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The 48 Volt Phantom Menace

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ABSTRACT

The authors encountered anecdotal evidence suggesting that field failures of existing line driver and microphone preamplifier integrated circuits (ICs) were correlated with accidental connections between line outputs and microphone inputs with phantom power applied. Analysis showed that the most probable mechanism was large currents flowing as a result of rapid discharge of the high-valued ac-coupling capacitors.

Commonly used protection schemes are measured, analyzed, and shown to be lacking. More robust schemes that address these shortcomings are presented. It is concluded that the small additional cost of these more robust protection schemes is likely outweighed by the reduction in field failures and their associated repair cost.

0 INTRODUCTION

During the design phase of both a balanced line-driver IC and a microphone preamplifier IC, we encountered persistent reports from users of field failures of existing devices. Anecdotal evidence suggested that these failures were correlated with accidental connections between line-level outputs and microphone inputs, particularly if 48-volt phantom power was activated on the microphone channel.

The first section of this paper describes circuit simulator models that demonstrate scenarios under which potentially destructive currents can flow when line-level outputs are connected to microphone inputs with 48-volt phantom power applied. The next section examines some commonly used protection schemes, utilizing both simulations and measurements. In subsequent sections, more robust protection schemes are analyzed and the accompanying engineering tradeoffs are discussed. Additionally, changes to typical circuit design practice that will mitigate the problem are shown.

1 DESCRIPTION OF THE PROBLEM

Microphone preamplifiers that include 48-volt phantom powering capability almost universally include a pair of ac-coupling capacitors at the inputs to isolate the preamplifier input circuitry from the phantom-power supply. A typical configuration is shown in Figure 1. [1]

After power is applied, these capacitors (C_1 and C_2) are charged to 48 V via 6.8 kΩ resistors R_1 and R_2. Assuming a commonly-used value of 47 µF, the energy stored in each capacitor is:

$$E = \frac{CV^2}{2} = 54 \times 10^{-3} joules.$$

As a point of comparison, in an Electrostatic Discharge (ESD) sensitivity test using the "Human Body Model" [2] at the highest (optional) voltage level of 8 kV, the 100 pF tester capacitance stores only 3.2×10^{-3} joules. Thus the energy stored in the input coupling capacitors of a phantom-powered microphone preamplifier is more than an order of magnitude greater than that encountered in one of the most severe ESD tests used in screening integrated circuits. This is clearly a force to be reckoned with.

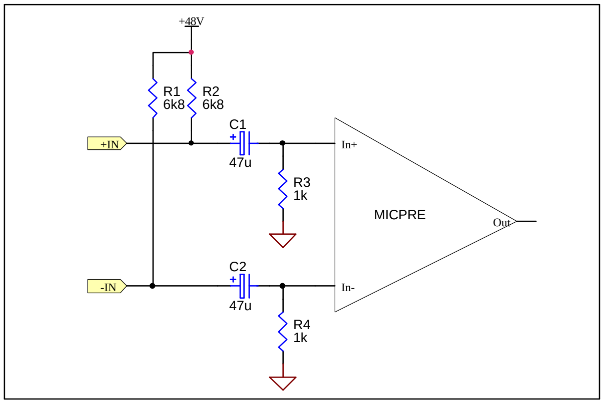

Figure 1 - Typical 48 V Phantom Power Configuration

1.1 Simplified Model

The circuit shown in Figure 2 shows a simple circuit for simulation purposes (using PSpice) that demonstrates how destructive currents can flow when a line-level output stage is connected to the microphone-preamplifier input with phantom power activated. Here, diodes D_1 through D_4 represent normally reverse-biased junctions associated with a line-level output stage constructed of opamps or a completely integrated balanced line-driver IC. Such junctions may appear in the form of ESD protection devices at the output pins, or a more complex combination of device junctions between the output pins and the power supply pins. Since, in this case, we are assuming that the line-level device does not have its own power supply turned on, the cathodes of D_1 and D_3, which would normally connect to the positive supply voltage, and the anodes of D_2 and D_4, which would normally connect to the negative supply voltage, are grounded. In an actual circuit, the power supply pins would presumably be incrementally grounded via the relatively large bank of filter capacitance.

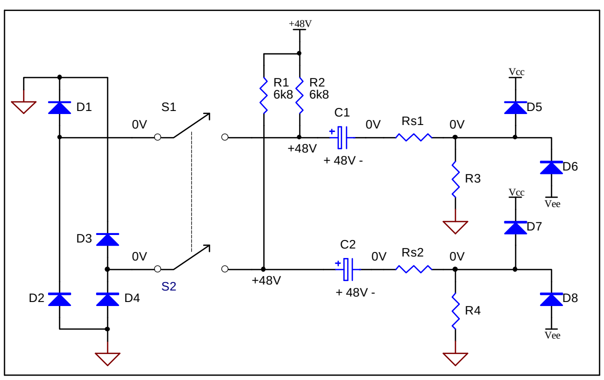

Figure 2 - Simplified Model for Simulation

Diodes D_5 through D_8 similarly represent device junctions associated with the input pins of an integrated microphone preamplifier IC. Here we assume that the power supply for the preamplifier and the phantom power have been turned on.

Resistors R_{S1} and R_{S2} represent any resistance added in series with the microphone preamplifier inputs for current limiting. For the purposes of simulation, any bulk resistance associated with the diodes D_1 through D_8, as well as any equivalent series resistance (ESR) associated with the coupling capacitors, can be lumped into R_{S1} and R_{S2}.

