead wire (4)	any

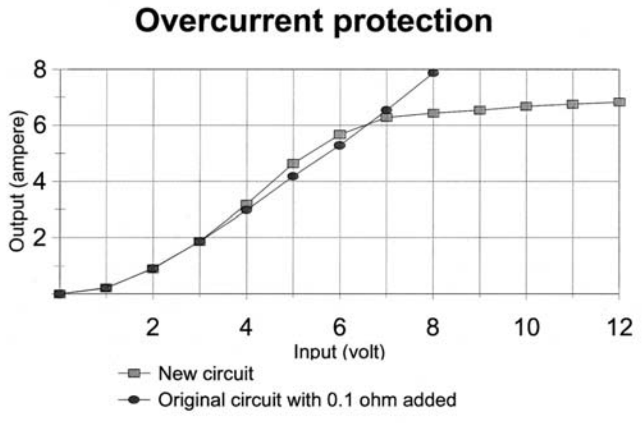

FIGURE 6: Drain current versus input voltage, for the new circuit, showing the current limiting action; the curve is identified by small squares. Without the current limiting action, the curve is identified by small circles. These measurements were made with a pulsed test signal, see text.

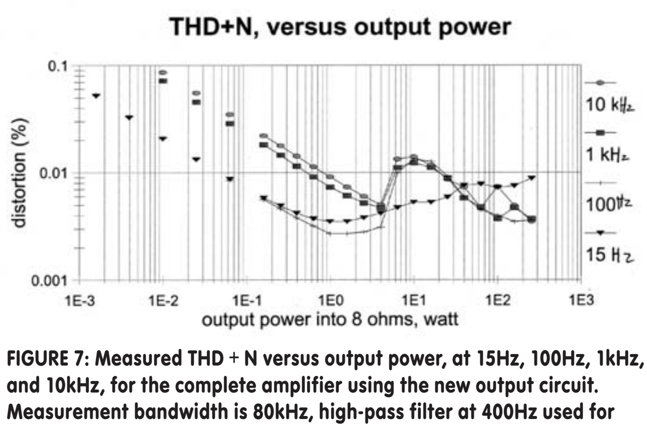

FIGURE 7: Measured THD + N versus output power, at 15Hz, 100Hz, 1kHz, and 10kHz, for the complete amplifier using the new output circuit. Measurement bandwidth is 80kHz, high-pass filter at 400Hz used for 1kHz and 10kHz measurements, RMS responding meter.

Vgs limiter circuit (**Fig. 5**) with a low duty cycle pulse test signal, of approximately 300µs duration, "ON" about 10% of the time. There was no voltage source connected to the drain supply terminal. The voltage limiting and protection is symmetrical and occurs at 12.7V. The curve stops with an input pulse amplitude of 18V due to the pulse generator limitation. This new circuit offers better protection than the original.

I also measured the current limiter circuit with good results (**Fig. 6**). The drain supply was about 14V. The curve for the transistor with no current limiting—represented with small circles—shows that the current goes to 8A with an 8V input. This represents the original circuit, except that a 0.1Ω resistor was added in series with the MOSFET source lead for current sensing. I stopped at 8A peak—the maximum rated current value—so as not to damage the device.

With the new circuit the current clearly starts to limit at about 6A, the curve with the small squares. You can get to almost 7A with an input of 12V, at which input voltage value the overvoltage circuit starts to limit. Clearly this new circuit protects against both overvoltage and overcurrent.

Modifications to the Hafler DH-500. Because not everyone who reads this will have a DH-500, I decided to keep this section rather short. However, anyone can request, by e-mail, the full and detailed modification instructions and get an Adobe Acrobat® type format file. The file contains the parts list, list of tools and test equipment required, wiring lists, modification instructions, and the various test procedures. All this to make sure you will be able to do the modifications with the least risk of failure.

Send an e-mail to d22dufresne@yahoo.ca with a short message or subject heading "Hafler DH-500" stating your interest in the Hafler DH-500 modification instructions, and I will send the information to your return address. The complete parts list for the output assembly is in **Table 1**. You can order the parts from the suppliers listed in **Table 3**.

