Common-Mode Noise: Sources and Solutions

Application Note 1043

Introduction

Circuit designers often encounter the adverse effects of common-mode noise on a design. Once a common-mode problem is identified, there are several ways that it can be resolved. However, common-mode interference manifests itself in many ways; therefore, it may be hard to determine whether or not this is the cause of your circuit's misbehavior. If a system is connected and running but only produces erroneous data, common-mode noise may be the reason. This application note describes sources of common-mode problems, presents possible solutions, and concludes with a description of Hewlett-Packard's approach to addressing common-mode noise.

Common-mode noise problems exist in many electrical circuits. Any device or system with either its input or its output floating may be susceptible to common-mode noise. A common-mode signal is a signal that appears common to either set of floating points. It can be either ac or dc. The overall effect is that excessive common-mode noise causes spurious results at the output, disrupting safe, precise measurements.

Common-mode interference is sometimes inherent in a system design, but most often it is inductively or capacitively coupled from an external source. A good example of common-mode noise is the 60-Hz signal induced on a pair of wires by nearby power lines. In this case, the noise signal is "common" to each of the two wires. An inherent common-mode signal is one in which the circuit itself causes the interference. An example of this is the half bridge power inverter. In such an application, the driver circuits of the power transistors rise and fall hundreds of volts with respect to signal ground in only tens of nanoseconds.

Definition of CMR

Common-mode rejection (CMR) is a measure of the ability of a device to tolerate common-mode noise. It can be specified in several ways. The common-mode specification is sometimes given as CMV, or common-mode voltage. This value specifies the maximum common-mode voltage amplitude that can be applied to the device without causing a problem. The CMR of analog devices is commonly specified in dB as the ratio of the differential-mode gain to the common-mode gain. This specification is often called the common-mode rejection ratio, or CMRR. Another way to specify CMR is as a common-mode transient rejection (CMTR). CMTR describes the maximum tolerable rate-of-rise (or fall) of a common-mode voltage. It is usually given in volts per micro-second. In order to be complete, the CMTR should also include the amplitude of the common-mode voltage that can be tolerated. Common-mode interference that exceeds the maximum specification might result in abnormal voltage transitions or excessive noise on the output signal.

Sources of CMR Problems

Common-mode signals can originate from several different sources. A full-bridge power inverter, shown in Figure 1, is a good example of an application that can exhibit large amounts of common-mode noise. Full bridge inverters are commonly found in motor-speed control and
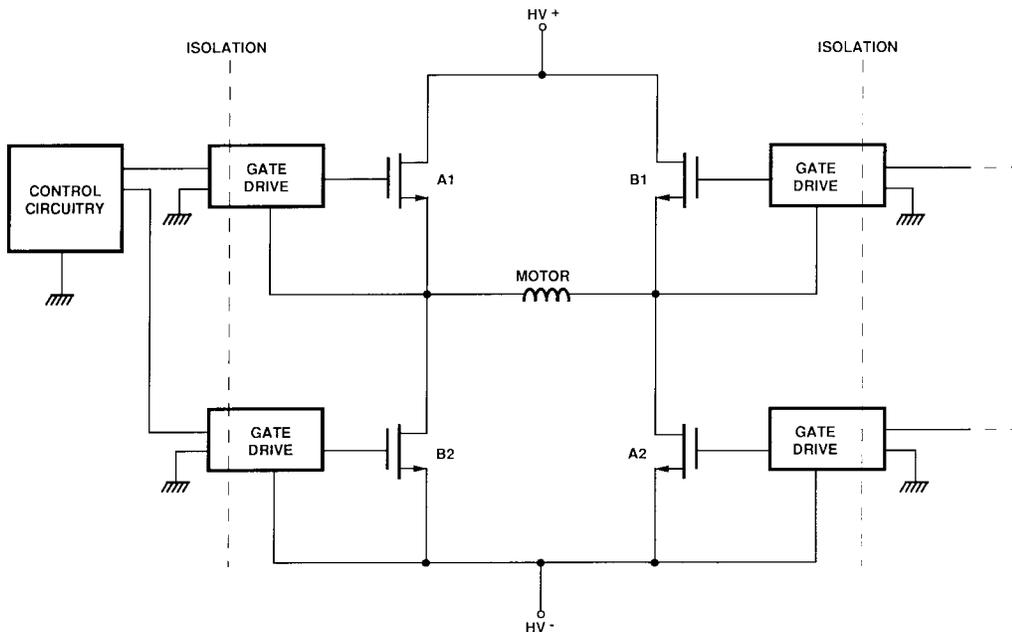
Figure 1. Full-Bridge Power Switch Configuration.

switching power supply applications. The power inverter is generally used to produce an ac output from a dc input. In a full-bridge inverter application like that shown in Figure 1, the source of one set of transistors (A1, B1) is attached to the drain of a second set of transistors (A2, B2). When transistor set A turns on, set B turns off. Current flows from the positive supply, through transistor A1, through the load, and through transistor A2. When set B turns on, set A turns off, and the polarity of the current through the inductive load is reversed.