Switches S_1 and S_2 simulate a user connecting a cable between the output of the line-level processor and the phantom-powered microphone preamplifier. The voltages shown in Figure 2 are the dc voltages in the circuit before S_1 and S_2 are simultaneously closed. When S1 and S_2 are closed, diodes D_1 and D_3 begin conducting immediately, clamping the positive (left) terminals of C_1 and C_2 to a diode-drop above ground. Since the capacitor voltages cannot change instantaneously, the negative (right) terminals of C_1 and C_2 are forced more negative in voltage, turning on diodes D_6 and D_8. The voltages in the circuit immediately after switch S_1 and S_2 are closed are shown in Figure 3.

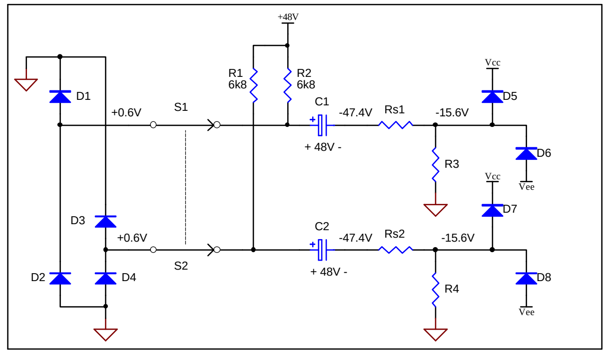

Figure 3 - Simulation Circuit Immediately After Switches Close

An exponentially decaying current flows (through D_6, R_{S1}, C_1, and D_1, for example) with an initial value set by:

$$I_0 = \frac{(V_{EE} - 2V_{DIODE} + 48V)}{R_S}.$$

The current will stop when C_1 and C_2 have discharged such that the voltage across them is about one diode drop, leaving D_1 and D_3 conducting current from R_1 and R_2, and the microphone inputs back at ground (via R_3 and R_4).

Figure 4 shows the simulation results for the current flow through R_{S1} (or R_{S2}) after the switches close. For this simulation the component values were: $C_1 = C_2 = 47\ \mu F$, $R_{S1} = R_{S2} = 10\ \Omega$ and, $R_3 = R_4 = 1\ k\Omega$, with $V_{CC} = -V_{EE} = 15$ V.

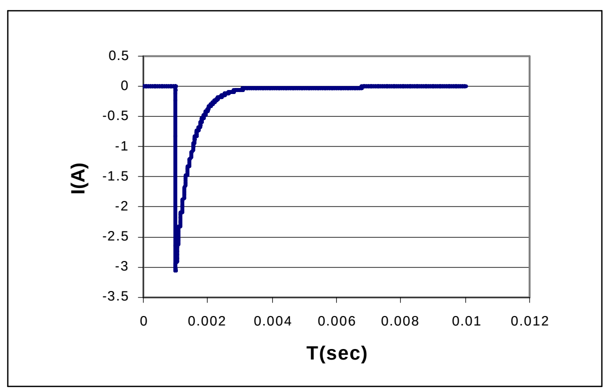

Figure 4 - Current through R_{S1} After S_1 Closes

These substantial transient currents can lead to destruction of metallization or semiconductor junctions in integrated circuits through localized heating effects.

It should be noted that shorting either of the microphone preamplifier input lines to ground (as might occur if the preamplifier is connected to a line-level output with a single-ended output driver) will result in similar current flow. Also, if the line-level device is under power, the initial voltage across R_{S1} and R_{S2} will be reduced by the positive supply voltage of the device. This will reduce the peak current accordingly.

