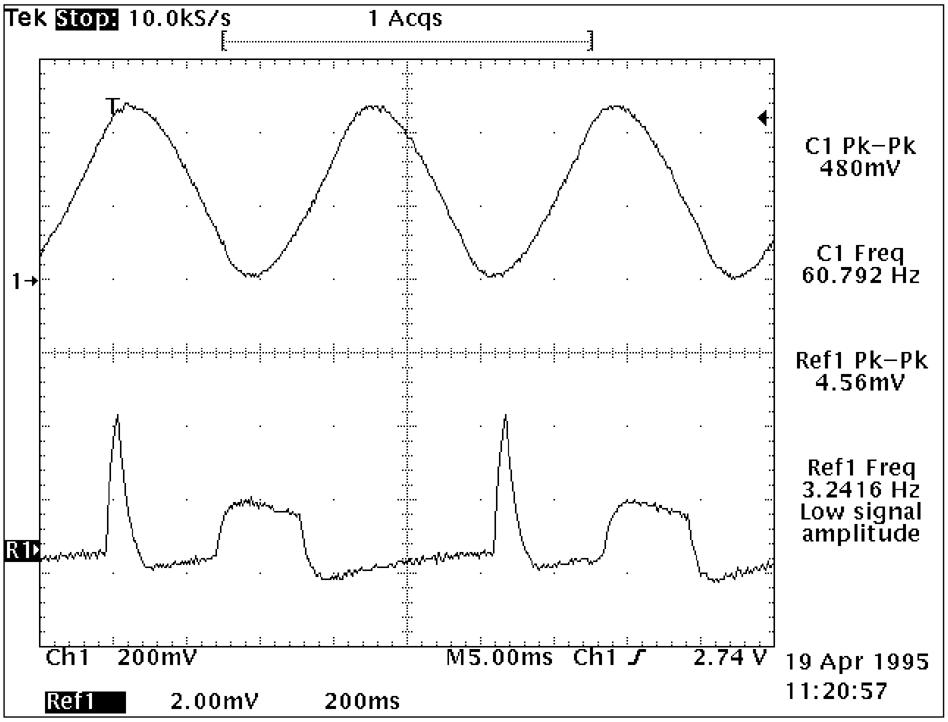
Technical Note

Differential Oscilloscope Measurements

A Primer on Differential Measurements, Types of Amplifiers, Applications, and Avoiding Common Errors



Simulated 4 mV_{p-p} heartbeat waveform can not be measured in the presence of 500 mV_{p-p}, 60 Hz common-mode noise, using a conventional oscilloscope probe (upper). A differential amplifier extracts the signal from the noise

Introduction

All Measurements Are Two-Point

Voltage is always measured between two points in a circuit. This is true whether using a voltmeter or an oscilloscope. When an oscilloscope probe touches a point in a circuit, a waveform usually appears on the display, even if the ground lead is not connected. In this situation, the reference for the measurement is conducted through the safety ground of the scope chassis to the electrical ground in the circuit.

By virtue of their two probes, digital voltmeters measure potential between two points. Because they are isolated, these two points can be anywhere in the circuit. This has not always been the case. Before the advent of the digital voltmeter, hand-held meters known as VOMs (Volt-Ohm-Meters) were used to measure “floating” circuits. Because they were passive, they tended to load the circuit-under-test. Less invasive measurements were made with the high-impedance VTVM (Vacuum Tube Volt Meter). The VTVM had one major limitation – the measurement was always referenced to ground. The VTVM housing was grounded and connected to the reference lead. With the introduction of solid-state gain circuits, high performance voltmeters could be isolated from ground, allowing floating measurements to be made.

Most oscilloscopes today, like the venerable VTVM, can only measure voltages that are referenced to earth ground, which is connected to the scope chassis. These are referred to as “single-ended” measurements – the probe ground provides the reference path. Unfortunately, there are times when this limitation lowers the integrity of the measurement, or makes measurement impossible.

If the voltage to be measured is between two circuit nodes, neither of which is grounded, conventional oscilloscope probing cannot be used. A common example is measuring the gate drive in a switching power supply (see Figure 1).

Signals which are balanced (between two leads without a ground return) such as a common telephone line cannot be measured directly. As we shall see, even some “ground referenced” signals cannot be faithfully measured using single-ended techniques.

When Ground Is Not Ground

We’ve all heard of “ground loops” and been taught to avoid them. But how do they corrupt a scope measurement? A ground loop results when two or more separate ground paths are tied

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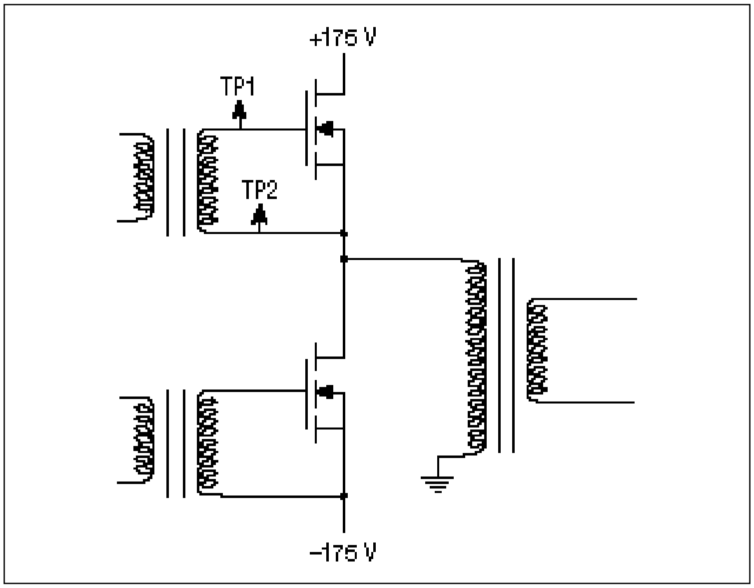

Figure 1. Gate drive signal in a switching power supply is measured between TP1 and TP2. Neither point is grounded.

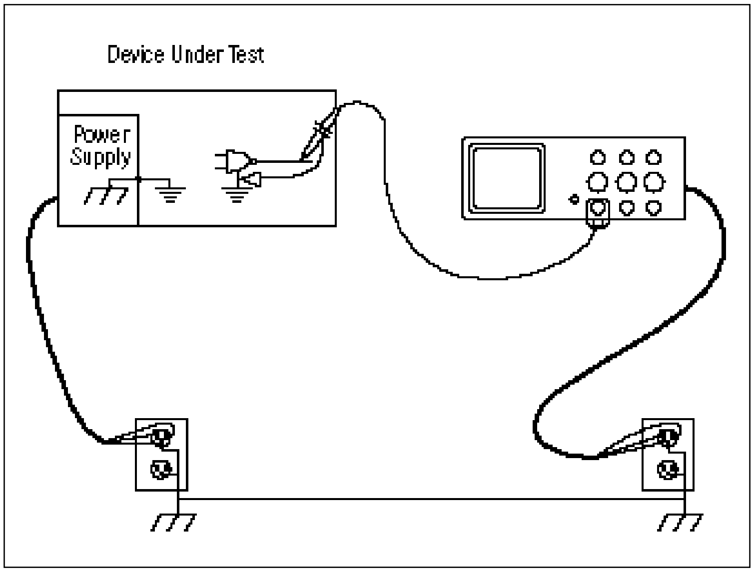

Figure 2. Ground loop formed by a scope probe. Metal chassis of both scope and device under test are connected to safety ground and internal power supply common. Scope probe ground connects to scope chassis at the input BNC connector.

together at two or more points. The result is a loop of conductor. In the presence of a varying magnetic field, this loop becomes the secondary of a transformer which is essentially a shorted turn. The magnetic field which excites the transformer can be created by any conductor in the vicinity which is carrying a non-DC current. AC line voltage in primary wiring or even the output lead of a digital IC can produce this excitation. The current circulating in the loop develops a voltage across any impedance within the loop. Thus, at any given instant in time, various points within a ground loop will not be at the same potential.

Connecting the ground lead of an oscilloscope probe to the ground in the circuit-under-test results in a ground loop if the circuit is “grounded” to earth ground (see Figure 2). A voltage potential is developed in the probe ground path resulting from the circulating current acting on the impedance within the path.

Thus, the “ground” potential at the oscilloscope’s input BNC connector is not the same as the ground in the circuit being measured (i.e., “ground is not ground”). This potential difference can range from microvolts to as high as hundreds of millivolts. Because the oscilloscope references the measurement from the shell of the input BNC connector, the displayed waveform may not represent the real signal at the probe input. The error becomes more pronounced as the amplitude of the signal being measured decreases, as is common in transducer and biomedical measurements.

In these situations, it’s often tempting to remove the probe ground lead. This technique is only effective when measuring very low-frequency signals. At higher frequencies, the probe begins to add “ring” to the signal caused by the resonant circuit from the tip capacitance and shield inductance (see Figure 3). (This is why you should always use the shortest ground lead possible.)

