

WHY DIFFERENTIAL?

Voltage, The Difference

Whether aware of it or not, a person using an oscilloscope to make any voltage measurement is actually making a differential voltage measurement. By definition, voltage is the measure of the difference of electric potential between two points. The concept of voltage being the difference of potential between two points is easily understood by a person using a voltmeter. One cannot measure a voltage using only one voltmeter lead. The other lead needs to be connected in order to provide a reference point. When using a scope, we sometimes forget that the signal displayed on the scope is not simply the "signal at that point". It is actually the voltage at that point as it differs from some other point.

"Ground" Referenced Measurements"

This other point is usually the circuit's ground which is assumed to be zero volts. For an example, let's assume we wish to use a scope to measure the voltage (referenced to ground) at the emitter of the transistor in Figure 1. This may appear to be a simple circuit, but by referring to Figure 2, we can see how complex the actual signal measurement environment can become when we include the scope probe and the ground connections between the scope and the circuit. v_{A-B} represents the transistor emitter voltage waveform that we wish to display on the scope. $Z_{Circuit}$ is the resistance of the emitter connected resistor R_1 in parallel with the emitter impedance of the transistor. We will assign a point as an IDEAL EARTH GROUND in the circuit so we have a solid point of reference. $Z_{SCOPE GND}$ is the impedance of the scope's power cord ground lead. Z_{COMMON} is the impedance between the circuit common and the ideal earth ground point. i_{COMMON} represents currents (ground loop) flowing through Z_{COMMON} from other sources such as other

instruments connected to the circuit under test and results in V_{COMMON} .

What the scope actually displays on screen is a voltage waveform that appears as the difference between the voltage at the center conductor of its input connector and the connector's ground or v_{C-G} . In most cases, the displayed waveform, v_{C-G} , is fairly representative of the signal at the probe tip, v_{A-B} . By examining the various elements of the circuit in Figure 2, we can understand how and why v_{C-G} may differ from v_{A-B} .

To begin with, if the values of i_{COMMON} , Z_{COMMON} and $Z_{SCOPE GND}$ were zero we would not need to use the probe's ground lead since there could be no voltage difference between the circuit common and the scope's ground. They are not zero so we must try to shunt their effects by adding a ground connection at the probe. While the probe's ground lead

shunts the effects of i_{COMMON} , Z_{COMMON} , and $Z_{SCOPE GND}$, it does have some resistance and inductance of its own. This impedance, which we will call $Z_{GND LEAD}$, depends on the ground lead's length. Some current must flow out of the circuit under test and into the scope's input in order to develop a voltage waveform within the scope for it to measure. The signal current flowing through the impedance of the probe ground lead, $Z_{GND LEAD}$, causes a voltage drop that makes v_{C-G} differ from v_{A-B} . To illustrate this effect, Figure 3 shows a squarewave measured with a scope and a compensated standard scope probe. The first waveform measurement is taken using a probe tip adaptor that minimizes the length of the ground connection. The second and third waveforms are taken with the same equipment but using 36cm (14") and 58cm (23") ground leads on the probe. In many measurements, the signal corruption caused by the ground lead impedance may be acceptable, but it is

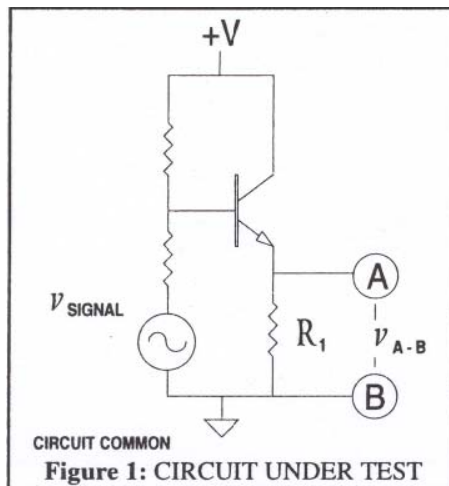


Figure 1: CIRCUIT UNDER TEST

important to know that it is present. Again referring to Figure 2, as i_{COMMON} flows through Z_{COMMON} , it develops a voltage we have chosen to call V_{COMMON} . If the scope probe is not connected, V_{COMMON} will appear

through $Z_{\text{GND LEAD}}$ since $Z_{\text{SCOPE GND}}$ is in parallel with a complex impedance formed by the scope's power transformer inter-winding capacitance in series with the impedance of the power system, $Z_{\text{POWER TO GND}}$.