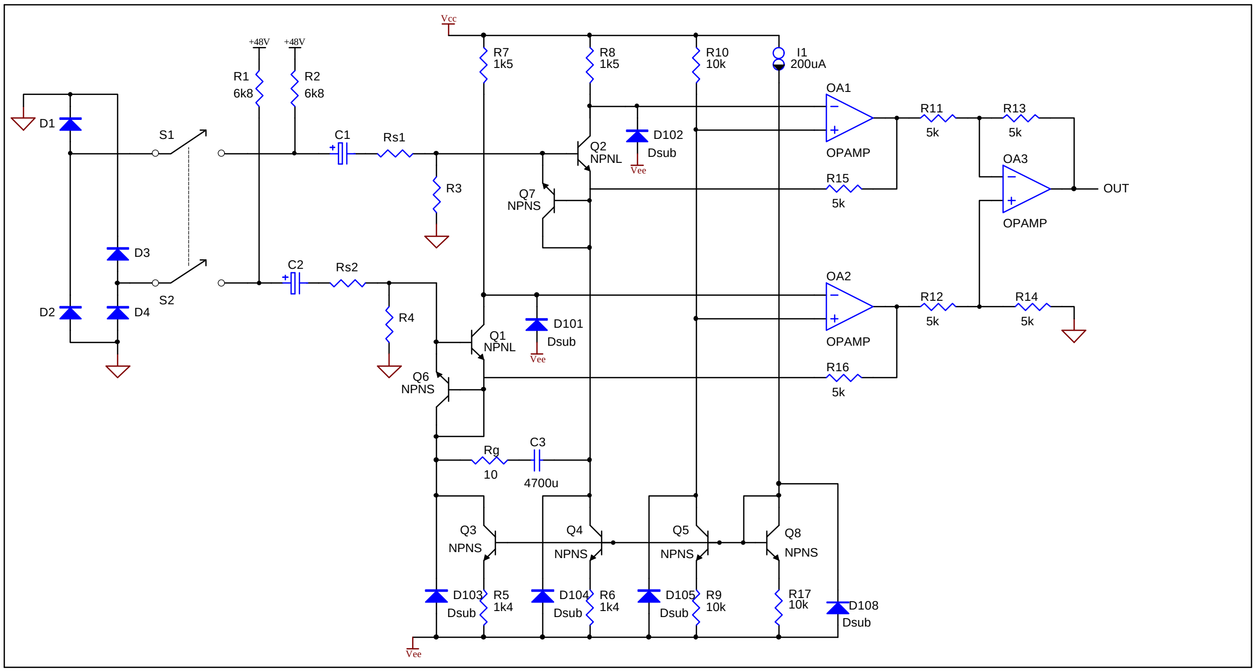

Figure 5 - Simulation Circuit Including Microphone Preamplifier

1.2 Microphone Preamplifier Model

The circuit shown in Figure 5 contains a simplified model of a current-feedback instrumentation amplifier. This topology serves as the basis for two widely used microphone preamplifier integrated circuits [1] [3]. The model was designed to include the devices close to the input pins that would likely be encountered in a device implemented in a typical high-voltage junction-isolated-bipolar semiconductor process. Thus, the input differential pair, Q_1 and Q_2 include collector-to-substrate diodes, D_{101} and D_{102} connected to V_{EE} , as do current-source transistors Q_3 and Q_4. Also included are diode-connected transistors Q_6 and Q_7, which are intended to prevent Zenering of the input pair, which could degrade noise performance and transistor current gain. The models for the transistors and diodes were taken from a 36-volt junction-isolated bipolar process, and bulk resistance effects are included in the models. Transistor areas were chosen based on the currents to be accommodated under normal operation, with the exception of the input devices which are based on a large area device designed for a 15-Ω base resistance to minimize their input voltage noise contribution. The subsequent amplification stages are modeled using generic Boyle-model opamps with specifications similar to the industry-standard 5532 type [4] and are connected to the same supply voltages as the rest of the preamplifier circuitry.

The schematic in Figure 5 also includes circuitry identical to that of Figure 2 to simulate the connection of a line-level device to the microphone preamplifier with phantom power applied. The results are quite similar, except that, in this case, the current path on the preamplifier side is through collector-substrate diodes D_{103} and D_{104} and base-emitter protection diodes Q_6 and Q_7. Figure 6 shows the results of a transient simulation similar to the one that generated Figure 4, except using the Figure 5 circuit. Again, $C_1 = C_2 = 47\ \mu F$, $R_{S1} = R_{S2} = 10\ \Omega$ and, $R_3 = R_4 = 1\ k\Omega$, with $V_{CC} = -V_{EE} = 15$ V. The peak current is lowered to approximately 2.1 A due to the bulk resistance of the diodes adding to the 10 Ω series input resistors.

Since the peak current varies inversely to the resistance in series with each input, one simple approach to protection would be to increase R_{S1} and R_{S2} to values that would limit the current to safe values. Figure 7 shows the peak current that flows through the emitter of diode-connected transistor Q_6 (or Q_7) of Figure 5 immediately after switches S_1 and S_2 are closed as a function of Rs. THAT Corporation's

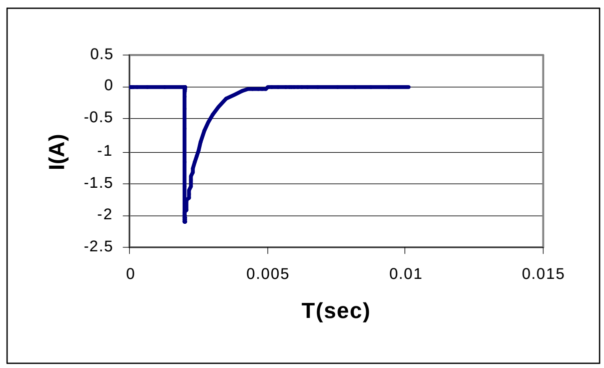

Figure 6 - Current Through R_{S1} in Figure 5

design rules, which are representative of industry practice, allow for a maximum peak current of 280 mA in an 8µm-wide (minimum width) trace of 1 µm-thickness aluminum metallization for devices with a maximum chip temperature of 125°C. Such metallization is typical for the high-voltage bipolar processes that are employed for analog ICs that operate from supply voltages of ±15 V or greater. The curve in Figure 7 crosses 280 mA at $R_s = 96\ \Omega$. Thus, to safely limit the peak

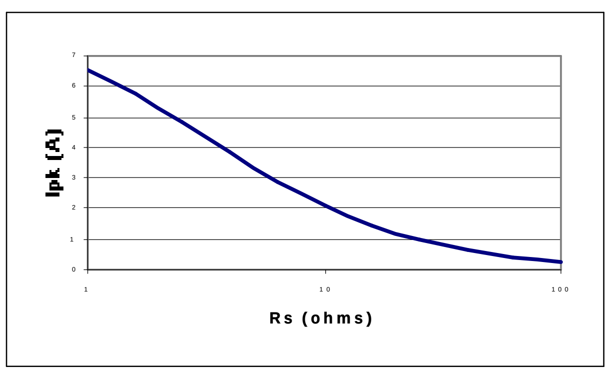

Figure 7 - Peak Current Through Q_6 or Q_7 vs. Rs

current into the device using external series resistance alone, 100 Ω resistors would need to be employed.

These series resistors directly affect the equivalent input noise due to their thermal noise contribution. In the simulation circuit of Figure 5, the input devices, Q_1 and Q_2, are biased at collector currents of 1.2 mA each. The shot noise from these devices, along with their 15 Ω base resistances, and the 10 Ω gain-setting resistor R_G yield an equivalent input noise for the preamplifier alone of 1.06 nV/√Hz at 60 dB of gain, or -134.3 dBu in a 20 Hz - 20 kHz bandwidth. Figure 8 shows the effect of the added noise of the series input resistors. It is a plot of the audio bandwidth equivalent input noise of the circuit as a function of the value of R_{S1} and R_{S2} (with a zero Ω source resistance).