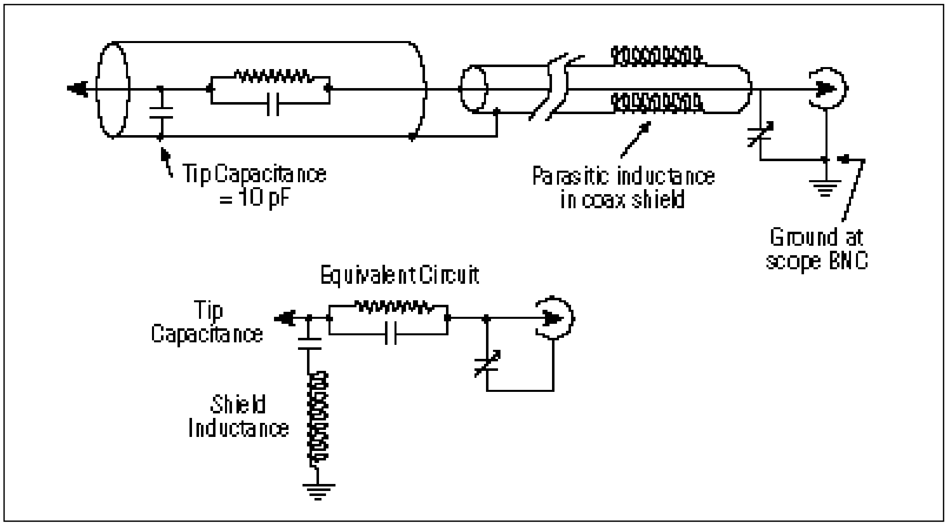

Figure 3. Series resonant tank circuit formed by probe-tip capacitance and ground inductance.

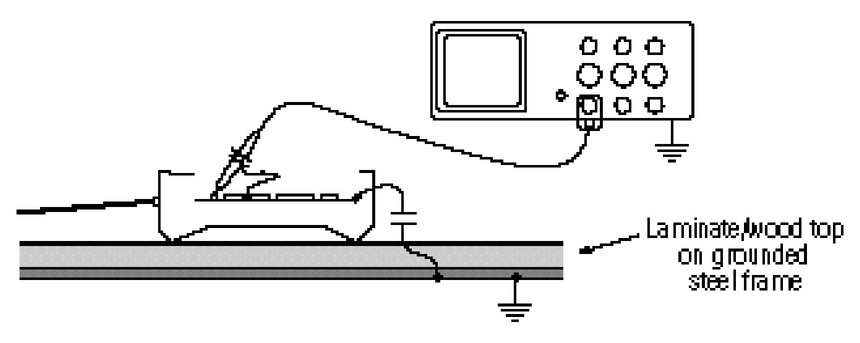

Figure 4. “Floating” battery-powered cellular telephone probed with a grounded oscilloscope. Capacitance between the phone circuitry and steel bench frame forms a virtual ground loop at high frequencies.

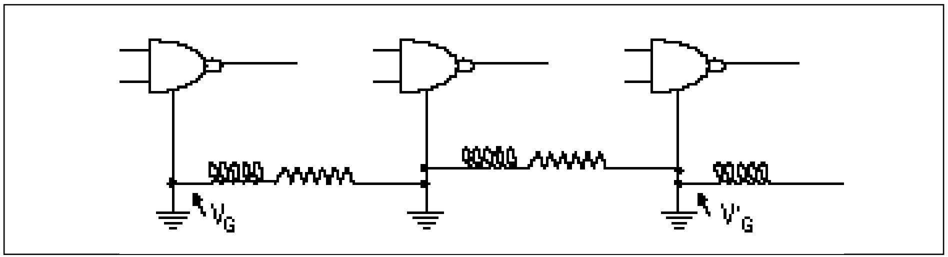

Figure 5. Minute parasitic inductance and resistance in ground distribution system result in $V_G \neq V'_G$.

We now have a dilemma: create a ground loop and add error to the measurement or remove the probe ground lead and add ring to the waveform!

The next technique often tried to break ground loops is to “float” the scope or “float” the circuit being measured. “Floating” refers to breaking the connection to earth ground by opening the safety-ground conductor – either at the device-under-test or at the scope. Floating either the scope or the device-under-test (DUT) allows the use of a short ground lead to minimize ring without creating a ground loop.

This practice is inherently dangerous, as it defeats the protection from electrical shock in the event of a short in the primary wiring. (Some special battery-operated portable scopes incorporate insulation which allows safe floating operation.) Operator safety can be restored by placing a suitable ground-fault circuit interrupter (GFCI) in the power cord of the oscilloscope (or device-under-test) with the severed ground. However, be aware that without a low-impedance ground connection, radiated and conducted emissions from the scope may now exceed government standards – as well as interfere with the measurement itself. At higher frequencies, severing the ground may not break the ground loop as the “floating” circuit is actually coupled to earth ground through stray capacitance (see Figure 4).

Even when the measurement system doesn’t introduce ground loops, the “ground is not ground” syndrome may exist within the device being measured (see Figure 5). Large static currents and high-frequency currents act on the resistive and inductive components of the device ground path to produce voltage gradients. In this situation, the “ground” potential referenced at one point in the circuit will be different than that referencing another point.

For example, ground at the input of the high-gain amplifier in a system differs from the “ground” potential at the power supply by several millivolts. To accurately measure the input signal seen by the amplifier, the probe must reference the ground at the amplifier input.

These effects have challenged designers of sensitive analog systems for years. The same effect is seen in fast digital systems. The small inductance within the ground distribution system can create a potential across it, resulting in “ground bounce”. Troubleshooting systems affected by ground-voltage gradients is difficult because of the inability to really look at the signal “seen” at the individual component. Connecting the oscilloscope probe ground lead to the “ground” point of the device results in the uncertainty of what effects the new path adds to the ground gradient. A sure clue that a change is occurring is seen when the problem in the circuit either gets better (or worse) when the probe ground is connected. What we really need is a method to make a scope measurement of the actual signal at the input of the suspect device.

By using an appropriate differential amplifier, probe, or isolator, accurate two-point oscilloscope measurements can be made without introducing ground loops or otherwise corrupting the measurement, upsetting the device-under-test, or exposing the user to shock hazard.

There are several types of differential amplifiers and isolation systems available for oscilloscopes, each optimized for a particular class of measurements. In order to choose the proper solution, an understanding of terminology is necessary.

Differential Measurement Fundamentals

Overview of Differential Measurements

An ideal differential amplifier amplifies the “difference” signal between its two inputs and totally rejects any voltage which is common to both inputs (see Figure 6). The transfer equation is:

$$V_O = A_V(V_{+in} - V_{-in})$$

where V_O is referenced to earth ground.

The voltage of interest, or difference signal, is referred to as the differential voltage or differential mode signal and is expressed as V_{DM} (V_{DM} is the $V_{+in} - V_{-in}$ term in the transfer equation above).

The voltage which is common to **both** inputs is referred to as the Common-Mode Voltage expressed as V_{CM}. The characteristic of a differential amplifier to ignore the V_{CM} is referred to as Common-Mode Rejection or CMR. The ideal differential amplifier rejects all of the common-mode component, regardless of its amplitude and frequency.

In Figure 7, a differential amplifier is used to measure the gate drive of the upper MOSFET in an inverter circuit. As the MOSFET switches on and off, the source voltage swings from the positive supply rail to the negative rail. A transformer allows the gate signal to be referenced to the source. The differential amplifier allows the scope to measure the true V_{GS} signal (a few volt swing) at sufficient resolution such as 2 V/division while rejecting the several hundred volt transition of the source to ground.

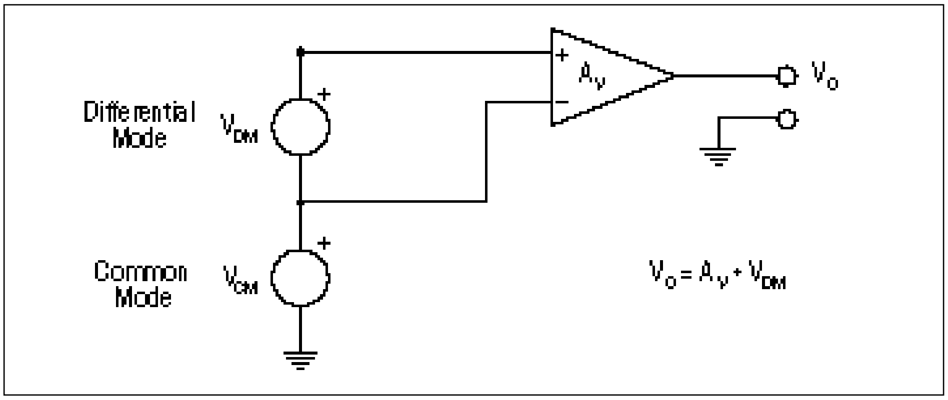

Figure 6. Differential amplifier.