Add TVS, Diodes, and Bleeder Resistors. You need to add a few more parts so you can limit the MOSFET drain-to-source voltage. You could install the parts directly across the MOSFET, connected from the drain to the source. However, doing so will divert the current associated with the overvoltage directly to the output terminals and then to the loudspeaker.

Instead, I connected the protection device across the power-supply line. The parts for these modifications are in a

TABLE 3: SUPPLIERS.

Digi-Key Corp.
www.digikey.com
Source for most components for this project, except the MOSFETs.
701 Brooks Avenue South
Thief River Falls, MN 56701
800-344-4539 or 218-681-6674
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Exicon
www.profusionplc.com
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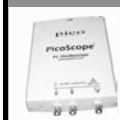
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separate parts list, **Table 2**, so as not to risk parts mixup between these and the ones that go onto the new output assembly printed wire board (PWB).

The transient voltage suppressor diodes (TVS) for overvoltage protection go across the DC supply lines and the circuit common. They are wired directly to the dual fuse holders on the load side. The cathode goes to the more positive voltage. A new wire connects the TVS common terminal to the main filter capacitors, C404 and C405, return connection. You must absolutely connect the TVS after the fuse. Should the TVS fail short-circuit, the fuses will open and stop further damage.

I also added bleeder resistors across the two main filter capacitors—C404 and C405, also identified as CL and CR in the pictorial diagram of the manual. They make the unit safer to work on. I soldered the resistors to closed ring lugs and mounted the part onto the capacitors—one per capacitor—making sure not to obstruct the vent hole.

Modifications to PC-19. I added a 47Ω 5% 0.25W resistor in series with the base of Q12 on PC-19, the original amplifier main or driver PWB. I then did the same for the base of Q13. Cut the copper foil closest to the base terminal with a sharp knife and then solder the resistor across the gap. This mandatory modification improves stability and will limit the peak available current from the transistors to a safer value. I did this on both channels.

Although not widely known, an emitter follower can oscillate, and adding a resistor in series with the base is a simple but efficient solution to this problem. More details on emitter-follower oscillations are in references 21, 22, and 23.

Other modifications to the Hafler. Those who have a DH-500 and wish to get the most out of it can consult the following references for further improvements: specific DH-500 upgrades[24], general upgrades[25], or capacitor upgrades[26]. This last reference is quite extensive and backed with measurements of utmost refinement.

Output Stage Modification. To hold all the added parts, I decided to design a new PWB, which will also help tame the oscillations, because the parasitic elements will be closer in value between different amplifiers. To this end I strongly suggest using the PWB available from me to make the modifications. However, I produced the prototype using a bare board, onto which I soldered the parts and added the wires as needed and it worked fine.