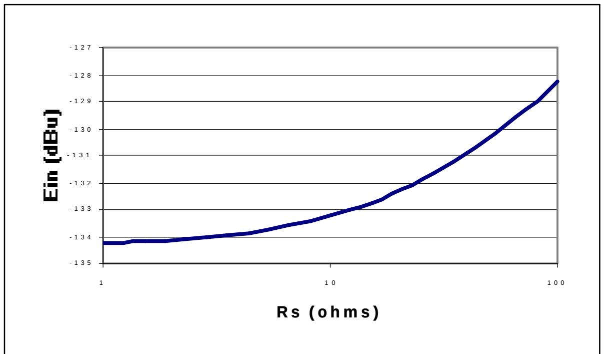

Figure 8 - 20-20 kHz BW Equivalent Input Noise vs. R_S

Adding 100 Ω per input leg of series resistance exacts a 6 dB penalty in equivalent input noise. For the purposes of evaluating various protection schemes, we chose to use 5 Ω for R_{S1} and R_{S2}, which results in only a 0.5 dB increase in equivalent input noise over that of the preamplifier itself. It should be noted that if a 150 Ω source resistance is assumed for the microphone, the 5 Ω series resistors add only a 0.16 dB increase to the combined equivalent input noise of the microphone preamplifier and the source. The authors have also seen this value in a number of existing designs.

2 PROTECTION SCHEMES

2.1 Test Circuit

The circuit shown in Figure 9 was used to evaluate various protection schemes for both the preamplifier and line-output driver. The ICs chosen are widely used in the professional audio industry [1] [5] [6]. All devices were operated from ±15 V power supplies.

We first tested the circuit with each device (alternately) unprotected, to confirm the results of the simulations. To test the unprotected microphone preamplifier, the output driver IC was removed from its socket, and reverse-biased Schottky diodes to the power supply rails as in Figure 5 were left in its place. The power supplies to the output driver were turned off. The oscilloscope trace shown in Figure 10 is the resulting current waveform into an input pin of the microphone preamplifier IC. (The waveform is for pin 2, pin 3 was similar). Note that the current probe (a Tektronix A6302 probe with AM503 probe amplifier) was set to measure the current coming out of the IC pin, thus the polarity discrepancy between the scope trace and the simulation results.

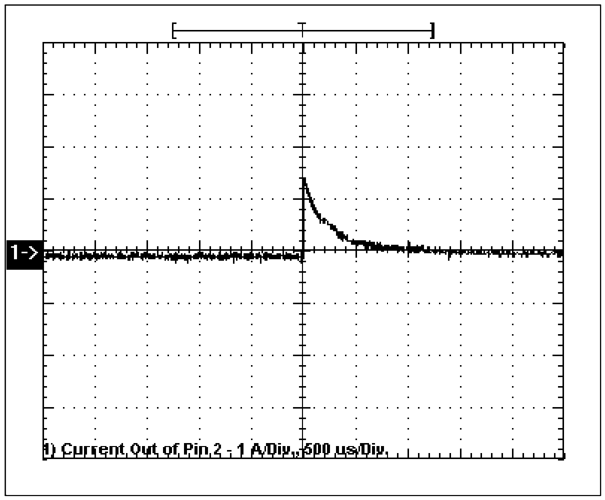

Figure 10 - Current Out of Pin 2 of Unprotected Mic Pre IC

The peak current, at 1.4 A, is less than indicated by the simulation results, probably due to higher resistance in the internal junctions, metal interconnect resistances, and capacitor ESR. Of five devices tested, two failed catastrophically. The others exhibited distortion about one order of magnitude greater than before the test, as well input bias currents that exceeded the maximum specification.

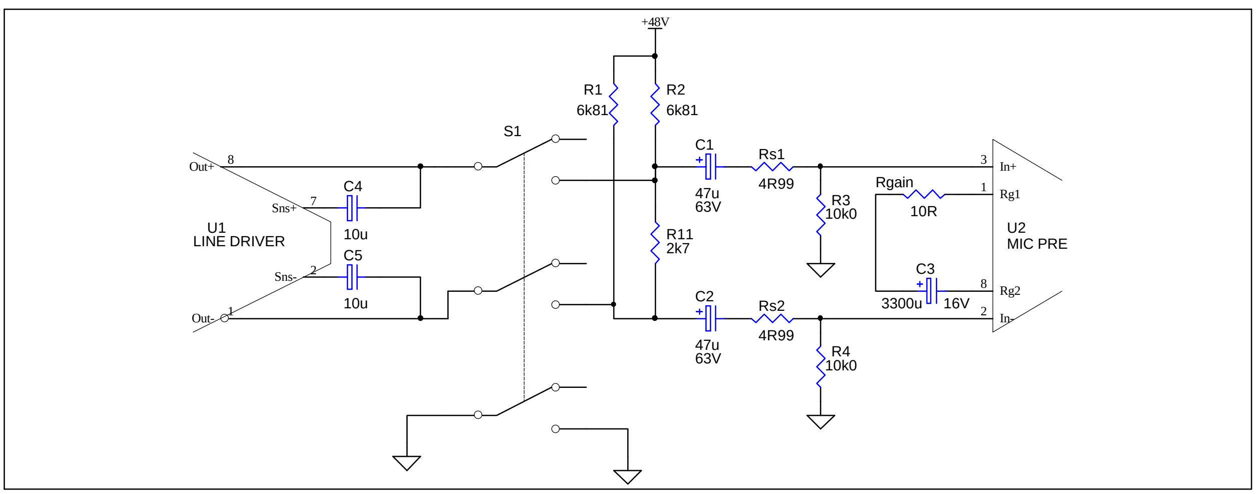

Figure 9 - Basic Test Circuit With No Protection

Similarly, unprotected output driver ICs were tested with the microphone preamplifier removed from its socket, and reverse-biased Schottky diodes to the supply rails substituted in its place.