Common-Mode Rejection Ratio (CMRR)

Real implementations of differential amplifiers cannot reject all of the common mode signal. A small amount of common mode appears as an error signal in the output, making it indistinguishable from the desired differential signal. The measure of a differential amplifier’s ability to eliminate the undesirable common-mode signal is referred to as Common-Mode Rejection Ratio or CMRR for short. The true definition of CMRR is “differential-mode gain divided by common-mode gain referred to the input”:

$$\text{CMRR} = \frac{A_{DM}}{A_{CM}}$$

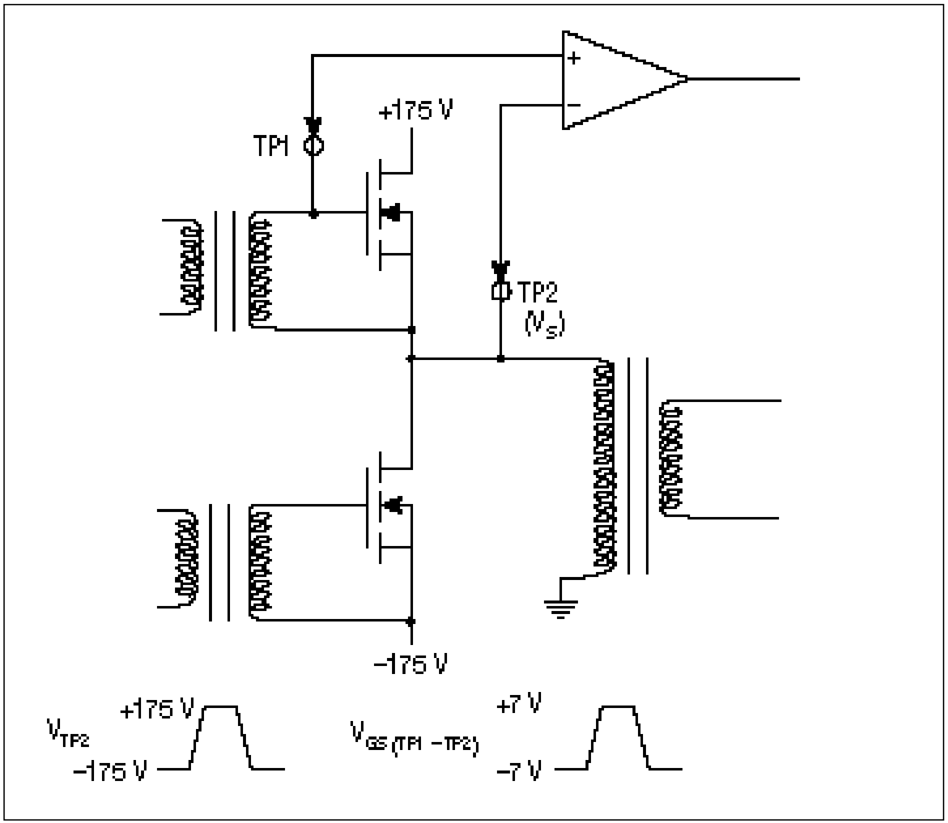

Figure 7. Differential amplifier used to measure gate to source voltage of upper transistor in an inverter bridge. Note that the source potential changes 350 volts during the measurement.

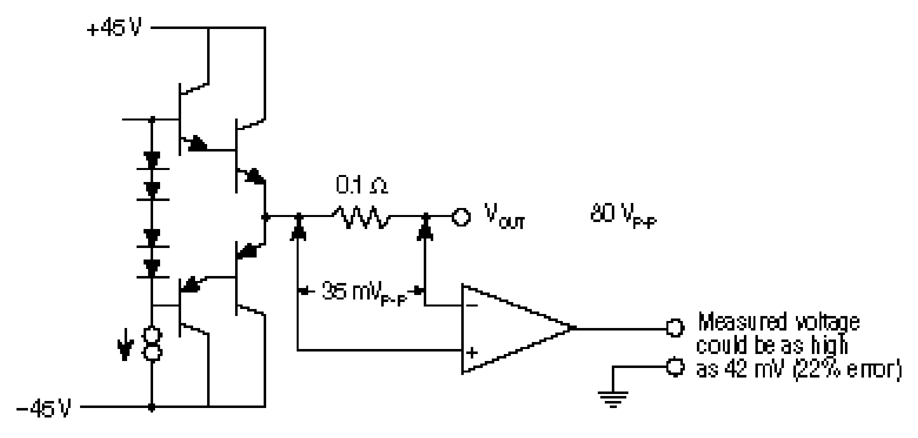

Figure 8. Common-mode error from a differential amplifier with 10,000:1 CMRR.

For evaluation purposes, we can assess CMRR performance with no input signal. The CMRR then becomes the apparent V_{DM} seen at the output resulting from common mode input. It's expressed either as a ratio – 10,000:1 – or in dB:

$$\text{dB} = 20\log\left(\frac{V_{DM}}{V_{CM}}\right)$$

A CMRR of 10,000:1 would be equivalent to 80 dB.

For example, suppose we need to measure the voltage in the output damping resistor of an audio power amplifier as shown in Figure 8. At full load, the voltage across the damper (V_{DM}) should reach 35 mV, with an output swing (V_{CM}) of 80 V p-p. The differential amplifier we use has a CMRR specification of 10,000:1 at 1 kHz. With the amplifier driven to full power with a 1 kHz sine wave, one ten thousandth of the common-mode signal will erroneously appear as V_{DM} at the output of the differential amplifier, which would be 80 V/10,000 or 8 mV. The 8 mV represents up to a 22% error in the true 35 mV signal!

The CMRR specification is an absolute value, and does not specify polarity (or degrees of phase shift) of the error. Therefore, the user can not simply subtract the error from the displayed waveform. CMRR generally is highest (best) at DC and degrades with increasing frequency of V_{CM}. Some differential amplifiers plot the CMRR specification as a function of frequency.

Let's look at the inverter circuit again. The transistors switch 350 V and we expect about a 14 V swing on the gate. The inverter operates at 30 kHz. In trying to assess the CMRR error, we quickly run into a problem. The common-mode signal in the inverter is a square wave, and the CMRR specification assumes a sinusoidal common-mode component. Because the square wave contains energy at frequencies considerably higher than 30 kHz, the CMRR will probably be worse than specified at the 30 kHz point.

Whenever the common-mode component is not sinusoidal, an empirical test is the quickest way to determine the extent of the CMRR error (see Figure 9). Temporarily connect **both** input leads to the MOSFET source. The scope is now displaying only the common-mode error. You can now determine if the magnitude of the error signal is significant. Remember, the phase difference between V_{CM} and V_{DM} is not specified. Therefore subtracting the displayed common-mode error from the differential mea-

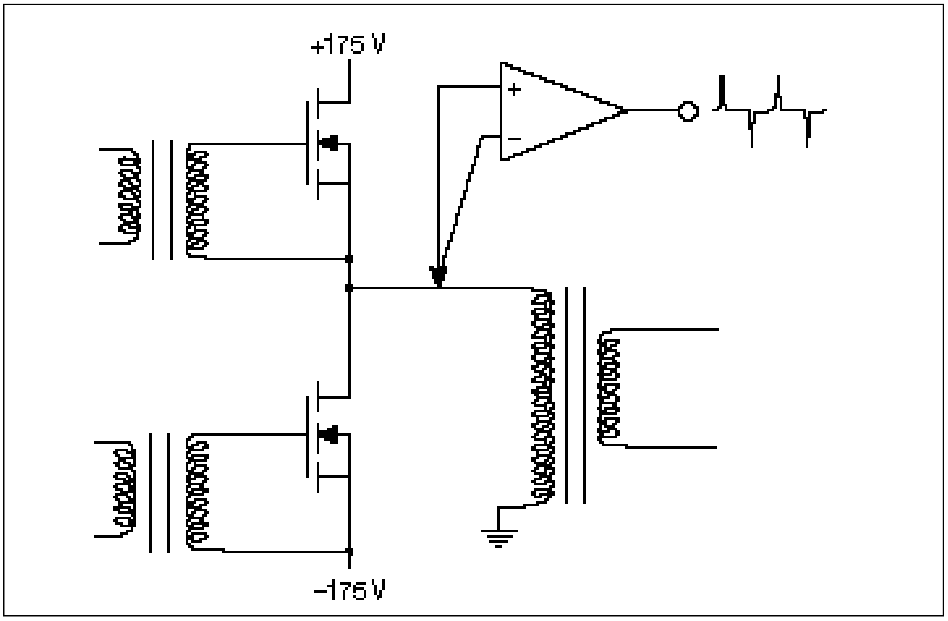

Figure 9. Empirical test for adequate common-mode rejection. Both inputs are driven from the same point. Residual common mode appears at the output. This test will not catch the effect of different source impedances.

surement will not accurately cancel the error term.