How does this operation create a common-mode problem? The input of each gate drive circuitry is referenced to the ground of the digital control circuitry; the output common, on the other hand, is floating and referenced to the source of its associated power transistor. The floating common of the gate drive circuitry rapidly switches between the positive and negative power supplies. This

rapid switching creates a large voltage swing across the input to output of the gate drive circuitry. As an example, a half bridge circuit that switches between +250 V and -250 V in 100 ns creates a common-mode transient

signal of 5000 V/µs with an amplitude of 500 V (see Figure 2). The device that carries the control information to each MOSFET must be able to withstand this level of common-mode interference. Although this example may seem
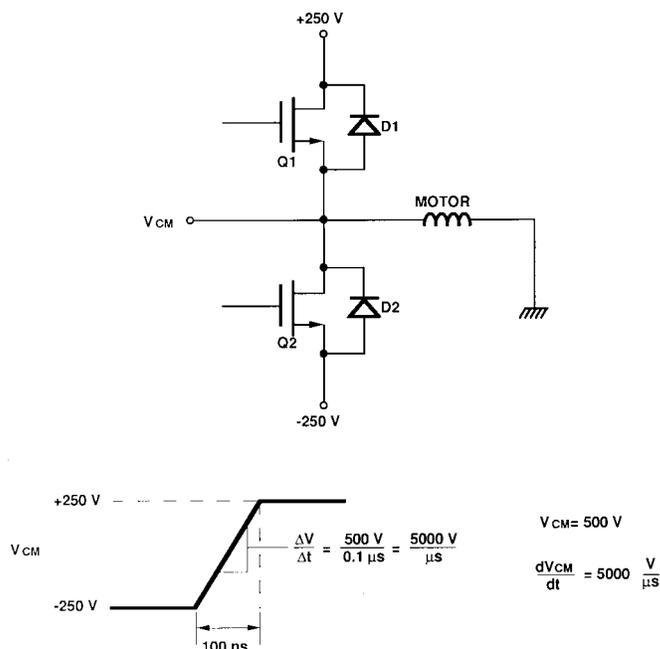

$$\frac{\Delta V}{\Delta t} = \frac{500\ V}{0.1\ \mu s} = \frac{5000\ V}{\mu s}$$

$$V_{CM} = 500\ V$$

$$\frac{dV_{CM}}{dt} = 5000\ \frac{V}{\mu s}$$

Figure 2. Half-Bridge Example.

extreme, it is a fact that engineers continue to use faster switching transistors to increase efficiency. Power MOSFETs, for example, are commonly used in power inverter applications because they are capable of high frequency, high power switching. The fast switching speeds of the transistors, however, can generate common-mode signals with very high rates of change (dVcm/dt).

The common-mode signal rate-of-rise can also be affected by the reverse recovery characteristics of diodes D1 and D2 in the power inverter shown in Figure 2; these diodes are often referred to as "free-wheeling" diodes. If the inverter is driving an inductive load, such as a motor winding, these diodes may become forward biased during the normal operation of the inverter. For example, assume that Q1 of Figure 2 is turned on, Q2 is off, and current is flowing through Q1 and into the inductive load. When Q1 turns off, voltage Vcm swings in the negative direction until diode D2 becomes forward biased and conducts the load current.

It is when Q1 turns back on that very high rates of rise can be generated. In extreme cases, when Q1 turns on again, the rate of rise of voltage Vcm is determined by how quickly diode D2 recovers from forward conduction. The voltage and current waveforms shown in Figure 3 illustrate what happens when Q1 turns back on. As Q1 starts to turn on, the current through D2 begins to decrease. The current through D2 continues to decrease and actually goes negative for a short time due to the storage of minority carrier charge in its junction. It is when

this charge has been depleted that D2 begins to turn off and Vcm begins to increase. If D2 turns off very quickly, Vcm can also rise very quickly, generating a large common-mode transient signal.

High electrical noise levels can also contribute to common-mode problems. A significant amount of electrical noise is found in industrial environments as a result of the starting and operating of electric motors. When a large motor first turns on, it normally requires a large inrush current to reach operating speed. This large current spike can generate a significant amount of electrical noise in its own and nearby systems. Even the electric motors in a typical household environment vary in size from fractional to low integral horsepower units and are often noisy ac-operated or brushed dc-motors. Other sources of electrical noise include microwave ovens, welding equipment, and automobile ignitions.