You will need to disassemble the

TABLE 4.	CHARACTERISTIC (my measurement conditions are in parenthesis), *italics are computerized data*	Original	New	Units
Power Rating	less than 0.25% THD at any power level up to 255W continuous average power per channel into 8Ω at any frequency between 20Hz and 20kHz with both channels driven	255	see figure	W
IM Distortion (SMPTE)	less than 0.007% from 1W to 255W into 8Ω (60Hz and 7kHz, 4:1)	0.007	see figure	%
Typical THD at 255W into 8Ω	(THD + N at 1kHz, measurement bandwidth is 80kHz, RMS detection) my measurements are higher, see text	0.002	0.0036	%
	(THD + N at 10kHz, measurement bandwidth is 80kHz, RMS detection, see above)	0.007	0.01	
Freqency Response into 8Ω	–3dB low end at 1W (I referred to the measurement done at 1kHz)	0.5	1.7	Hz
	–3dB high end at 1W (I referred to the measurement done at 1kHz)	120	155	kHz
	±0.5dB, low end at 255W	5	–	Hz
	±0.5dB, high end at 255W	40	–	kHz
Typical Channel Separation at 1kHz	(my measurement condtions: driven channel at 1W into 8Ω, un-driven channel open input, no load)	60	80	dB
Signal to Noise Ratio	un-weighted, referred to 255W into 8Ω (my measurement with shorted input connector, measurement bandwidth 2Hz to 200kHz)	100	101.6	dB
	Corresponding output wideband noise and hum	0.452	0.377	mV
	A weighted, referring to 1W into 8Ω (right channel, shorted input)	90	98.1	dB
	Output noise, input shorted, "A" weighted, left channel/right channel	89	30/35	µV
Input Impedance	(I measured at 1kHz and with 0.145V at the input	47	44.7	kΩ
Input Sensitivity	for 255W into 8Ω (my results are computed from 1W 1kHz measurements)	2.35	2.24	V
	for 1W into 8Ω (at 1kHz)	0.145	0.140	V
Gain, voltage	for 1W into 8Ω (at 1kHz)	19.50	20.18	–
Gain in dB	for 1W into 8Ω (at 1kHz)	25.80	26.10	dB
Damping Factor	at 1kHz referred to 8Ω (I measured with 0.353A)	200	333	–
	at 10kHz referred to 8Ω (I measured with 0.353A)	60	45	–
	Equivalent output resistance at 1kHz	0.040	0.024	Ω
	Equivalent output inductance at 10kHz	2.12	2.85	microHenry
Rise Time	with a 10kHz 80V p-to-p squarewave at the output (into 8Ω) from 10% to 90%	2.50	2.35	microsecond
(Fall Time)	same as above	–	2.15	microsecond
Slew Rate	with a 1kHz 120V p-to-p squarewave at the output (into 8Ω) +	45	50	V/microsecond
	same as above (–)	–	40	V/microsecond
Semiconductor Complement	bipolar junction transistors	27	43	–
	MOSFETs	12	16	–
	diodes (signal)	33	49	–
	diodes, zener	8	40	–
	diode bridge	1	1	–
	integrated circuits	1	1	–
Power Consumption	Quiescent	240	235.3	VA
	(no load, input power at 120V and 60Hz)	–	169.3	W

Printed Wire Board and Parts Kit

You can order the bare, double-sided, solder mask over bare copper (SMOBC), printed wire board (PWB), directly from the author at *d22dufresne@yahoo.ca*. The boards are manufactured by a professional PWB manufacturer.

Kits of parts and assembled and tested boards are also available from the author. They come complete with detailed step-by-step modification instructions, stuffing guide, parts list with supplier's part numbers, a list of the tools you will need, wiring tables, and exhaustive checking procedures to ensure that each step is done correctly. All this is done to maximize the chances that your modified amp will work the first time. The data package is available for free, *only via e-mail*, so you can check out the complexity of this project before deciding to do the modification by yourself. Contact the author via mail at Daniel Dufresne, 1280 rue Latour, Ville Saint-Laurent, QC Canada H4L 4S4 for further details should you not have access to e-mail.

amp. Remove the original PC-19 board. Modify the PC-19 as per the instructions. Remove the old power transistors and their sockets. Assemble the new PWB with all the parts. Test the assemblies. Then install the new PWB directly onto the heat exchanger. The new plastic transistors go onto the heat exchanger and are fastened using the original holes, so no new drilling is needed. The heat exchanger is already full of holes—more holes would increase the heat exchanger thermal resistance.

Mount the new PWB onto the heatsink in place of the PC-19. The original PC19 board now goes on top of the new PWB using spacers. Add bleeder resistors and the TVS. Rewire according to the original schematic to complete the mod.

MEASUREMENTS

Just to make sure everything was working as it was supposed to, I checked my modified DH-500 against the manufacturer's original specifications. Both sets of measurements are shown in **Table 4.** I added some notes, specific to the test conditions, when the manufacturer's information was not clear enough. I measured the distortion under the following general conditions: load 8Ω resistive, line voltage held at 120V ±3V, and one channel driven at a time (test resistor limitations).

Figure 7 is the measured total harmonic distortion plus noise (THD + N) versus output power, at 15Hz, 100Hz, 1kHz, and 10kHz for the new circuit. The measurement bandwidth is 80kHz and the detection type is RMS. I used a 400Hz high-pass filter for the 1kHz and the 10kHz runs.