This is a handy test for determining the extent of common-mode rejection error in the actual measurement environment. However there's one effect this test will not catch. With both inputs connected to the same point, there's no difference in driving impedance as seen by the amplifier. This situation produces the best CMRR performance. When the two inputs of a differential amplifier are driven from significantly different source impedances, the CMRR will be degraded. The specifics of the effect are discussed later – see ***Input Impedance Effects on CMRR***, page 13.

Other Specification Parameters

Differential-mode range is equivalent to the input range specification of an amplifier or single-ended oscilloscope input. Input voltages which exceed this range will overdrive the amplifier, resulting in output clipping or nonlinearity.

Common-mode range refers to the voltage window over which the amplifier can reject the common-mode signal. The common-mode range is usually larger than or equal to the differential range. Depending on the amplifier topology, the common-mode range may or may not change with different amplifier gain settings. Exceeding an amplifier's common-mode range may have various results in the output. In some situations, the output will not clip and may produce a close approximation of the true input, with some additional offset. In this situation, the display may be close enough to what is expected that it's not questioned by the user. It's always a good practice to verify that the common-mode signal is within the acceptable common-mode range before making any differential measurements.

Maximum common-mode slew rate is specified for some differential amplifiers and most isolators. This specification is often confusing but very important. Part of the confusion results from a lack of standard definition between instrument manufacturers. Also, differential amplifiers and isolators behave differently when their maximum common-mode slew rate is exceeded. Essentially, maximum CM slew rate is a supplemental specification to CMRR. The specification is usually given in units of kV/µs.

Some types of differential amplifiers, like other amplifiers, reach a large-signal slew rate limitation before the small-signal bandwidth specification is exceeded. When one or both sides of a differential amplifier are driven to slew-rate limiting, the common-mode rejection is degraded very rapidly. Unlike CMRR, maximum slew rate does not imply an increasing amount of common-mode feed-through in the output. Once the maximum common-mode slew rate is exceeded, all bets are off – the output is likely to clamp at one of the power supply rails.

In isolators, however, the effect is more gradual – like CMR in a differential amplifier. As the common-mode slew rate increases (as opposed to the frequency), more of the common-mode component "feeds through" to the output. Intuitively, the specification would imply a maximum slew rate at which a known amount of feed-through appears in the output. It's important to note that with some isolators, the CM slew rate specification is actually a maximum non-destructive limit. The ability to make meaningful measurements is lost at slew rates much lower than the maximum specification. When using an isolator, it's best to test the common-mode feed-through before making critical measurements. This is easily done by driving both the probe tip and the reference lead with the same common-mode signal and observing the output.

Types of Differential Amplifiers and Probes

Built-in differential amplifiers. Many scopes have the ability to make the simplest differential measurements built right in to them. This mode is referred to as “channel A – channel B” or “quasi-differential”. While limited in performance, this technique may be adequate for some measurements. To make a differential measurement, two vertical channels are used – one for the positive input and one for the negative input. The channel used for negative input is set to invert mode and the display mode is set to “ADD Channel A + Channel B”. For proper operation, both inputs must be set to the same scale factor, and both input probes must be identical models. The display now shows the difference voltage between the two inputs.

To maximize CMRR, the gain in both channels should be matched. This can be easily done by connecting both probes to a square wave source with an amplitude within the dynamic range of the volts/division setting (about ±6 divisions). Set one of the channels to “uncalibrated – variable” gain and adjust the variable-gain control until the displayed waveform becomes a flat trace.

The primary limitation of this technique is the rather small common-mode range, which results from the scopes vertical channel dynamic range. Generally, this is less than ten times the volts/division setting from ground. Whenever $V_{CM} > V_{DM}$, this mode of obtaining a differential result can be thought of as extracting the small difference from two large voltages.

Most digital storage oscilloscopes perform waveform math in the digital domain, after the analog signal has been digitized. The limited resolution of the analog-to-digital converter is often not adequate to view the resulting differential signal after the common-mode signal is subtracted out. Because the AC gain in the two channels is not precisely matched, CMRR at higher frequencies is rather poor.

This technique is suitable for applications where the common-mode signal is the same or lower amplitude than the differential signal, and the common-mode component is DC or low frequency, such as 50 or 60 Hz power line. It effectively eliminates ground loops when measuring signals of moderate amplitude.

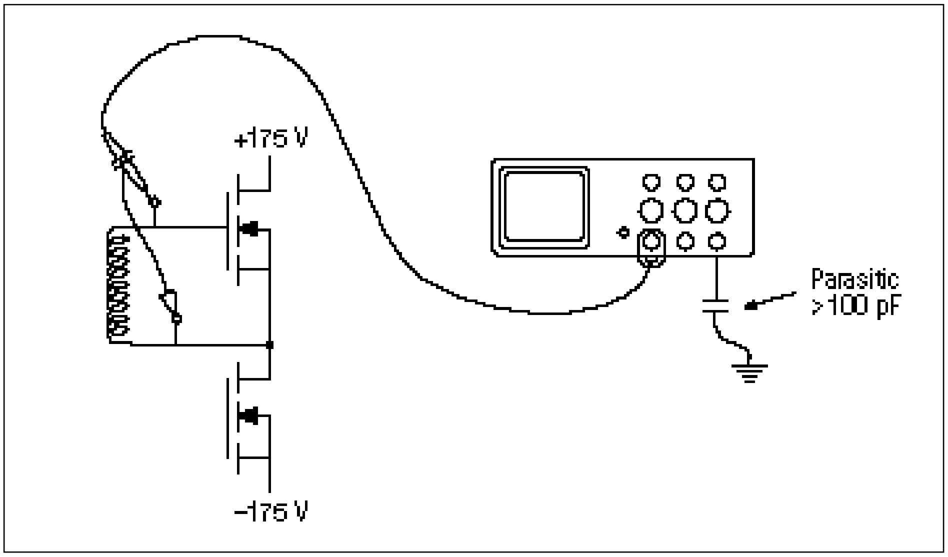

Figure 10. Even when the scope is “floating”, parasitic capacitance forms an AC voltage divider which adds error to the measurement. Note that reversing the probe leads will load the gate with >100 pF, possibly destroying the circuit-

High-voltage differential probes. Recently, high-voltage active differential probes have appeared on the market. A new topology using fixed attenuation with switchable differential gain allows these probes to keep their full common-mode range in all gain settings. The single attenuator greatly reduces complexity resulting in lower cost to the user.

These probes provide an affordable, safe method of measuring line-connected circuits commonly found in switching power supplies, power inverters, motor drives, electronic-lamp ballasts, etc. With common-mode ranges up to 1,000 V, these probes eliminate the need for the extremely dangerous practice of “floating the scope”. Recently, workplace hazard monitoring organizations such as the U.S. OSHA (Occupational and Safety and Health Act) have intensified their verification of equipment grounding, issuing costly fines to violators.

In addition to the safety benefits, the use of these probes can improve measurement quality. An obvious benefit is the full use of the scopes multiple channels with the simultaneous viewing of multiple signals referenced to different voltages. Because the probes are true differential, both of the inputs are high impedance – high resistance and low capacitance. Floating scopes and isolators do not have balanced inputs. The reference side (the “ground” clip on the probe) has a significant capacitance to ground. Any source impedance the reference is connected to will be loaded during fast common-mode transitions, attenuating the signal.

Worse yet, the high capacitance can damage some circuits (see Figure 10). Connecting the scope common to the upper gate in an inverter may slow the gate-drive signal, preventing the device from turning off and destroying the input bridge. This failure is usually accompanied with a miniature fireworks display right on your bench – something many power electronics designers can attest to.

With the balanced low input capacitance of high-voltage differential probes, any point in the circuit can be safely probed with either lead.

High-gain differential amplifiers. A high-gain differential amplifier, often an external accessory, allows scopes to measure very small amplitude signals – down to a few microvolts. To avoid corruption from ground-loop and ground-gradient effects, these signals are always measured differentially – even when they are ground referenced. When the source is not ground referenced, the common-mode can be several orders of magnitude greater than the differential mode signal of interest. To cope with this, these amplifiers have extremely high CMRR, often 1,000,000:1 or greater.

Some high-gain differential amplifiers include additional functionality to improve the integrity of low-amplitude measurements. Selectable low-pass filtering allows the user to remove out-of-band noise from lower-frequency signals. Differential offset can be used to remove galvanic potentials introduced in the input wiring or transducer-bridge bias voltage. To allow use with signal sources which have high driving impedance, some models allow the user to set the input to virtually infinite impedance.

As with any differential amplifier, the slightest mismatch in channel gain greatly reduces the amplifier's high CMRR. When the application requires use of a scope probe, only identical non-attenuating (1X) models should be used, as attenuating probes can not be matched well enough to preserve the CMRR.