Common-mode noise can enter a system through conductive, inductive, or capacitive coupling.
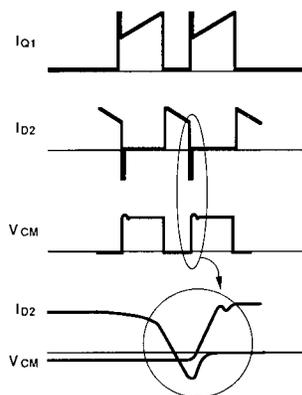
Figure 3. Half-Bridge Inverter Wave-forms.

An example of a "conducted" noise voltage is the difference in ground potential that may exist between two connected systems in a plant. The two systems may experience a small voltage difference between their ground references. This voltage difference might cause a ground-loop current to flow. If the impedance of the path through which the ground-loop current flows is large enough, a significant amount of interference will result. Capacitive or inductive coupling may occur when signal wires run close to ac power cables. Electromagnetically induced interference (EMI) can also be coupled from adjacent signal lines or nearby equipment, especially in factory environments. Other sources of common-mode noise that can be coupled into a system include lightning strikes and electro-static discharge (ESD).

Solutions
There are a number of ways to limit the amount of common-mode noise entering a system. Employing good design techniques is one way to obtain better common-mode rejection. For example, a designer should carefully lay out his board to ensure that signal lines do not run adjacent to power lines. This minimizes the amount of 60-Hz noise coupled onto the signal lines. Generous use of bypass capacitors and filters helps to reduce the effect of common-mode voltages coupled onto the power supply lines. An engineer might also design a completely differential circuit, taking advantage of the inherent common-mode rejection of differential circuitry. Ideally, both inputs to the differential circuit should be referenced to the same

point. Otherwise, a small potential between the two reference points will add directly to the differential signal and may cause problems. Especially in high-frequency circuits, the positive and negative lines should run parallel and have the same length. This ensures that the two lines have the same impedance and balanced common-mode coupling.

$$V_{CM} = (I_{CM}Z1) - (I_{CM}Z2)$$

Figure 4. Twisted Pair Line.

Capacitive isolation is an effective and inexpensive way to eliminate dc common-mode signals. The most common application for capacitive isolation is in interstage coupling. For example, multi-stage amplifiers are often ac coupled. Coupling capacitors are useful for removing dc common mode voltages but do not block ac common-mode interference. Because capacitors block dc voltages, this technique cannot be used in applications for which dc signals must be transferred.

Twisted-pair wire, when used with a differential line receiver, can help to reduce the effects of common-mode noise by balancing the common-mode coupling of both electric and magnetic effects. However, if an interfering common-mode signal is not coupled equally to both lines, the net unbalance will appear as a differential-mode signal. Another problem may result if the impedances measured to ground of the two lines differ; a fraction of the common-mode signal at the end of the twisted-pair line will appear differential and interfere with the desired signal, as illustrated in Figure 4. A typical application involves the use of twisted-pair wire with an RS-422 differential line receiver. An advantage of the differential line
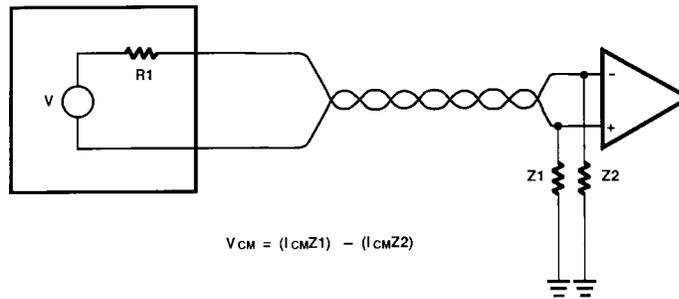
receiver is its fast response. Also, a differential line receiver can pass both ac and dc signals. Disadvantages of line receivers are that they do not provide isolation between input and output and can tolerate only a limited range of common-mode voltages. For example, a typical RS-422 receiver can tolerate common-mode voltages of +15 V. Shielding a twisted-pair wire will provide better common mode rejection because the shield provides additional protection from electric and magnetic interference.

Transformers also provide common-mode rejection. They are often used in power applications and frequently in data communication applications such as Ethernet. An advantage of the transformer is that it provides isolation. This means that the input and the output of a system are electrically separated, and common ground connections are broken. In general, the input and the output of a transformer are symmetrical, which means that data can be transmitted in either direction across the transformer. Also, a transformer does not require an isolated power supply to operate.