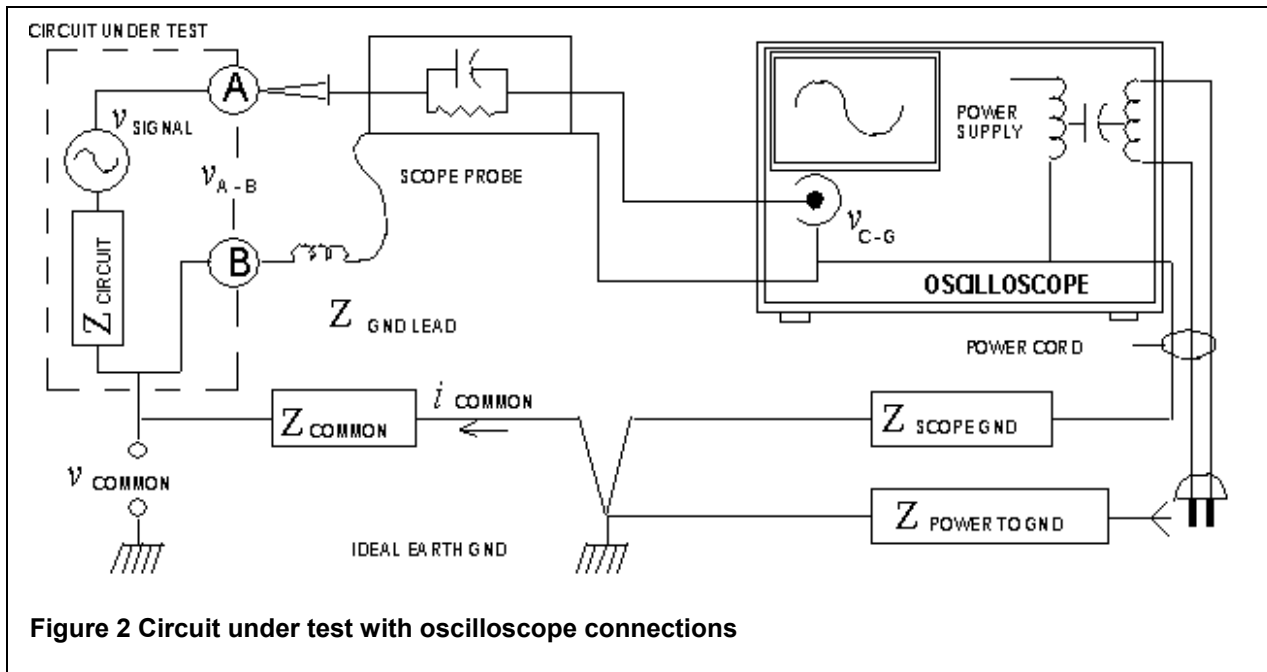


Figure 2 Circuit under test with oscilloscope connections

as a voltage that is "common" to both points A and B. The voltage waveform at either of these points with respect to the IDEAL EARTH GROUND will include V_{COMMON} . Point B will equal V_{COMMON} and point A will be $V_{A-B} + V_{\text{COMMON}}$. By applying the scope probe ground lead to point B we can reduce, but not eliminate, V_{COMMON} from the measurement. The reason we cannot eliminate V_{COMMON} is because of the finite value of $Z_{\text{GND LEAD}}$.