High-performance differential amplifiers. With the advent of oscilloscopes with plug-in amplifiers, high-performance differential amplifiers became available. These amplifiers combined many features to allow their use in diverse applications. Calibrated slideback allowed the amplifiers to be used in single-ended mode, with the trace referenced thousands of divisions away from ground.

This makes it possible to precisely measure ripple valley in power supplies and power amplifier headroom. Sophisticated high-speed clamp circuits enable the amplifier to quickly recover from input overloads hundreds of times over-range. This provides the ability to directly measure settling time of amplifiers and DAC circuits.

These amplifiers feature bandwidth specifications of 100 MHz or more, with good CMRR as well. However, the CMRR is specified with both inputs tied directly together and driven from a low-impedance source. In an actual application, the CMRR at higher frequencies will be considerably degraded by differences in source impedance and channel gain.

Differential passive probes. To minimize this degradation, only specially matched differential passive probes should be used with these amplifiers. Be sure to calibrate the individual probe to the amplifier using the procedure provided by the probe manufacturer.

High-bandwidth active differential probes. These probes maintain high-frequency CMRR by buffering the signal right at the probe tip, thereby eliminating the degradation caused by passive probe cables. These probes have high bandwidth (100 MHz or more), high-sensitivity, and excellent high-frequency CMRR performance. They are commonly used to perform measurements in disk-drive read electronics, where the signals are inherently differential. Their use is becoming more common in probing high-speed digital circuits as they do not alter the ground gradient when searching for ground-bounce problems.

Voltage isolators. While voltage isolators are not really differential amplifiers, they provide a means of safely measuring floating voltages. Compared with differential amplifiers, isolators have advantages as well as trade-offs, and the selection of one over the other depends on the application. As the name implies, isolators have no direct electrical connection between the floating inputs and their ground-referenced output. The signal is coupled via optical or split-path optical/transformer means. Two physical configurations are available: integrated one-piece systems and split transmitter/receiver systems.

The models with separate transmitters and receivers are interconnected with fiber-optic cable. The transmitter, which is powered by rechargeable batteries, can be remotely located from the receiver. This is useful in situations where the signal originates in environments not hospitable to humans or oscilloscopes. They can also be used with very high common-mode voltages. The floating voltage specification is usually limited by the insulation voltage of the hand-held probe. If the probe connections can be made with the DUT powered off,

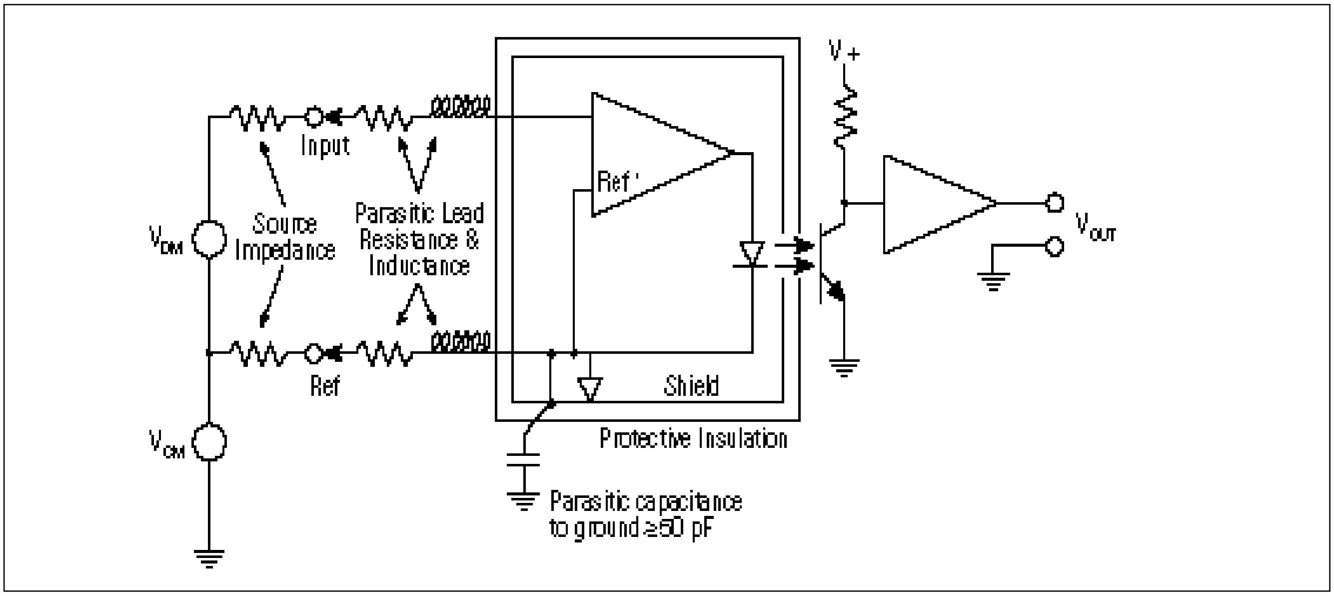

Figure 11. Unequal input capacitance caused by the isolated shield. This forms an AC voltage divider, resulting in the Vref' ≠ Vref at the probe clip.

the floating voltage is limited only by the physical separation between the transmitter and ground.

Because isolators have no resistive path to ground, they are a good choice for applications which are extremely sensitive to leakage currents. Circuits equipped with sensitive GFCI (Ground Fault Circuit Interrupters), such as medical electronics, may experience GFCI tripping when connected to a differential amplifier. The lack of ground terminated attenuators also gives isolators infinite CMRR with static (DC) common-mode voltages.

The disadvantage of isolators is the fact that they are not true differential amplifiers, meaning that the input is not balanced (see Figure 11). The capacitance to earth ground is considerably different in the measurement (+) input and the reference (–) input. This results in the same problems as already described when floating scopes. Source impedance in the reference lead forms an attenuator at high frequencies with the ground capacitance. These problems can be minimized by connecting the reference to the point in the circuit with the lowest driving impedance (invert the scope channel to regain correct polarity if necessary). If the isolator has separate transmitter and receiver units, physically isolate the transmitter from grounded surfaces as much as possible to minimize capacitive coupling to ground. Placing the transmitter on a cardboard box or wooden crate can make a marked improvement in performance!

Differential Measurement Applications

Power Electronics

High-voltage differential amplifiers provide an ideal means of measuring circuits which are line connected, such as switching power supply primaries, motor drives, electronic-lamp ballasts, and similar systems. They eliminate the need for the dangerous practice of “floating the scope”. The low input capacitance will not affect operation of inverters by loading down gate-drive circuits.

The characterization of power switching devices such as MOSFETs and IGBTs often includes measuring dynamic saturation characteristics. High-performance differential amplifiers with high-speed input clamps allow accurate measurement of turn-on saturation, nanoseconds after being overdriven (hundreds of times full scale) when the device was off. This allows the use of the high sensitivities necessary to accurately measure the saturation characteristics.

These amplifiers are also useful when measuring secondary circuits. By activating the calibrated slideback (also known as comparison voltage), the amplifier can be used in a single-ended mode to monitor ripple valley and linear-regulator headroom (see Figure 12). With the slideback set to the output voltage, the V_{CE} headroom can be directly measured, at high sensitivity, under a variety of dynamic load conditions.

System Power Distribution

Developing high-precision analog, mixed signal, and high-speed digital systems often involves troubleshoot-

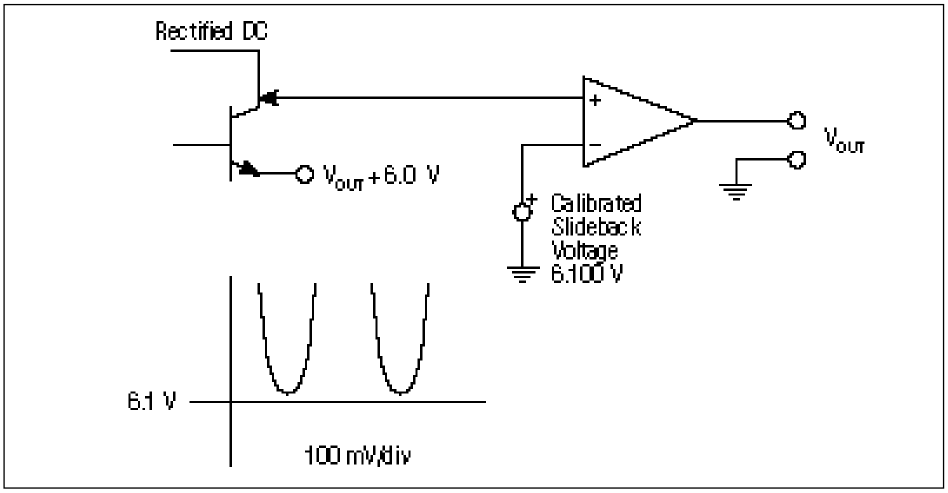

Figure 12. Using calibrated slideback to accurately measure power-supply ripple valley on the collector of the output regulator. Note that the scope is set to 100 mV/division with ground being 61 divisions off screen.