A disadvantage of the transformer is that although it can pass high-frequency signals with relative

ease, it cannot pass dc. Therefore, the transformer is not useful for data formats like Non-Return-to-Zero (NRZ) where the duty factor can range from zero up to 100 percent. With a transformer, NRZ data would require the use of more complex encoding and decoding circuitry, such as Manchester, which is used in Ethernet applications. In some applications, it may be difficult to obtain a usable waveform with the transformer. The transformer experiences a "sag" in the waveform which may cause problems with the design. Another difficulty with the transformer is that obtaining good common-mode rejection requires a balanced primary with symmetrical capacitances. Otherwise, a common-mode voltage injected into the center tap causes unbalanced voltages in the primary winding which, in turn, becomes a differential mode signal. A transformer with an electrostatic shield between its primary and secondary offers higher common-mode rejection than a transformer without a shield. The shield makes the transformer more expensive, but minimizes noise transferred across the windings. Other disadvantages of transformers are that they radiate and are susceptible to magnetic fields; they can be complex to design with; and they

may occupy a significant amount of space on the printed circuit board.

Optical isolation is another useful technique for reducing common-mode interference. Optocouplers, like transformers, provide isolation between the input and output of a system. Optocouplers use light for data transmission; therefore, they do not radiate nor are they affected by stray magnetic fields. Optocouplers typically provide better common-mode rejection than transformers because optocouplers do not have the high primary-to-secondary capacitance that transformers do. The CMR specification of an optocoupler ranges from 10 -1500 V amplitude and 50-30,000 V/µs rate of change, depending on the product. Another advantage of the optocoupler is that it can pass both ac and dc signals, eliminating the need for data conversion when transmitting NRZ data. Also, optocouplers are usually available in standard DIP or small-outline packages, so they require minimal board space. Disadvantages of the optocoupler are that it may require the use of an isolated power supply, and it can pass data only in a single direction.

HP's High CMR Technology

An optocoupler consists of an input LED and an output photodetector in a single package. The photodetector can be either a phototransistor, a photodiode with a transistor, or a photodiode with an integrated logic circuit. Ideally, an optocoupler would have complete isolation between its input and its output. However, the physical proximity of the input
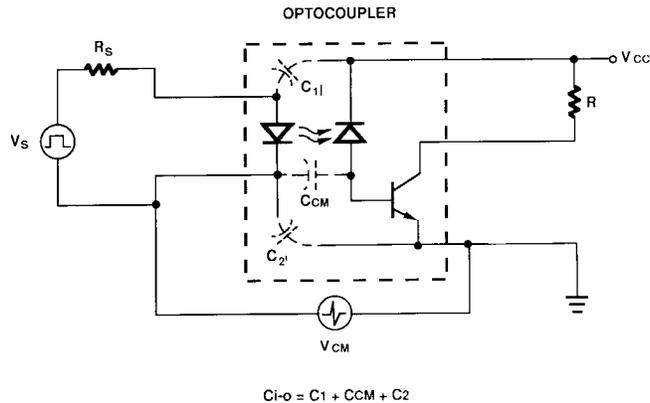

$$Ci\text{-}o = C1 + CCM + C2$$

Figure 5. Input-to-Output Capacitance.

lead frame to the output lead frame creates a small capacitance between the two. This capacitance, known as Ci-o, is measured between shorted input pins and shorted output pins.

The most important factor in the common-mode interference capability of an optocoupler is the common-mode coupling capacitance, Ccm. Ccm, as shown in Figure 5, is only a fraction of the total input-to output capacitance Ci-o, but it is the main parameter that affects the common-mode capability of an optocoupler. Therefore, the smaller the value of Ccm, the better the common-mode rejection. As an example of how a common-mode signal can affect an output, Figure 6 shows a positive common-mode transient coupled through Ccm. This noise signal is amplified by the output gain stages, and tends to turn the output ON when it should be OFF. To enhance the common-mode rejection capability of its optocouplers, Hewlett-Packard inserts an internal shield between the input LED and the photodiode of each device. The internal shield is a transparent conductive shield which allows optical coupling to

the photo diode but diverts electrically coupled current to the ground pin. The shield, as shown in Figure 7, reduces Ccm by at least an order of magnitude, improving the common-mode rejection of the optocoupler. A typical unshielded optocoupler might have a specified common mode rejection of 10 or 50 V peak and 1000 V/µsec rate of change. Using the electric shield technology, HP is able to produce high CMR optocouplers with CMR ratings up to 1500 V peak and 30,000 V/µsec rate of change (HCPL-4503).

