

Protecting Instrumentation Amplifiers

All data acquisition board designs have to contend with ESD, EMI, and overvoltages. Can one solution protect the circuitry against all three hazards?

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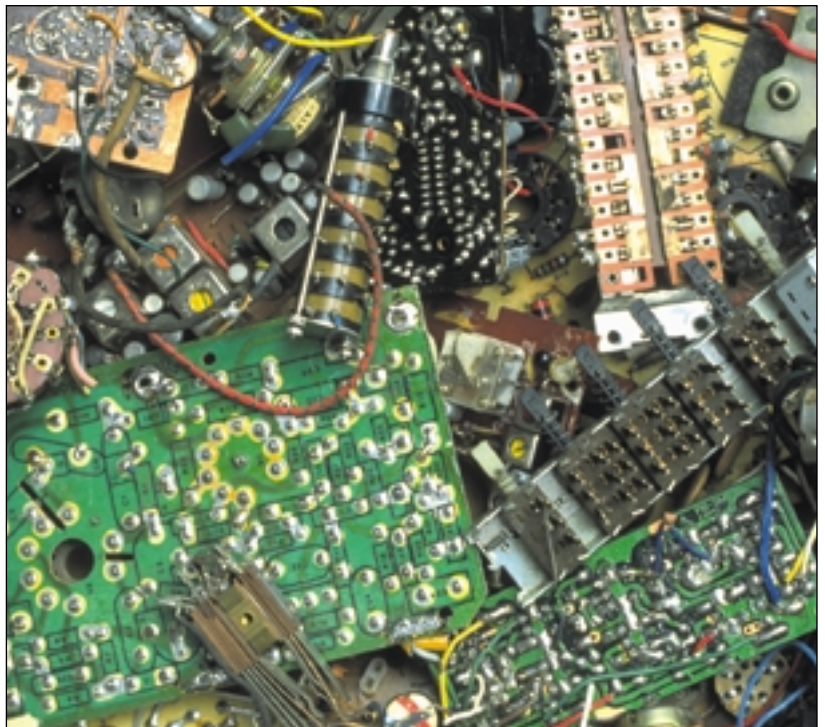
By their nature, instrumentation amplifiers are used in applications where their inputs are often exposed to electromagnetic interference (EMI), electrostatic discharge (ESD), and overvoltage events. Although these conditions are fundamentally different, the circuits used to protect against each of them are similar. This implies the possibility of a single application circuit that can protect against all three conditions.

In this article, we look at each interference source and propose suitable protection circuitry as we work toward a universal input-protection circuit. As is often the case, there's a tradeoff—in this case, between the level of protection and the corresponding effect on circuit performance.

Overvoltage Protection

Whenever an amplifier's input voltage goes outside its supply range, the unit can be damaged, usually by high current flow, even when it is turned off. Typical maximum ratings limit the allowable input voltage to the positive and negative supplies, or possibly 0.3 V outside the supplies. But some devices incorporate internal, current-limiting resistors, which let the input voltage exceed the supplies by varying degrees. Furthermore, some instrumentation amplifiers can tolerate—and indeed are designed to operate under—high-input, common-mode voltages.

To avoid damage, engineers generally use clamping to limit the input current to either 10 mA or 20 mA, depending on the device. This value is a conservative rule of thumb based on metal trace widths in a typical amplifier input stage. Higher currents can cause metal migration, which will eventually lead to an open trace. Migration is a cumulative effect that might not lead to a failure for a long time. Failure can be caused by multiple overvoltage events, making the failure modes difficult to identify. Even though an amplifier may appear to withstand overvoltage currents well above this level for a short time, limiting