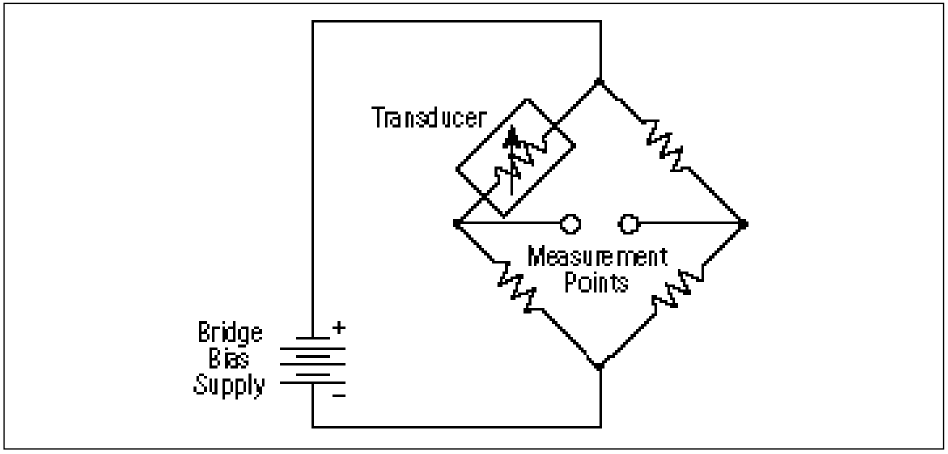

Figure 13. A transducer in balanced bridge configuration. A differential measurement is made between the taps of the two divider legs.

ing power-distribution problems. These can be a designer's worst nightmare. CAD systems offer little help as the minute parasitics which create these problems are difficult or impossible to model. A scope equipped with a differential amplifier is the best tool to track down and pin-point the trouble spots in the system.

Single-ended measurements often hide power-distribution problems as they provide an alternate ground path from which the signal is measured. Not only does this change the measurement, it often affects the circuit operation as well – either improving or degrading it.

Placing the inputs of a differential probe right on an IC's power supply lead gives a true picture of the device's power condition. Lead inductance in logic devices often isolates the IC from local bypassing capacitance. Even if the power supply looks clean, both the ground and power pins may be moving with respect to other grounds in the system. By moving the probe, it's possible to track down dynamic ground gradients between an individual device ground and other grounds in the system. The effects of ground bounce in digital systems can be easily measured. Probing between an IC's input and its ground pin gives a picture of the actual signal as seen by that device.

Balanced Signals

Some systems employ signals which are inherently differential in nature. When both sides of the signal share the same driving impedance they are said to be balanced. Balanced systems are common in professional audio equipment, telephony, and magnetic recording systems (analog and digital memory) to name a few. Differential signal distribution is becoming more common in high-speed digital systems as well. Ineffective attempts to measure these signals one side at a time and "adding" the results are error prone at best. Often, loading only one side of the signal with the probe diverts energy to the side not being measured. Measuring a balanced system differentially provides a true picture of the signal.

Transducers

Differential measurements are used universally in transducer systems. The small signal amplitudes and necessity to eliminate ground loops preclude the use of single-ended measurements. The word "transducer" brings to mind connotations of devices used for measuring mechanical phenomena such as acceleration, vibration, pressure, etc. The application of differential measurement techniques goes beyond these to include visual and medical imagers, microphones, chemical sensors… the list is endless.

Transducers which produce a change in resistance are often operated in a configuration known as a balanced bridge (see Figure 13). This configuration uses three known resistances and the transducer to produce a pair of voltage dividers. The pair is biased with a bridge supply and the voltage is measured differentially between the divider taps. The advantage of this configuration is the elimination of the effects of power supply fluctuations.

Often, a transducer produces a DC output voltage representing the steady state before excitation is placed in the system. To get high resolution, it's desirable to remove the DC component. AC coupling the amplifier input is not effective if very low-frequency components (<2 Hz) need to be measured. To accommodate this need, many high-gain differential amplifiers incorporate a differential offset feature. This effectively inserts a floating, adjustable power supply in series with one of the inputs, allowing the amplifier to remain DC coupled. The offset control has considerable range – as much as ±1 million divisions at the higher gain settings.

Biophysical Measurements

***CAUTION:** Do not connect any electrical instrument, including a differential amplifier, to a human subject unless it is specifically designed for use on humans. Suitable equipment will be certified to a specific regulatory standard as mandated by the individual country where it is used.*

Measuring the electrical signals resulting from neurological activity presents several challenges. The signals have minute amplitudes – often below a millivolt. The common-mode component can be hundreds or even thousands of times greater than the signal of interest. The source impedance is rather high. Usually, the differential signal is corrupted with high-amplitude noise. Fortunately, high-gain differential amplifiers are equipped to measure these signals.

CMRR specifications of 1,000,000:1 or more can effectively eliminate the common-mode component. To deal with the high input impedance, the amplifier can be configured to infinite input resistance mode. (Note that if the specimen is not shunted to ground by other equipment, a separate probe tied through a 100 kohm resistor to ground should be used to reduce the chance of common-mode range overload.) Skin contact is usually made with silver/silver chloride electrodes. These provide an ionic connection to the specimen. They also generate a galvanic cell (battery) with a half-cell voltage of 400 mV which adds a bias voltage to the measurement. The amplifier's differential offset can be used to remove the bias while preserving low-frequency response. Because most biophysical activity occurs at frequencies below 20 Hz, bandwidth-limiting filters can be used to reduce higher-frequency differential noise without altering the signal of interest.

Maintaining Measurement Integrity

Sources of Measurement Errors

Just like other measurements, differential measurements are subject to conditions which generate errors. These errors may or may not be obvious in the results, and may be misread as the desired measurement. Some of the more common sources of error are covered below. To understand what causes these errors and how to avoid them, we first need a basic understanding of what's inside a differential oscilloscope or probe.

The heart of the system is the differential amplifier stage (see Figure 14). The schematic symbol is the same as an op amp. Like the operational amplifier, a differential amplifier rejects the input common-mode signal and only amplifies the voltage difference between the two inputs. Unlike the op amp, the differential amplifier has a known, finite gain. In some configurations, the gain is user-selectable. The output is singled-ended and referenced to ground. The inputs are often FETs to give very high impedance. The input signal may pass through a high-impedance attenuator to reduce larger signals to a range the ampli-

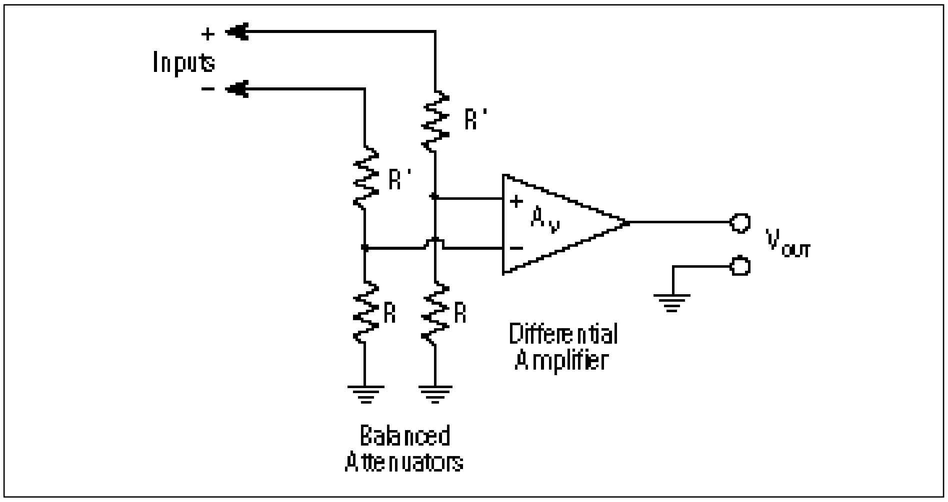

Figure 14. Simplified schematic of a differential amplifier with attenuator.

fier can handle. The demands on the attenuator are much greater than those in a single-ended amplifier. Both sides must have identical DC and AC attenuation. The amount of mismatch has a first-order effect on the CMRR. For example, to maintain a 100,000:1 CMRR specification, the attenuators must match to better than one part in 100,000 (0.001%); this leaves no margin for error in the differential amplifier! Of course, this match needs to be maintained all the way from the signal source.