For one model of output driver IC, what were probably ESD protection diodes from the outputs to the positive supply pin conducted high currents, as shown in Figure 11. The device failed immediately with both outputs shorted to V_{CC}.

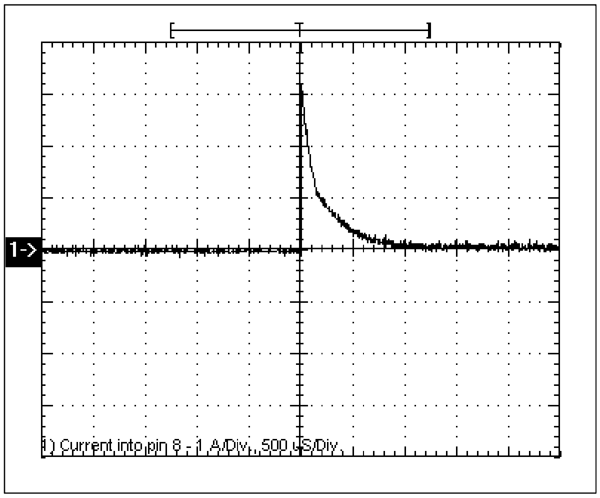

Figure 11 - Current Into Pin 8 (Output Pin) of the First Model of Unprotected Output Driver IC

The other model of output driver IC fared somewhat better. The currents into the output pins were substantially lower as shown in Figure 12.

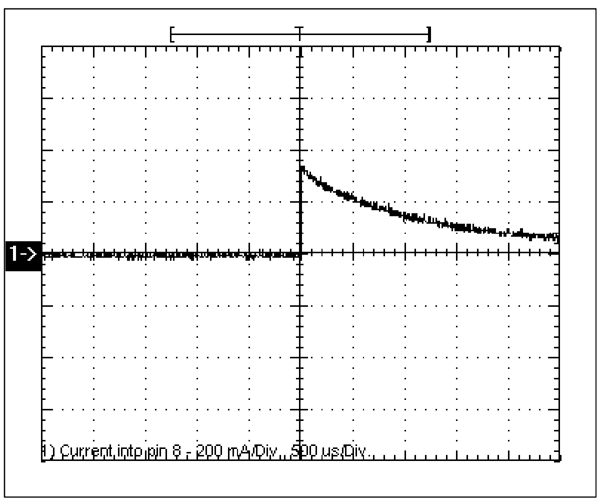

Figure 12 - Current Into Pin 8 (Output Pin) of the Second Model of Unprotected Output Driver IC

The device from which this current waveform was taken survived. However, another device tested similarly failed non-catastrophically. It continued to operate, but exhibited excess distortion (>.6% into a 600 Ω load, with a 1 kHz, 1 Vrms input signal).

2.2 Diodes to the Rails

One of the simplest protection schemes is to add external reverse-biased diodes from each of the microphone preamplifier inputs to the device power-supply voltage terminals. The authors have observed from customers application circuits that small signal diodes such as the 1N4148 are often used in this application. Such a configuration is shown in Figure 13. This device is rated for a peak forward current of 500 mA [7].

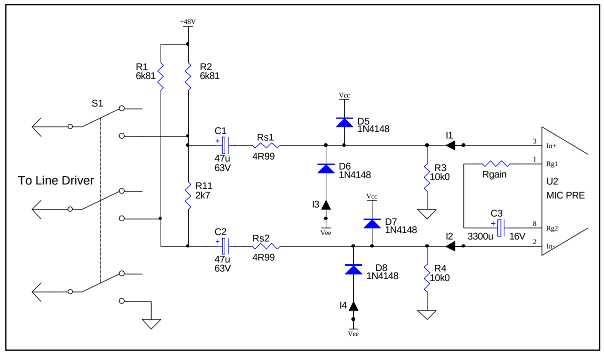

Figure 13 - Microphone Preamplifier IC with Diode Protection

In this test the output driver was removed from it socket, as it was for all tests of microphone preamplifier protection schemes. This left the SB160 Schottky diodes to the unpowered supply rails. Upon performing the test, one of the 1N4148 diodes failed (open circuit), and the microphone preamplifier IC was damaged (open circuit on one input) as a result.

A more robust approach is to use Schottky diodes that are appropriately rated. The lower forward drop of the Schottky diode compared to the P/N junction diode prevents the input pins from being pulled far enough beyond the supply rail to turn on internal junctions. However, this scheme does not prevent the inputs from exceeding the manufacturer's specified maximum input voltage range.

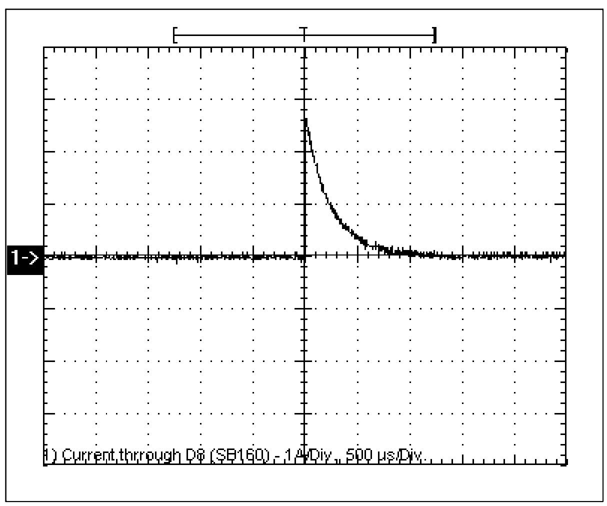

Figure 14 - Current Through SB160 Protection Diode

This was tested by substituting SB160 [8] diodes for the 1N4148's in Figure 13. Figure 14 shows the current through the SB160 protection diode upon the closing of S_1. The magnitude of the current through the diode peaks at 2.6 A. This is more in line with the earlier simulation results due to the lower series resistance of these diodes. All of the samples tested showed no degradation of noise or distortion performance after the test.