The kink in the distortion curve looks weird. Further analysis showed it to be real and probably due to the unmatched MOSFETs. In **Fig. 8**, one trace is the measured distortion analyzer notch filter output versus time at 250Hz, the other trace is the output signal for reference. You can see some transconductance modulation, where the various MOSFETs turn on and off at different voltages. The output power for the **Fig. 8** measurement was close to the peak of the kink in the distortion curve of **Fig. 7**. However, even with unmatched devices, the amp still meets its original distortion specifications.

Also note the graphs of the IMD, done according to both the Society of Motion Picture and Television Engineers (SMPTE) and the disappearing CCIF IMD also called twin tone, versus output power (**Figs. 9** and **10**). The CCIF is now ITU-R, hence the name change to IMD ITU-R and future disappearance of references to CCIF IMD. The SMPTE graph shows the same hump around 10W, possibly due to the

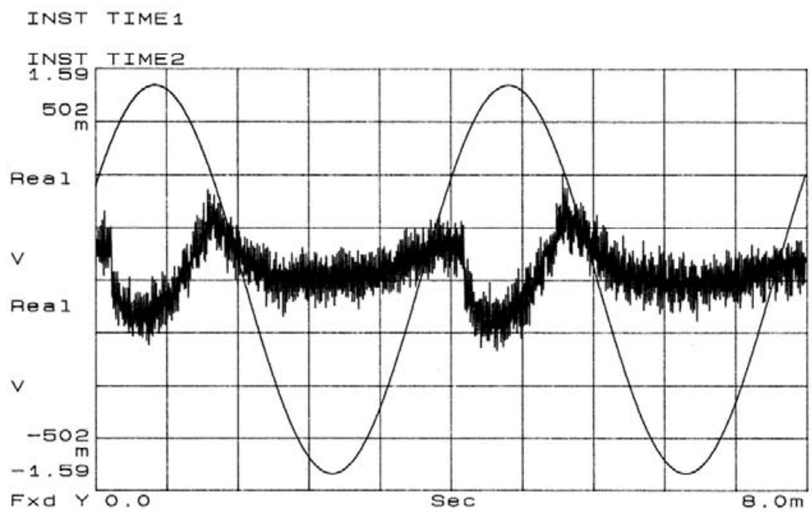

FIGURE 8: Measured THD + N versus time, 250Hz, at 10.11V or 12.8W, into 8Ω. The wiggly curve is the distortion analyzer notch output signal. It shows transconductance modulation where one transistor turns on at a different voltage than the others of the same polarity and thus the need for matching MOSFETs. The sine wave is the analyzer input signal scaled.

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mismatched MOSFETs.

Without any load and with the output adjusted just below visible clipping, the maximal output signal voltage is 170V peak-to-peak. I tested the current capability with a 1kHz sine wave, one cycle ON, 15 cycles OFF. The load was a 2Ω resistor in series with a 0.1Ω 1% current sensing resistor, across which I measured the voltage with an oscilloscope. The onset of visible current clipping occurred at 57.6A peak-to-peak. This corresponds to 28.8A peak, or 7.2A per transistor on average, close enough to 7A per transistor for me.

Most low-level distortion measurements were corrupted by hum and noise. The spectral analysis of the output voltage with the input in short-circuit is mostly line-related harmonics. The hum level rises a bit with an open input connector.

At idle and with a supply of 120.10V at 60.014Hz, the amplifier supply current is 1.959A RMS. The total apparent power consumption is 235.3 VA. This total is made up of 169.3W in real power and 168.2 VAR in reactive power. The corresponding power factor is 0.7153, or a phase angle of 44.28° leading.

The peak supply voltage is 165.7V—it would be 169.8V if the supply waveform were an ideal sine wave without clipping. The peak current is 5.12A—it would be 2.77A for an ideal linear load. The difference is due to the charging of the capacitors.

CONCLUSION

I performed listening tests and found the amp quite nice sounding. I did not have access to an original DH-500, so I cannot comment on the differences in sound, if any. The only problem is the low-level acoustical fan noise, which you can take care of by placing the amp in another room or adding some sound-absorbing material around it, while making sure there is ample airflow. My amp has been running at least five times a week for the last two years without incident.