$Z_{\text{GND LEAD}}$, Z_{COMMON} and $Z_{\text{SCOPE GND}}$ form a loop through which i_{COMMON} flows. The voltages caused by i_{COMMON} flowing in this loop will further corrupt the waveform V_{C-G} .

"Non-Ground" Referenced Measurements

The effect of i_{COMMON} can usually be reduced by opening the safety ground on the scope. Depending on the magnitude of V_{COMMON} this technique can be very hazardous and under NO circumstances is it recommended. Opening the safety ground lead of the scope does not fully eliminate the flow of i_{COMMON}

The model of V_{COMMON} we have used can also explain measurement constraints that we usually think of when we are making "floating" measurements. Let's assume that V_{COMMON} is the output of a low impedance voltage source, of i_{COMMON} to flow. This is the case when trying to measure voltages in a "floating" power supply control circuit where V_{COMMON} is the power line voltage. Even if the practice of floating the scope by opening the safety ground lead weren't hazardous, the measurement is still corrupted by the effects of the flow of i_{COMMON} through the scope's power transformer inter-winding capacitance and the power line impedance. Also, the flow of signal current through $Z_{\text{GND LEAD}}$ will contribute the same signal corruption as it did in our earlier ground referenced measurement example. Another, somewhat unrelated point: the practice of floating the chassis of a scope to line level voltages may place more voltage between the scope's power transformer primary and secondary windings than it was designed to handle and could possibly damage the scope.

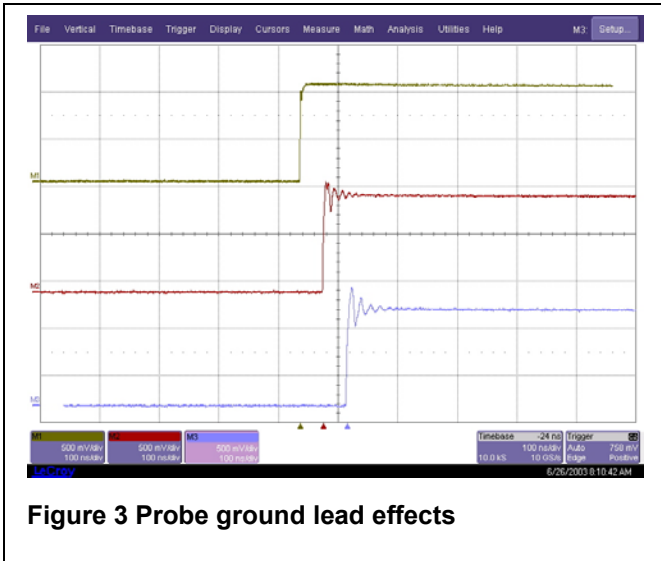


Figure 3 Probe ground lead effects

Differential Voltage Measurements

One can greatly reduce these corruptive measurement effects by using a scope or a pre-amplifier that has differential measurement capability. Figure 4 shows our equivalent circuit with the same ground referenced scope and a differential pre-

points to find the voltage difference between them. As the differential amplifier amplifies the difference between the two points, it rejects any voltage that is common to both. Since V_{COMMON} appears at both points A and B in our circuit, the differential amplifier rejects it and presents the scope with the difference between points A and B, which is V_{A-B} .

$$(V_{A-B} + V_{COMMON}) - (V_{COMMON}) = V_{A-B}$$

The loop current effects of V_{COMMON} are also greatly reduced because the high impedance of the probes prevents V_{COMMON} from generating an appreciable amount of current into the scope ground. Since the probe ground clip is not connected to Point B, the effects of $Z_{GND LEAD}$ are eliminated. For all of these reasons, V_{C-G} is much more representative of V_{A-B} than was possible when the scope probe ground lead was used to provide the minus reference.