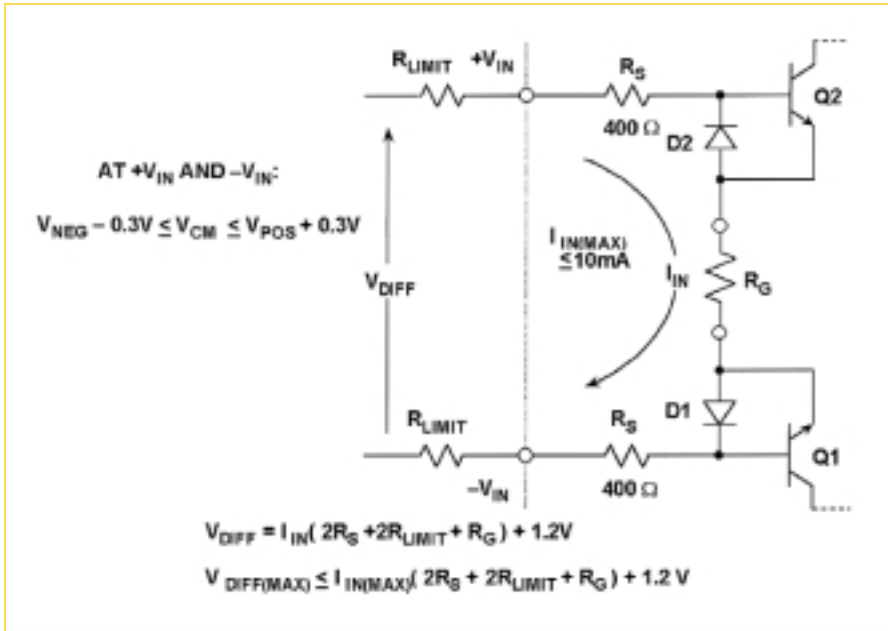


Figure 1. The equivalent circuit for the input stage of Analog Devices' AD620 during an overvoltage event includes two 400 Ω series resistors. Up to 20 mA can safely flow through the resistors. Adding external series resistors (R_{LIMIT}) provides additional protection.

Device	Input Noise	Max input Current	Rext for 10% additional noise	Rext for 40% additional noise
AD620	9 nV/√Hz	20 mA	348 Ω	2.49 kΩ
AD623	35 nV/√Hz	10 mA	8.08 Ω	40.2 kΩ
AD627	38 nV/√Hz	20 mA	10.0 Ω	45.3 kΩ

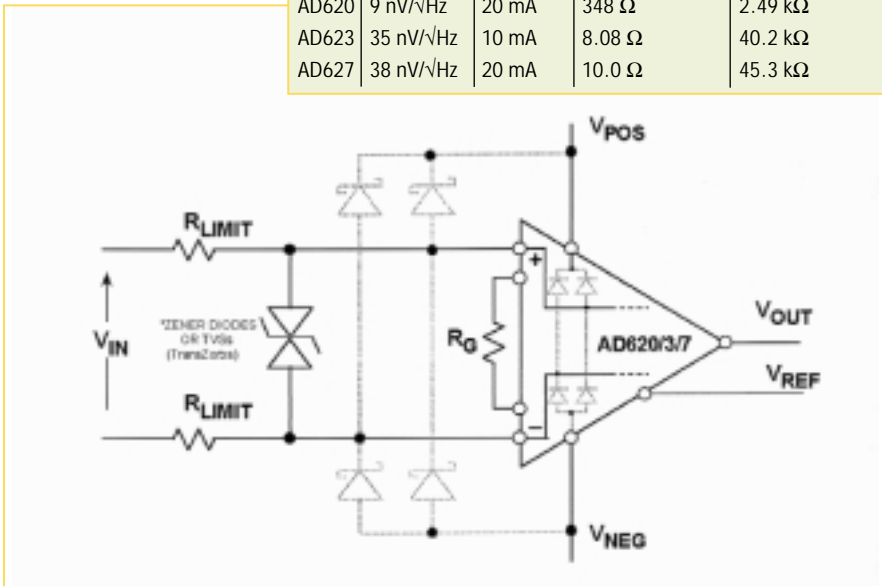


Figure 2. External series resistors combine with internal electrostatic discharge diodes to create an overvoltage, current-limiting clamping circuit. Higher currents can be carried by external Schottky diodes, allowing smaller series resistors. Zener diodes or TransZorb diodes provide differential overvoltage protection if R_{LIMIT} is small or is omitted.

the current is important to guarantee long-term reliability.