Figure 15 shows the much smaller, though not insignificant, current into the corresponding pin of the microphone preamplifier IC.

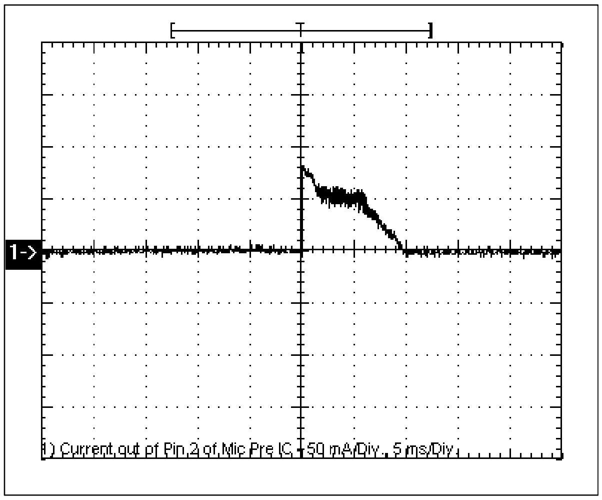

Figure 15 - Current Out of Pin 2 of Schottky-Protected Mic Pre IC

We also evaluated Schottky diodes to the power supply rails as a means to protect the output line driver ICs. The configuration is shown in Figure 16. For these tests, the microphone preamplifier IC was removed from it socket, and the SB160 Schottky diodes to the powered supply voltage rails were left it its place.

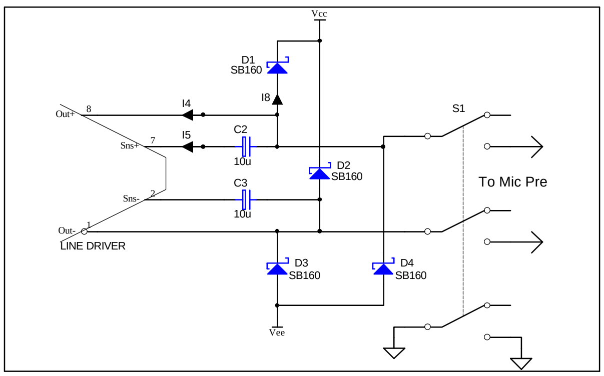

Figure 16 - Output Driver IC with Schottky Diode Protection

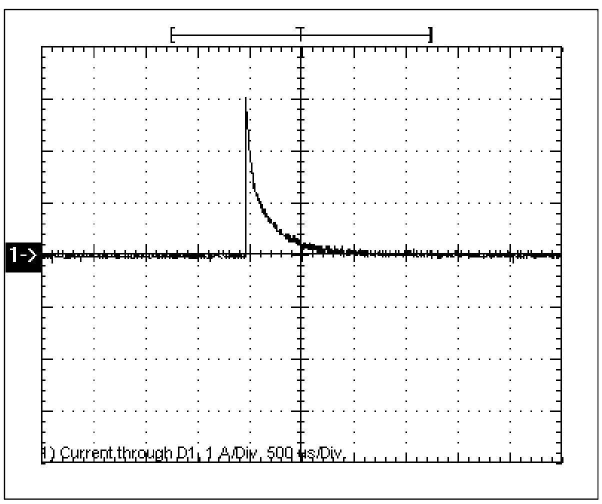

Figure 17 - Current Through D1 in Figure 16

The resulting current though D_1 is shown in Figure 17. The current through D_2 was substantially similar. The currents into pins 1, 2, 7, and 8 of the output driver IC were less than 80 mA for both models of output driver IC tested. All of the tested samples showed no measurable change in distortion performance after the test.

2.3 Back-to-Back Zener Diodes

Another protection scheme that the authors have encountered is the used of back-to-back Zener diodes to ground from each of the microphone preamplifier inputs, as shown in Figure 18. The devices shown are 12 V, 1W devices, though the use of 400 mW devices is not uncommon. The 1N4742A diodes have a maximum surge current rating of 380 mA at 25 °C (no duration is specified). [9]

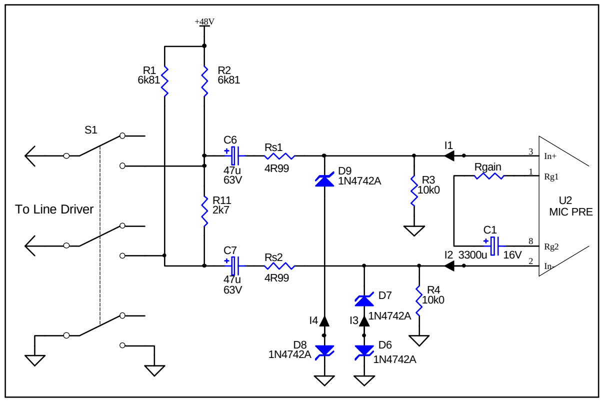

Figure 18 - Microphone Preamplifier with Zener Diode Protection

Figure 19 shows the current through D_6 and D_7 in Figure 18 during the test. The current through D_8 and D_9 was substantially similar. After testing, the Zener diodes were damaged, and resulted in distortion in the microphone preamplifier greater than 0.3% with a 1 kHz, 1 Vrms input with the preamplifier set for 0 dB gain. We verified that the distortion returned to normal after the diodes were removed from the circuit.