TRANSIENT AMPLITUDE = V_{CM}

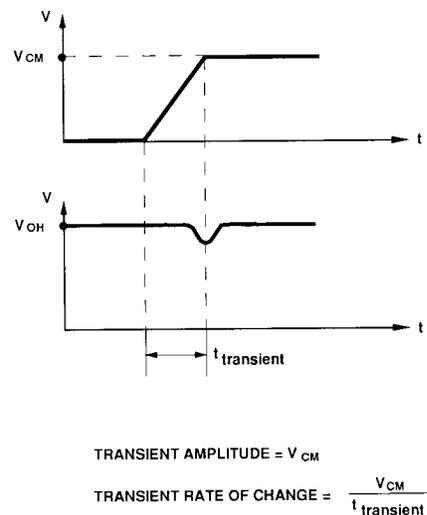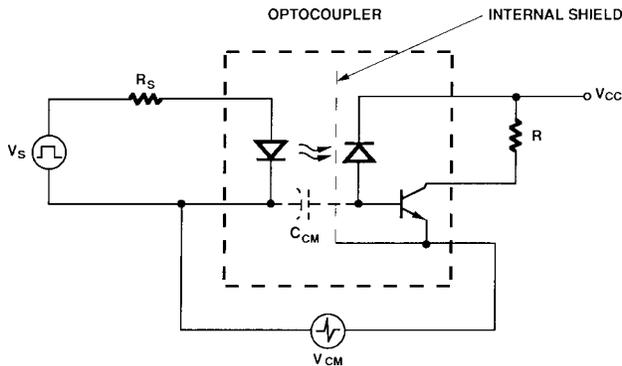TRANSIENT RATE OF CHANGE = $\dfrac{V_{CM}}{t_{transient}}$

Figure 6. Common-Mode Interference Effect.

Figure 7. Enhanced Common-Mode Transient Immunity.

As shown in Figure 8, the interference by a common-mode signal can be explained in terms of a current and a voltage. A common-mode signal with a large dVcm/dt produces an interfering signal, which is a current, Ib. This current, Ib, adds or subtracts from the photodiode current, Ip. A common-mode signal with a large amplitude (Vcm) produces an interfering signal which is a voltage, Vbe. This voltage can turn on or turn off the base emitter junction of the transistor. The overall impact of a common-mode signal results from the combined effects of dVcm/dt and Vcm. For this reason, it is important for an optocoupler to specify both the slope (dVcm/dt) and the amplitude (Vcm) of a tolerable common-mode signal. A common-mode signal of 10 kV/µs at 1 kV, for example, is much worse than a common-mode signal of 10 kV/µs at 10 V.
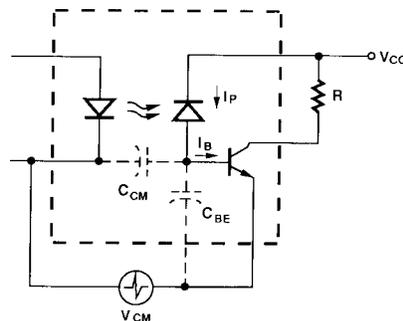
Hewlett-Packard specifies the CMR of its optocouplers as $|CM_H|$, Common Mode Transient Immunity at High Output Level, and as $|CM_L|$, Common Mode Transient Immunity at Low Output Level. CM_H is the maximum tolerable rate-of-rise of the common-mode voltage to ensure

that the output will remain in a high logic state. Likewise, CML is the maximum tolerable rate-of-fall of the common-mode voltage to ensure that the output will remain in a low logic state. Each CM_H and CM_L specification includes the common-mode voltage amplitude (Vcm) as well as its rate of rise (dVcm/dt).

Hewlett-Packard offers a variety of high CMR optocouplers for both analog and digital applications. Specifications for these optocouplers can be found in the current Optoelectronics Designer's Catalog.

$$I_B = C_{CM} \left(\frac{dV_{CM}}{dt} \right)$$

$$V_{BE} = V_{CM} \left(\frac{C_{CM}}{C_{CM} + C_{BE}} \right)$$

Figure 8. Common-Mode Interference Model.

Conclusion

In summary, common-mode noise problems can occur in almost any electrical circuit. The noise can be coupled from an external source, as in data communications, or be an inherent part of the design, as in switch-mode power supplies. Several techniques for reducing the effects of common-mode noise have been discussed. Hewlett-Packard offers a wide variety of high CMR opto-couplers to help solve these types of noise problems. Additionally, Applications Engineers and Field Sales Engineers are available for technical assistance and product support.