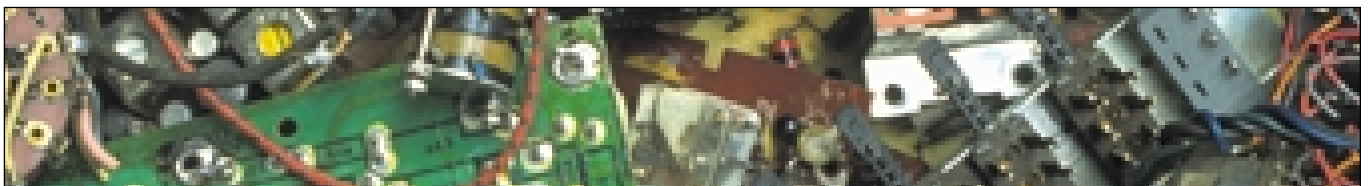
Figure 1 shows an equivalent input circuit for the input stage of Analog Devices' AD620 during an overvoltage condition. The unit has internal 400 Ω resistors in series, with the input transistor junctions and their protection diodes. The AD620 series was designed to handle maximum input currents of 20 mA, so the internal diodes protect the unit from input voltages 8 V greater than either supply voltage ($20 \text{ mA} \times 0.4 \text{ k}\Omega$). So, for $\pm 15 \text{ V}$ supplies, the maximum safe input level is $\pm 23 \text{ V}$.

In addition, the differential input voltage should also be given a value that limits the maximum input current to 10 mA. The equivalent circuit shows that the input current flows through two external R_{LIMIT} resistors, the two internal R_S resistors, the gain-setting resistor R_G , and two diode drops (D1 and the V_{be} junction of Q2). For a given differential input voltage, the input current is a function of R_G and the amplifier gain. Therefore, a gain resistor of 49.9 Ω (gain = 1000) affects the input current more than does an R_G of 5.49 kΩ (gain = 10).

A generalized external protection circuit using Schottky diodes and external current-limiting resistors can ensure input protection (see Figure 2, page 64). The circuit incorporates protection against both differential- and common-mode overvoltages. If the amplifier has internal protection diodes to the supplies (as shown), the diodes conduct at about 0.6 V forward drop above or below the supply rails. So the internal diodes—whose primary function is to protect against ESD—actually serve a dual role because they also clamp the input voltage to 0.6 V beyond the supply rails. In such cases, external diodes may be unnecessary.

You must choose the external current-limiting resistor so that the maximum input current is limited to 20 mA. This can cause large values of R_{LIMIT} , and the resulting increase in resistor (Johnson) noise might not be acceptable. Resistors contribute noise according to the following equation:

$$\text{Noise (nV}/\sqrt{\text{Hz}}) = \sqrt{4KRT} \times 10^9$$



where:

K = Boltzmann's constant (1.38×10^{-23})

R = resistance in ohms

T = temperature in kelvin (~ 300 K at room temperature)

For example, a 1 k Ω resistor has a Johnson noise of 4 nV/ $\sqrt{\text{Hz}}$ at room temperature.

Because the protection circuit includes two equal resistors, whose noise is uncorrelated—that is, the two noise sources are independent of each other—the above result must be multiplied by the square root of 2 (the root sum square of the two noise voltages).

So you have to find a reasonable balance between the protection provided and the increased resistor noise introduced. Circuits that use amplifiers with relatively high noise are able to tolerate more series protection without experiencing a serious deterioration of performance. A good rule of thumb for choosing protection resistors is to select values that contribute no more than an additional 10% to 30% to the total circuit noise. For example, a circuit using an amplifier with a rated noise level of 20 nV/ $\sqrt{\text{Hz}}$ can tolerate an additional 2–6 nV/ $\sqrt{\text{Hz}}$ of Johnson noise. Because the lower value is root sum squared with the higher value, the effect of the lower value on the total noise is almost negligible.

In situations where the required protection resistor generates too much noise, you can use the external Schottky protection diodes shown in Figure 2. These begin to conduct at about 0.3 V, so the overvoltage current is shunted through them to the supply rails rather than through the internal diodes. Therefore, you can set R_{LIMIT} by the maximum allowable diode current, which can be much larger than the internal limit of 10 mA or 20 mA. For instance, a 500 Ω R_{LIMIT} resistor would limit the diode current to 200 mA for a V_{IN} of 100 V.