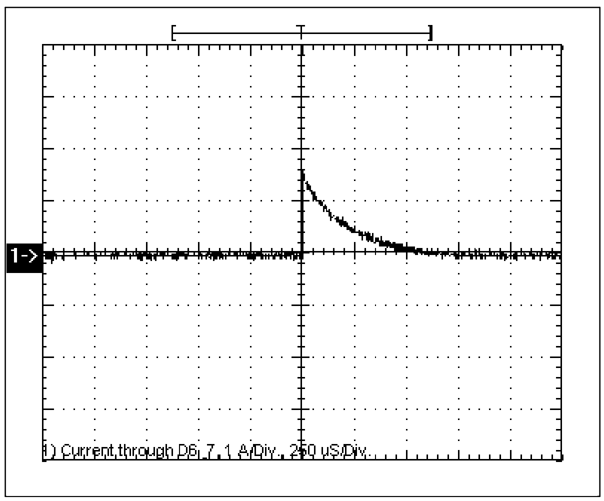

Figure 19 - Current Through D_6 and D_7 in Figure 18

At these current levels, the dynamic impedance of the Zener diodes can result in substantially higher voltages than the nominal Zener voltage. This can lead to the voltage on the preamplifier inputs exceeding the supply voltage, with the potential of again turning on internal junctions unless the Zener voltage chosen is substantially lower than the supply voltage.

2.4 Diode Bridge to Transient Voltage Suppressor Diodes

This approach, depicted in Figure 20 provides protection from overvoltage as well as high currents. Transient voltage suppressor diodes (TVS diodes) are Zener diodes that are intended and specified for overvoltage protection. TVS diodes are specified to handle much higher peak surge currents than similarly sized regulator diodes.

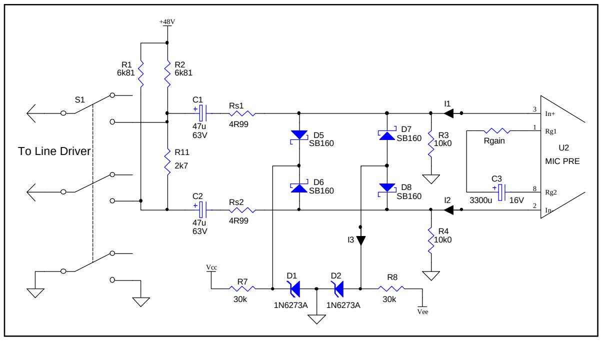

Figure 20 - Microphone Preamplifier with TVS Diode Protection

One potential drawback of TVS diodes is the fairly large, nonlinear junction capacitance associated with these devices, which could lead to increased distortion. The solution shown uses a Schottky diode bridge across the preamplifier inputs. This isolates the inputs from the much larger capacitance of the TVS diodes. The bias resistors from the TVS diodes to the supply rails pre-bias them into conduction in order to minimize circuit turn-on time and to further minimize changes in capacitance with signal.

An added benefit of the Schottky bridge allows several microphone preamplifiers to share a single pair of TVS diodes. This assumes that the probability of multiple microphone inputs being simultaneously subject to a phantom-power fault condition (i.e. short to ground, or connection to a line output) is low.

In a phantom-power fault condition, the currents from both inputs are shunted through a single TVS diode. In our testing, the peak currents through D_2 were approximately 4 A, or nearly double those observed using the Schottky diodes alone. The voltages at the preamplifier inputs remained above the negative supply voltage of 15 V, and the peak currents into the preamplifier inputs were less than 10 mA.

The 1N6273A [10] devices tested were chosen on the basis of availability, and are considerably larger than necessary. A better choice for most applications would be the SMAJ11A. [11]

3 MINIMIZING CHARGE STORAGE

The energy stored in the microphone input ac-coupling capacitors is directly proportional to the capacitance value. Minimizing the size of these capacitors, and thus bringing the stored energy more in line with that encountered in ESD events, may make it possible for newer ICs with robust ESD protection to survive these events with no external protection circuitry. It will also maximize the chances of the many unprotected and under-protected designs in the field of surviving these accidents.

There are two design considerations driving the choice of capacitor size in this application. The first is the resulting first order high pass filter pole formed by the coupling capacitors (C_1 and C_2 in Figure 9) and the input bias resistors (R_3 and R_4 in Figure 9). This is usually chosen to be quite far below 20 Hz. This is especially true since the ac-coupling capacitor for the low-valued gain-setting resistor (C_3 in Figure 9) must be must be quite large to provide flat response to 20 Hz at high gains.

Thus, it is desirable to have C_3 and R_{GAIN} set the dominant pole for the low-frequency rolloff, with the additional attenuation from C_1/R_3 and C_2/R_4 beginning well below this frequency.

The authors have observed that the input bias resistors are often chosen to have fairly low values in order to set the load on the microphone to the 1 kΩ to 2 kΩ range that most microphone manufacturers recommend. Increasing these resistors allows a commensurate reduction in capacitor size. The desired bridging resistance for the microphone can be set with a single resistor between the input lines on the phantom-power side of the coupling capacitors, such as R_{11} in Figure 21.

The upper limit on the value of the input bias resistors is usually set by the output offset due to input offset current at the microphone preamplifier's inputs flowing through these resistors. One approach that will allow the use of larger input bias resistors is an input dc servo, as shown in Figure 21.