Input Connections

Interconnecting the differential amplifier or probe to the signal source is generally the greatest source of error. To maintain the input match, both paths should be as identical as possible. Any cabling should be of the same length for both inputs. If probes are used, they should be the same model and length. When measuring low-frequency signals with large common-mode voltages, avoid the use of attenuating probes. At high gains, they simply cannot be used as it is impossible to precisely balance their attenuation. When attenuation is needed for high-voltage or high-frequency applications, special passive probes designed specifically for differential applications should be used. These probes have provisions for precisely trimming DC attenuation and AC compensation. To get the best performance, a set of probes should be dedicated to each specific amplifier and calibrated with that amplifier using the procedure included with the probes.

It's common practice to twist the + and – input cables together in a pair. This reduces line frequency and other noise pick up. Input cabling that is spread apart (see Figure 15) acts as a transformer winding. Any AC magnetic field passing through the loop induces a voltage which appears to the amplifier input as differential and will be faithfully summed into the output! With the input leads twisted together (Figure 16), any induced voltage tends to be in the V_{CM} path, which is rejected by the differential amplifier.

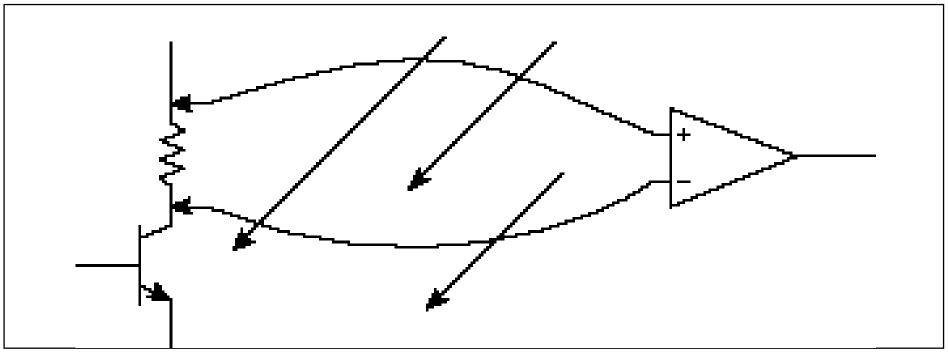

Figure 15. Time varying magnetic fields passing through the open leads induce a voltage as in a transformer winding. This voltage appears as a differential component to the amplifier and is summed into the true V_{DM} sig-

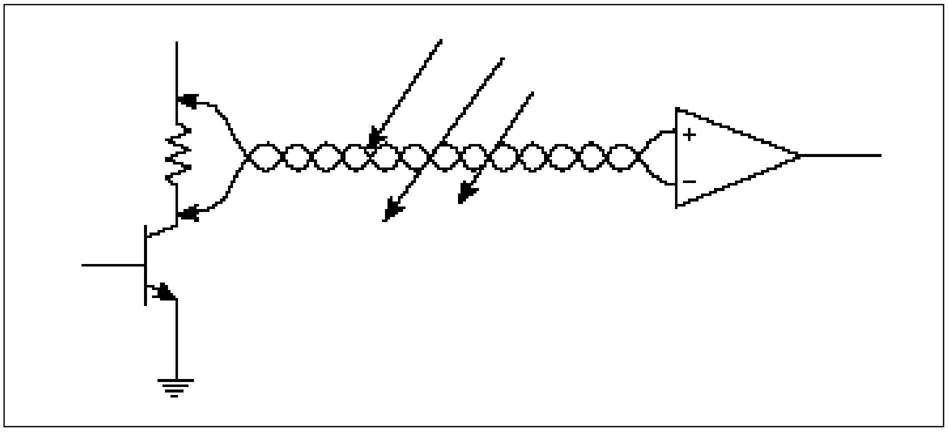

Figure 16. With the input leads twisted together, the loop area is very small, hence less field passes through it. Any induced voltage tends to be in the V_{CM} path which is rejected by the differential amplifier.

High-frequency measurements subject to excessive common-mode can be improved by winding both input leads through a ferrite torroid. This attenuates high-frequency signals which are common to both inputs. Because differential signals pass through the core in both directions, they are unaffected.

Grounding

The input connectors of most differential amplifiers are BNC connectors with the shell grounded. When using probes or coaxial input connections, there's always a question of what to do with the grounds. Because the measurement application varies, there are no hard and fast rules.

When measuring low-level signals at low frequencies, it's generally best to connect the grounds only at the amplifier end and leave both unconnected at the input end. This provides a return path for any currents induced into the shield, but doesn't create a ground loop which may upset the measurement or the device-under-test.

At higher frequencies, the probe input capacitance, along with the lead inductance, forms a series resonant "tank" circuit which may ring. In single-ended measurements, this effect can be minimized by using the shortest possible ground lead. This lowers the inductance, effectively moving the resonating frequency higher, hopefully beyond the bandwidth of the amplifier. Differential measurements are made between two probe tips, and the concept of ground does not enter into the measurement. However, if the ring is generated from a fast rise of the common-mode component, using a short ground lead reduces the inductance in the resonant circuit, thus reducing the ring component. In some situations, a ring resulting from fast differential signals may also be reduced by attaching the ground lead. This is the case if the common-mode source has very low impedance to ground at high frequencies, i.e. is bypassed with capacitors. If this is not the case, attaching the ground lead may make the situation worse! If this happens, try grounding the probes together at the input ends. This lowers the effective inductance through the shield.

Of course, connecting the probe ground to the circuit may generate a ground loop. This usually doesn't cause a problem when measuring higher-frequency signals. The best advice when measuring high frequencies is to try making the measurement with and without the ground lead; then use the setup which gives the best results. When connecting the probe ground lead to the circuit, remember to connect it to ground! It's easy to forget where the ground connection is when using differential amplifiers since they can probe anywhere in the circuit without the risk of damage.

Input Impedance Effects on CMRR

Any source impedance acts to form a voltage divider with the input resistance (DC) and capacitance (AC) of the input. With single-ended measurements, the impedance effect can usually be ignored as the error seldom reaches 1%. But with differential measurements, this small error contributes to the input-gain mismatch, which reduces common-mode rejection (see Figure 17).

The differential amplifier CMRR specification is usually measured with both inputs driven together via a BNC tee connector. This effectively gives zero impedance difference looking into the inputs. Ideally, the real-life signal source would also have identical driving impedance. However, they seldom do. As such, the real CMRR performance will be significantly less than the amplifier specification.

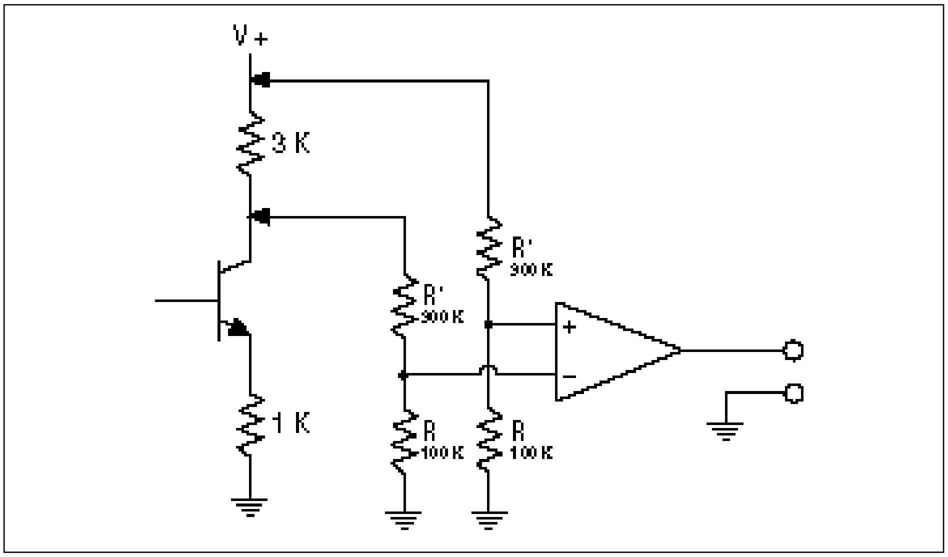

Figure 17. Effect of unequal source impedances. The + input attenuator is essentially driven from 0ohms, however the –input attenuator is driven from something less than 3 kohms. This adds to the 900kohms, increasing its attenuation and lowering the CMRR.

If the amplifier's input impedance, attenuation ratio, and source impedances are all known, it's possible to determine the actual CMRR by calculating the actual divider ratios in each input arm. However, it's easier just to make a subjective judgment of the measurement performance.

Many high-gain amplifiers have provisions for configuring them as instrumentation amplifiers. An instrumentation amplifier has no input attenuator. The input resistance is essentially infinite (>10^{12} ohms). This mode greatly enhances low-frequency CMR when the source impedance is rather high, such as physiological experiments. While instrumentation amplifiers have infinite input resistance, they still have input capacitance. The CMR improvement with high source impedances will quickly degrade as the common-mode frequency increases. Because instrumentation amplifiers don't have input attenuators, they have limited common-mode and differential-mode dynamic ranges.