Unfortunately, most ordinary diodes (e.g., Schottky, silicon, and germanium) have high leakage currents that cause large offset errors at the amplifier's input, and the leakage increases directly in proportion to temperature. This tends to rule out the use of external diodes in applications in which the amplifier is used with high-impedance

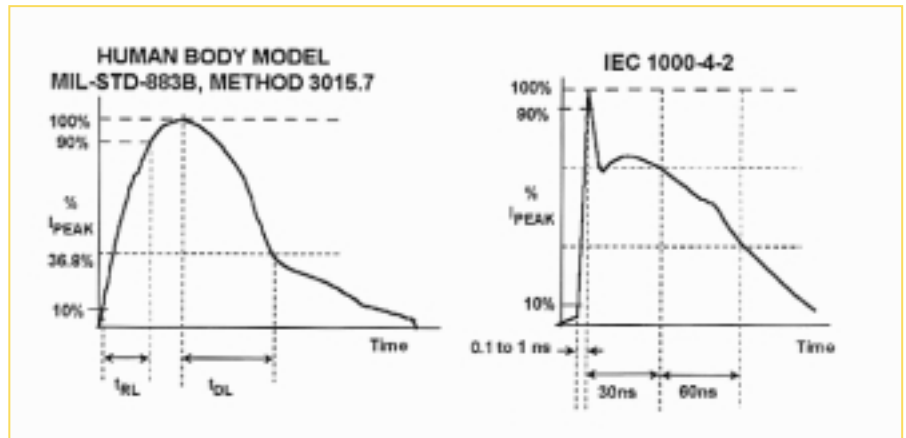


Figure 3. The IEC 1000-4-2 ESD test pulse can be up to 16 kV in amplitude (air-gap discharge) and has a much faster rise time than the Human Body Model pulse.

sources. For most applications, limiting resistors alone provide adequate protection against overvoltage conditions.

A series protection resistor also produces a voltage drop because of the amplifier bias current flowing through it. This drop appears as an increase in the circuit offset voltage (and as offset drift if the bias current changes with temperature). But because the same series protection resistance is generally used in both the amplifier's inputs, the effect is serious only with amplifiers that have large input offset currents (offset current is the difference between the amplifier's two bias currents).

Input series resistors also limit current when a differential overvoltage condition occurs. In low-noise applications, you achieve differential overvoltage protection using Zener or TransZorb diodes, as shown in Figure 2. The diodes in Figure 2 can limit the maximum differential input voltage to less than $|V_{\text{POS}} - V_{\text{NEG}}|$, if required. Two-op-amp instrumentation amplifiers don't generally need such differential protection because their input current is not a function of the gain-setting resistor, as is the case with a three-op-amp instrumentation amplifier configuration.

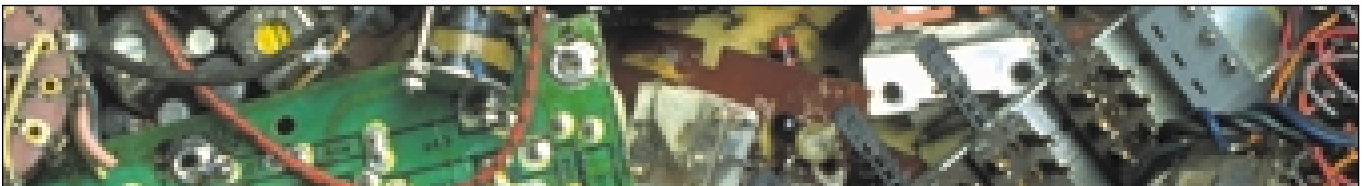
Electrostatic Discharge

The high voltages and high peak currents

generated by ESD can partially or permanently damage an IC. Several specifications related to the safe handling of semiconductors—such as MIL-STD-883B, METHOD 3015.7 (also called Human Body Model, or HBM), the Machine Model (MM), and the Charged Device Model (CDM)—are well known in the semiconductor business. But only recently have system-level standards for ESD susceptibility emerged.