The new circuit protects the MOSFETs and keeps the voltage and current applied to the output devices within the manufacturer's maximum limits. Of course, the electronics community at large has had 15 more years of experience in dealing with power MOSFETs, so this is not a condemnation of the original design as such, just an improvement on a good amp. But the most important aspect of this project is that this amp plays music again and that you can repair others like it and put them to good use. *aX*

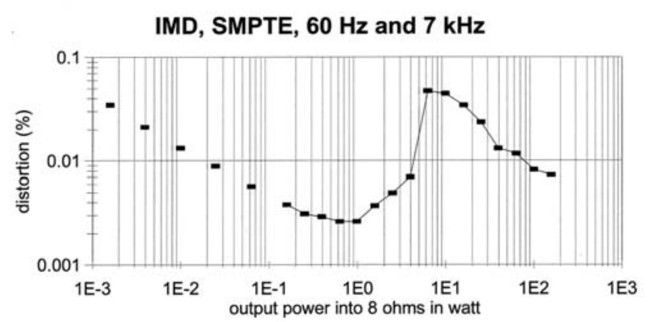

FIGURE 9: Measured IMD versus output power, SMPTE, 60Hz and 7kHz, with a ratio of 4 to 1 in amplitude, RMS responding meter, for the complete amp using the new output circuit.

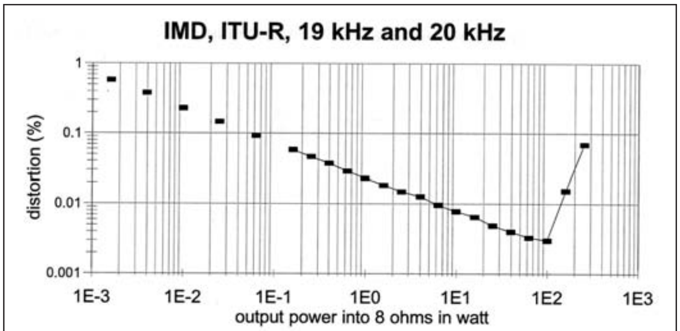

FIGURE 10: Measured IMD versus output power, ITU-R method (was CCIF), 19kHz and 20kHz, equal amplitude, RMS responding meter, for the complete amp using the new output circuit.

Daniel Dufresne *is an engineer and has been published in* Audio, EDN, Electronic Design, Audio Electronics, *and* audioXpress. *He has designed, among others, negative resistors, inverters, and frequency converters from 1kW up to 144kW for rail transit, industrial, and aerospace applications. He lives in Ville Saint-Laurent, Quebec, Canada, and can be reached at d22dufresne@yahoo.ca.*

Acknowledgment

I would like to thank my friend Daniel Faille for providing me with the amp used in this project. I would also like to thank Akiko Ishiyama from Renesas Technology America, Inc. for granting permission to reproduce part of the 2SK2220 datasheet.

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MOSFET OSCILLATION

This formula gives a condition for stability as

$$RG + Rs + rg + Rl - ((Cl\ Rl^2\ gm)/Ciss) \geq 0 \qquad (1)$$

where

RG is the resistor added to obtain stability, in ohms.
Rs is the signal source resistance, in ohms.
rg is the transistor internal gate resistance, in ohms.
Rl is the load resistance between the drain and source, in ohms.
Cl is the load capacitance between the drain and source, usually the case to heatsink plus circuit parasitic, in farads.
gm is the transistor small signal transconductance at the operating point, in siemens.
Ciss is the transistor input capacitance at the operating point, in farads.

The N-channel is usually more oscillation prone than the P-channel, so compute the resistor value for this case first. Using the following values for the N-channel 2SK2221, and assuming worst-case value for unknowns, Rs = 0, rg = 0, Rl = 10Ω, the Zobel network at frequencies above 1.6MHz, Cl = 10 nanofarads, the Zobel network, gm = 0.2 siemens at 10MHz, and Ciss = 600pF, you get 323Ω minimum for Rg. I chose 390Ω—this plus resistor R1, 220Ω, gives you a safety margin. This resistor must be physically close to the gate terminal, less than 2cm (1″).

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