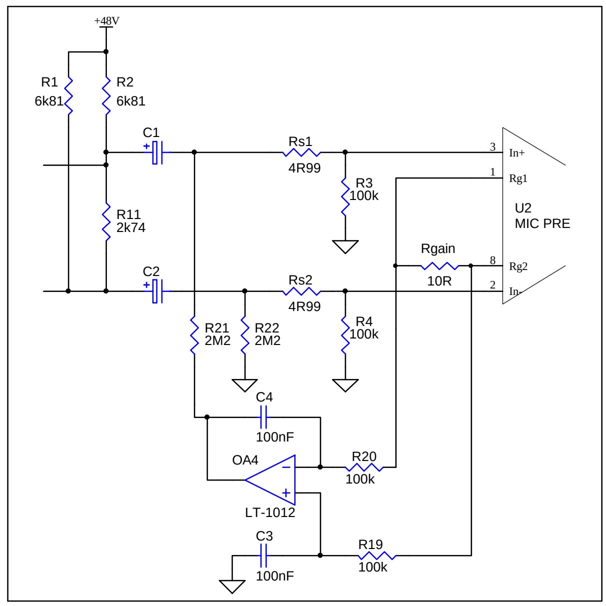

Figure 21 - Input DC Servo for Microphone Preamplifier

The servo opamp (OA4 in the Figure) forces the dc voltage across the gain-setting resistor to its own input offset voltage. Thus, in order to minimize offset variations (thumps) at the preamplifier output as gain is varied, OA4 must have a low input offset voltage. It should also have low offset currents, though this requirement can be relaxed if R_{19} and R_{20} are scaled down in value, and C_3 and C_4 are proportionately scaled up in value. The device shown [12] has an offset voltage less than 50 µV, and offset current below 150 pA. Thus, the maximum offset across R_{GAIN} will be less than 65 µV, and the maximum offset variation at the preamplifier output will be less than 65 mV when switching to a maximum gain of 60 dB.

The second design consideration that comes into play when choosing the coupling capacitor value is increased noise due to input noise currents flowing through the capacitor impedance at low frequencies. Typical input noise currents are on the order of 2 pA/√Hz [1]. Figure 22 shows equivalent input noise in a 20 Hz - 20 kHz bandwidth as the value of C_1 and C_2 in Figure 21 is varied from 470 nF to 47 µF. The microphone preamplifier was modeled with the circuit in Figure 5, with the input transistor h_{fe} parameters adjusted to yield 12.5 µA of input bias current, and thus 2 pA/√Hz of noise current. The source resistance was zero Ω.

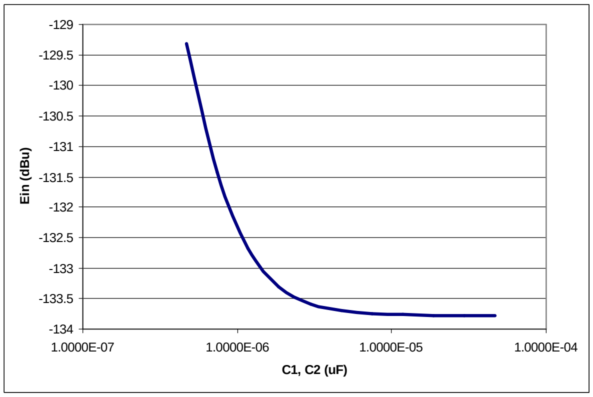

Figure 22 - Equivalent Input Noise vs. Coupling Capacitor Value

With a coupling capacitor value of 2.2 µF, the equivalent input noise is less than 0.4 dB greater than that with 47 µF capacitors. It should also be noted that the increased noise is all at low frequencies, where the ear is considerably less sensitive. This increase is even less significant (0.13 dB) if evaluated in the context of a 150 Ω source resistance.

In addition to allowing the use of small coupling capacitors on the microphone inputs, the use of an input dc servo also eliminates the need for the large coupling capacitor in series with the gain-setting resistor. This capacitor sits at a very sensitive node and makes an excellent antenna.

Another place where charge can be stored is on capacitors used to ac-couple line outputs. If such capacitors become charged by connecting an line-level device to a phantom-powered microphone preamplifier, and the line-level device is then disconnected and plugged into some other (non-phantom powered) input, large currents can flow. It is common practice to add resistors to ground to the connector side of such output coupling capacitors to keep the outputs from floating to a non-zero potential. It is advisable to make the resulting time constant at short as possible so that, if charged, the capacitors will discharge quickly.

4 RECOMMENDATIONS AND CONCLUSIONS

Based on the results of this investigation, the authors propose the following guidelines for new designs in order to minimize field failures due to the mechanism described.

1. Choose resistors in series with microphone inputs that are as high-valued as the desired noise specification will allow.

2. Protect microphone preamplifier inputs with either adequately rated Schottky diodes to the device power-supply rails, or, to provide added over-voltage protection, with Schottky diodes to biased TVS diodes as in Figure 20.

3. Protect balanced line driver output pins with Schottky diodes to the device power-supply rails.

4. To isolate microphone preamplifier inputs from 48V phantom power voltages, use coupling capacitors that are as small as possible commensurate with the desired low-frequency response and noise considerations. To facilitate this, choose input bias resistors to be as large as possible and set the microphone bridging resistance with a resistor across the inputs on the phantom-power side of the coupling capacitors. Consider using a servo as described in section 3.

5. If balanced line driver outputs are to be ac-coupled, add resistors to ground on the connector side of the capacitors, and make the resulting time constant as short as possible commensurate with adequate low-frequency response.

6. If a single-ended line driver is to be connected to balanced inputs via XLR connectors, use matched resistors in both the driven and grounded lines to provide current limiting.

In conclusion, the authors feel that small additional cost of more robust protection is likely more than outweighed by the reduction in field failures and their associated repair cost. The elimination of the sockets for input and output devices (which many designers feel are necessary) can provide additional cost savings.

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