Some devices require higher ESD immunity than others. For example, ICs on a PC board surrounded by other circuits are generally far less likely to be subject to ESD than are signal-conditioning devices (e.g., amplifiers that interface with sensors in the outside world).

Since 1996, all electronic equipment sold in the European community must be immune to ESD, as defined in specification IEC1000-4-2. This is a system-level specification applying to the end equipment, not to the individual ICs. The practical reality is that the signal-conditioning components (e.g., amplifiers, which are the “first line of fire”) must be protected from specified ESD or must exhibit immunity to it. However, precision analog circuits, which often feature low bias currents, actually tend to be more susceptible to damage than do common digital circuits. This is mainly because they cannot use the traditional ESD protec-



tion structures that tend to increase input leakage currents.

Traditional ESD test methods don't fully test a product's susceptibility to the type of discharge specified in IEC1000-4-2. Figure 3 (page 65) shows the profile of the test pulses used for the two types of testing. There are some important differences between the HBM method and the IEC specification. The IEC specification is far more stringent in terms of discharge energy. The peak current injected is more than four times greater. The current rise time is significantly faster in the IEC test, and the IEC test is conducted with the device under power.

IEC1000-4-2 specifies ESD compliance testing using two coupling methods: contact discharge and air-gap discharge. Contact discharge, which has a maximum discharge voltage of 8 kV, calls for a direct connection to the unit being tested. Air-gap discharge uses a higher test voltage (16 kV) but does not make direct contact with the test unit. With air-gap discharge, the ESD gun moves toward the test unit, developing an arc across the air gap. This method is influenced by humidity, temperature, barometric pressure, distance, and the discharge gun's closure rate. The contact-discharge method, although less realistic, is more repeatable and is gaining acceptance in preference to the air-gap method.

Figure 4 (page 66) shows a simple technique for protecting amplifiers against high-voltage ESD. The technique is quite simple and relies again on input-series-resistor protection to limit the current flowing into the device during the ESD. Carbon resistors, which are noninductive, should be used as protection resistors (R_{PROT} in Figure 4) instead of devices made of metal film or carbon film. There is, however, a tradeoff here, because carbon film resistors are imprecise and can add noise.

Reducing EMI

Radio frequency interference (also called EMI) can seriously affect the DC performance of high-accuracy circuits. Because of their relatively low bandwidth, amplifiers don't accurately amplify RF signals in the

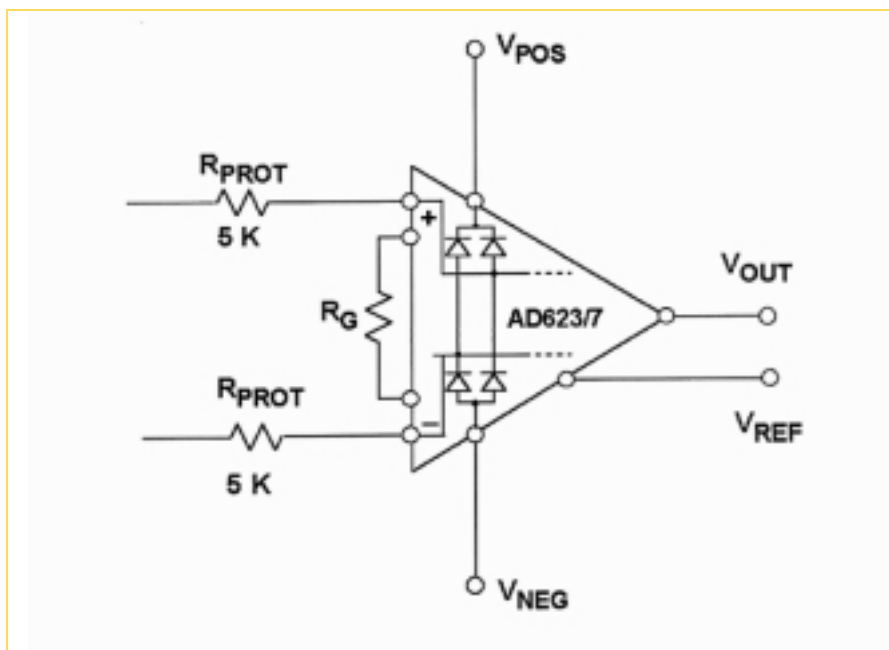


Figure 4. External series resistors augment internal ESD protection resistors by limiting fault current flow into the instrumentation amplifier's inputs.