Common-Mode Range

Any amplifier can be overdriven, causing the output to "clip". The same effect occurs in a differential amplifier when the input differential-mode signal is large enough to force the amplifier beyond its output dynamic range. Differential amplifiers are also subject to another overload condition – exceeding the input common-mode range. This condition occurs when the voltage that the desired signal is riding on (V_{CM}) exceeds the amplifiers input common-mode range.

Because the common-mode signal is rejected by the

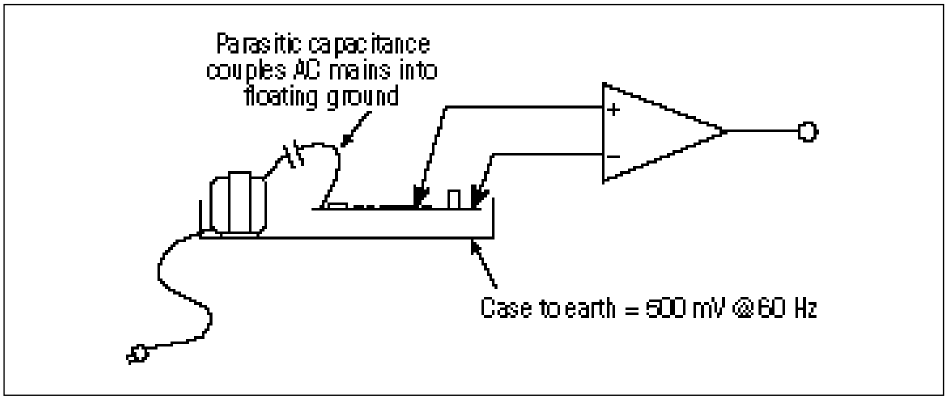

Figure 18. V_{CM} in a consumer audio electronic component. These devices usually have a two-wire power cord with their chassis and circuitry floating.

amplifier, the dynamic range is limited by the input stage rather than the output swing. Amplifiers with input attenuators have a greater common-mode range than differential-mode range. Because the common-mode component is (hopefully) not seen in the measurement, common-mode range overload may not be obvious to the user. This is especially true when the common-mode component is DC. Some amplifier topologies will still produce an approximate rendition of the differential signal with a significant gain error when the V_{CM} range is exceeded. Because the waveform appears correct, many users have been fooled by this erroneous measurement.

Some amplifiers have overload indicators to warn the user of a common-mode overload condition. It’s a good practice to verify that the common mode is within specified range before making critical measurements. This is easily done by moving one of the input connections to ground and measuring the common-mode component with the amplifier itself. The procedure is then repeated with the other input.

Measuring Totally Floating Signals

Signal sources which are totally floating, having no connection whatsoever to ground, pose a special problem when being measured with a differential amplifier. Common examples include battery-operated electronic equipment, consumer audio components, and experimental physiological specimens. Because there’s no shunting impedance to ground, any AC fields in the area will be capacitively coupled into the device being measured (see Figure 18). Line-frequency fields, radiated from fluorescent lighting and building wiring, are common in this measurement environment. When coupled into the DUT, the line-frequency field produces a common-mode voltage. With sufficient coupling and high input impedance of the amplifier, it’s possible to inadvertently exceed the common-mode range of the amplifier. This is especially true with amplifiers configured as instrumentation amplifiers, since the load impedance at line frequencies approaches infinity.

The overload situation can be avoided by providing a shunting impedance to ground, reducing the capacitive coupling, or reducing the field strength. Adding a shunt path to ground is the easiest approach. It need not be a direct short, often a 10 kohm resistor is sufficient. If adding the shunt impedance upsets the device being measured or the measurement, try reducing the capacitive coupling by enclosing the DUT with a metal screen which is tied to ground. This effectively adds a Faraday shield which provides a shunt path to ground for AC fields. A final approach is to try to minimize the field strengths. Substituting incandescent lighting for fluorescent, and maximizing the distance between line-connected wiring and the DUT are good starting points.

Bandwidth

Differential amplifiers, like single-ended scope amplifiers, often include a bandwidth limiting control. High-gain amplifiers may offer a choice of low-pass frequencies. Bandwidth limiting reduces high-frequency noise components with minimal degradation on lower frequencies. The bandwidth limiting filters are located after the input signal has been transformed to single ended. Therefore, their use will not increase input common-mode range at higher frequencies.

Glossary

ADC – Analog-to-Digital Converter. The “heart” of a digital storage oscilloscope where the analog input signal is converted into the digital domain. Several characteristics of the ADC such as sample rate, resolution, accuracy, and linearity directly relate to the oscilloscope’s performance.

Balanced – A signal transmitted through a pair of wires, each having the same source impedance. Ground does not serve as a return path for the signal.

Bandwidth Limit – A filter which may be selected by the user to attenuate noise outside of the bandwidth of interest. Unless otherwise specified, the filter is assumed to be a low-pass topology with a single-pole (–6 dB/octave) roll off.

Clamp – A circuit which limits the output voltage swing of an amplifier to keep it within the linear operating range. Usually this is done to reduce the overload recovery time.

Clip – A distorted waveform produced when an amplifier does not have sufficient output voltage range to reproduce the input signal. As the name implies, the output appears as if it was “clipped” off.

Common Mode – The component of an input signal which is common (identical in amplitude and phase) to both inputs of a differential amplifier. An ideal differential amplifier rejects all of the common-mode signal.

Common-Mode Range – The maximum voltage (from ground) of common-mode signal which a differential amplifier can reject. Usually, the common-mode range is greater than the differential-mode range. Depending on amplifier topology, the common-mode range may vary as a function of gain.

Common-Mode Rejection – The elimination of the input common-mode component by a differential amplifier.

Common-Mode Rejection Ratio – The performance measure of a differential amplifier’s ability to reject common-mode signals. CMRR is expressed as:

$$\text{CMRR} = \frac{\text{Differential-Mode Gain}}{\text{Common-Mode Gain}}$$

Because common-mode rejection generally decreases with increasing frequency, CMRR is usually specified at a particular frequency.

Differential Amplifier – A three-terminal gain circuit which processes the signal component which is different between two inputs while ignoring the component which is common to the two inputs.

Differential Mode – The signal which is different between the two inputs of a differential amplifier. The differential-mode signal (V_{DM}) can be expressed as:

$$V_{DM} = (V_{+Input}) - (V_{-Input})$$

Differential-Mode Range – The maximum amplitude of differential input signal that a differential amplifier can accept without overloading the output. Exceeding the differential-mode range results in the amplifier either clipping or clamping the signal. Generally the differential-mode range decreases as the amplifier gain increases.

Differential Offset – A circuit incorporated in high-gain differential amplifiers to null out a DC bias present in the differential input signal. Electrically equivalent to an adjustable battery inserted in series with one of the input leads.

Differential Probe – A probe designed specifically for differential applications. Active differential probes contain a differential amplifier at the probe tips. Passive differential probes are used with differential amplifiers and can be calibrated for precisely matching the DC and AC attenuation in both signal paths.

Floating – A signal which is not referenced to ground. A floating signal cannot be directly measured with a single-ended instrument input.

Floating the Scope – The practice of defeating the protective grounding system of an oscilloscope, allowing it to perform floating measurements. Because the entire scope chassis is common to the probe “ground” clip, this dangerous practice may expose the user to electrocution hazards.

Ground Loop – A circuit with multiple low-impedance paths connected to the same ground potential. A ground loop acts as a shorted transformer turn which induces circulating ground currents. These currents produce slight changes in the ground potentials within the circuit.

Isolator, Isolated Probe – A device which allows two-point floating voltage measurements to be made with single-ended ground referenced instrumentation. Isolation is accomplished by converting the input signal to optical and/or magnetic (via transformer) form.

Maximum Common-Mode Slew Rate – The upper limit of rate of change (dv/dt) of the common-mode component on the inputs of a differential amplifier or isolator. Signals with rise times that exceed the maximum common-mode slew rate specification may produce extreme distortion in the output signal. Sometimes this specification refers to a maximum non-destructive limit of the instrument.

Quasi Differential – A method of creating a differential amplifier by adding two conventional oscilloscope input channels with one set to invert mode. To produce meaningful results, both channels must be set to the same volts/division position. Compared with true differential amplifiers, quasi-differential mode has very limited common-mode range and lower CMRR, particularly at high frequencies.

Slideback (Comparison Voltage) – A configuration provided by some differential amplifiers which connects a precision calibrated voltage source to one of the amplifier inputs. This provides a single-ended amplifier with an extremely large range of calibrated offset. Unlike differential offset, slideback mode can only perform single-ended (ground referenced) measurements.

Single-Ended – A measurement of a voltage potential referenced to ground. A conventional oscilloscope input can only make single-ended measurements.

Related Tektronix Publications:

Biophysical Measurements, 3GW-10379-0

Floating Measurement Solutions Selection Guide, 51W-10457-0

Interpreting Mechanical Measurements, 3GW-10381-0

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