MHz range. But these out-of-band signals (either differential mode or common mode) can couple into the precision amplifier through its input, output, or power-supply pins. Then, through various junctions in the amplifier, an unexplained and unwanted DC offset at the output can result. Fortunately, proper filtering can minimize or prevent these errors.

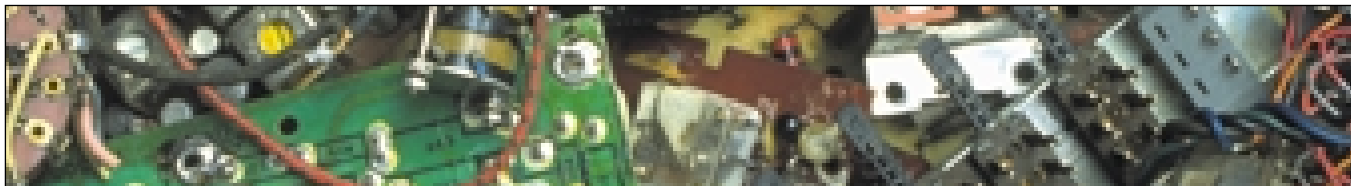
Precision amplifiers are particularly sensitive to common-mode RFI. Figure 5 (page 68) shows recommended filtering component values, along with equations for calculating appropriate components. The figure shows both common-mode filtering ($R1/C1$, $R2/C2$) and differential-mode filtering ($R1 + R2$, and $C3$).

If $R1/R2$ and $C1/C2$ are not well matched, some of the input common-mode signal at V_{IN} will be converted to a differential signal at the amplifier's inputs. For this reason, $C1$ and $C2$ should be matched to within at least 5% of each other. $R1$ and $R2$ should be 1% metal film resistors to ensure matching. Capacitor $C3$ helps attenuate the differential signal that can result from im-

perfect matching of the common-mode filters. In this type of filter, $C3$ should be much larger than $C1$ or $C2$ so that any differential signal caused by mismatching of the common-mode signals will be sufficiently attenuated. You can use either traditional 5% silver-mica capacitors, miniature micas, or Panasonic $\pm 2\%$ PPS film capacitors. The overall filter bandwidth should be at least $100 \times$ the input signal bandwidth.

For optimum filter performance, the EMI filter components should be symmetrically mounted on a PC board with a large ground plane and should be close to the amplifier input. Figure 6 (page 68) shows a typical layout for a standard 8-pin amplifier. This type of layout is easiest to achieve if you use surface-mount components. The board should have at least two layers, ideally with one continuous ground plane running under the component plane (as shown). Multiple vias should run between the sections of ground plane on the component layer and the continuous ground plane (either on the other side of the circuit board or in a buried layer).

We tested the common-mode rejection of



Device	R1/R2	C1/ C2	C3
AD620	402 kΩ	1000 pF	0047 μF
AD623	10 kΩ	1000 pF	0022 μF
AD627	20 kΩ	1000 pF	0022 μF

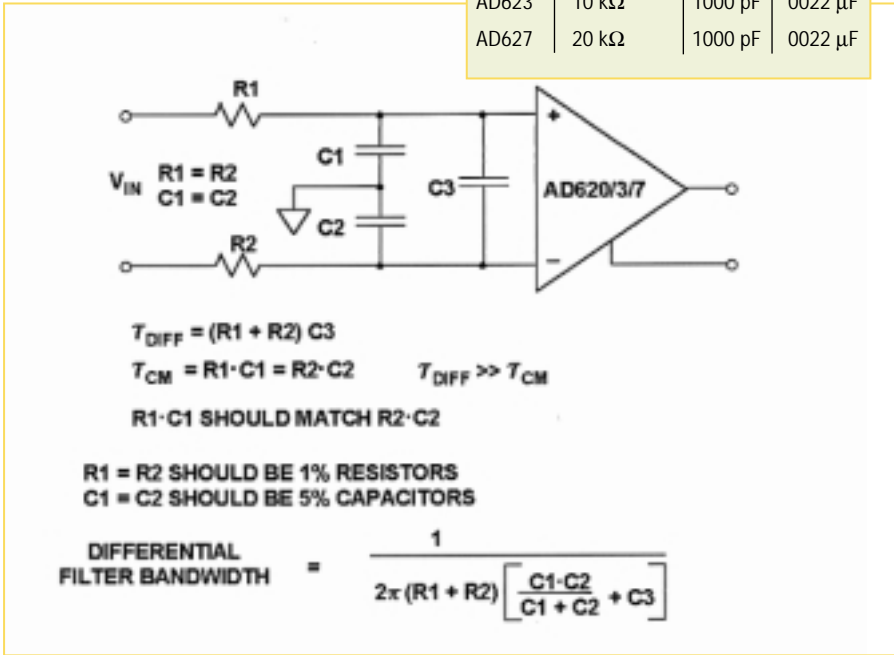


Figure 5. Protection against electromagnetic interference requires attention to both differential-mode and common-mode interference. R1/C1 and R2/C2 time constants should be closely matched to preserve high-frequency common-mode rejection.

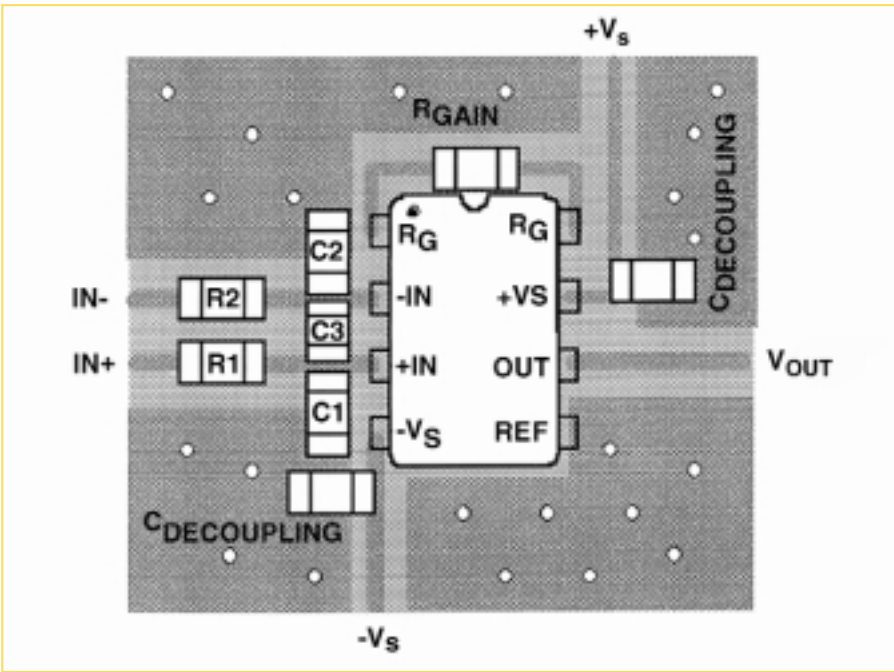


Figure 6. Symmetrical layout of EMI filter components increases the effectiveness of the filter. A continuous ground plane should run under the component layer (either on the other side of the circuit board or in a buried layer) with plenty of vias connecting to the sections of ground plane on the component layer.

the AD620 in the circuit shown in Figure 5 by applying a 1 V p-p common-mode signal to the input. The AD620 gain was 1000. We measured the RTI offset voltage as the frequency of the sine-wave source varied from DC to 20 MHz. The maximum input offset voltage shift was 1.5 μV. The filter bandwidth was ~400 Hz.

Common-Mode Chokes

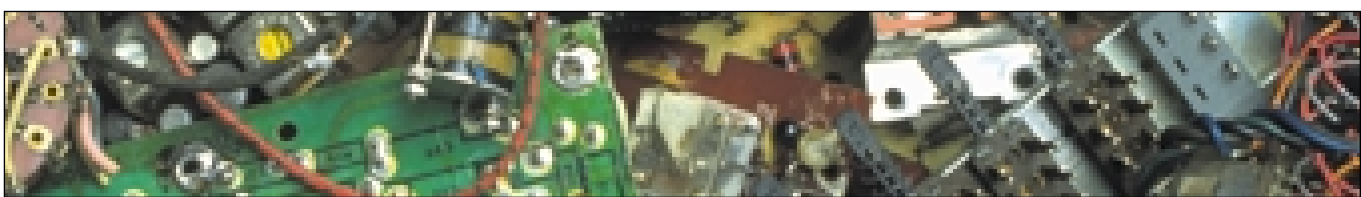
Common-mode chokes offer a simple, one-component alternative to RC passive filters. Because their DC resistance is low (a few ohms), they attenuate RFI and add little noise as compared with RC networks. Selecting the proper common-mode choke is critical, however. The choke used in the circuit shown in Figure 7 (page 69) is a Pulse Engineering B4001 designed for Digital Subscriber Line data receivers (through-hole mount). The B4003 is an equivalent surface-mount choke. The maximum RTI offset shift measured from DC to 20 MHz was 4.5 μV. Unlike the RC filter of Figure 5, the choke-based filter offers no differential-mode filtration.

But you can add an RC differential-mode filter after the choke. The advantage of this configuration is that there is no penalty of potential common-mode-to-differential-mode conversion, as there is with the combination RC networks discussed earlier.

In addition to filtering the inputs and the power pins, you have to protect amplifier outputs from RFI, especially if they must drive long lengths of cable. RFI on the output can couple into the amplifier, where it is rectified and appears again on the output as a DC offset shift. A resistor or ferrite bead in series with the output is the simplest output filter. Adding a capacitor and a resistor (as shown in Figure 7, page 69) improves the filter. In general, however, you shouldn't connect such a capacitor to the resistor's amplifier side because it could cause the amplifier to become unstable.

A Multipurpose Protection Circuit

It is clear from this discussion and from the examples that a simple circuit can protect against more than one type of interference. For example, the circuit in Figure 5



provides some protection against all three types of interference—the input series resistors limiting the current during ESD and overvoltage, as well as constituting part of a low-pass differential and common-mode filter. In this example, you don't need to protect against large differential voltages because the large series resistors limit the worst-case current (for a 160 V differential overvoltage) to around 20 mA.

For Further Reading

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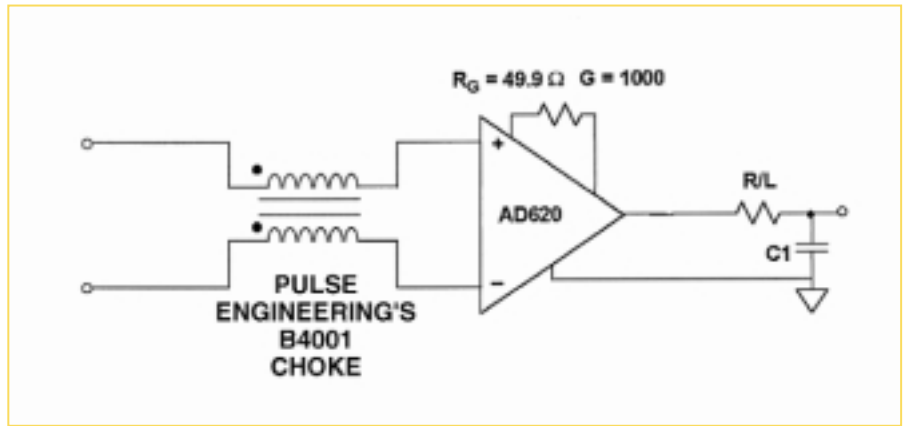


Figure 7. Common-mode chokes offer a simple, one-component alternative to RC filters. A simple RC filter can protect the amplifier's output from EMI.

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