Since a differential amplifier equipped with properly designed probes can reject common voltages of relatively high magnitude, there is no need to float the

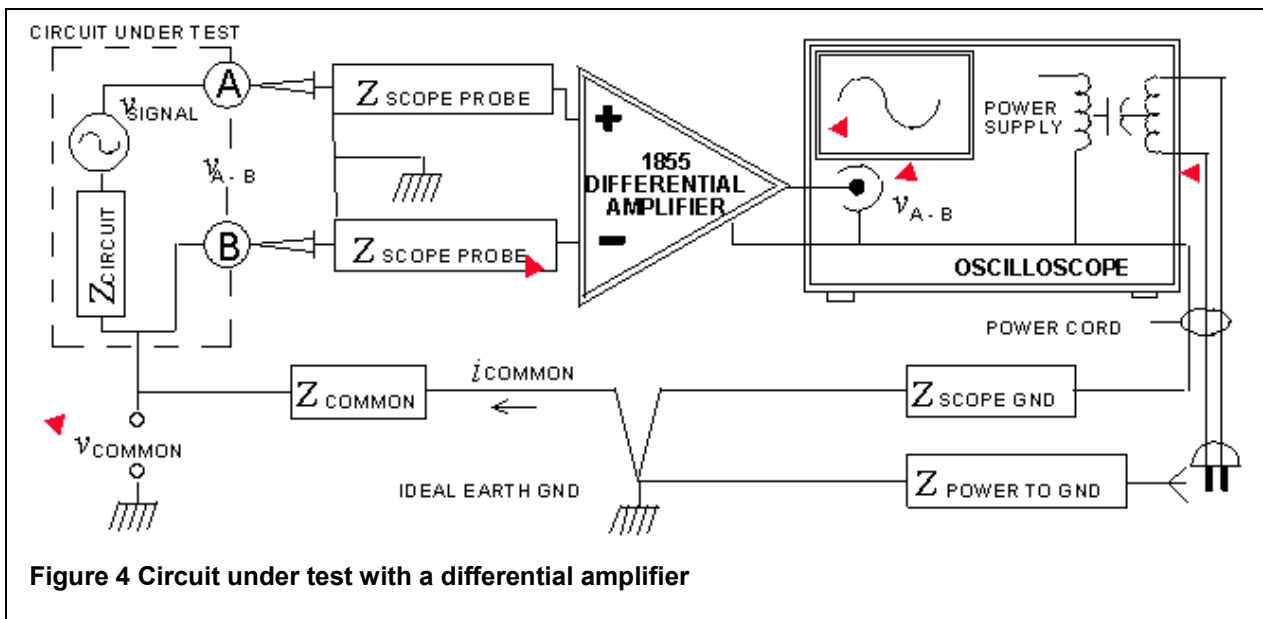


Figure 4 Circuit under test with a differential amplifier

amplifier.

An ideal differential amplifier will only amplify the difference it sees at its + and - inputs. In this respect, it is very similar to the voltmeter where we probe two

scope to an unsafe level in order to make good quality measurements.

Common Mode Rejection Ratio or CMRR

We have been discussing the benefits of using an ideal differential amplifier to make voltage waveform measurements. Unfortunately, the ideal differential amplifier does not exist so we need to understand some of its characteristics and limitations. By again referring to figure 4, we can see that the differential amplifier deals with two voltage waveforms; one we want to see and one we don't. We can call these differential mode (the difference between point A and point B) and common mode (that which is common to both point A and B) waveforms. The waveform we want to see is the differential mode signal, v_{A-B} . All of the characteristics of a single-ended amplifier such as gain and bandwidth apply to the differential mode of the differential amplifier. So if you need a scope with a bandwidth of 50MHz and enough gain to adequately measure a ground referenced signal such as v_{A-B} , then you would need a differential amplifier with the same capability in its differential mode. As we have seen earlier, dealing with the common mode signal, v_{COMMON} , with a single-ended scope input is either done by applying a low impedance shunt ($Z_{GNDLEAD}$) or by placing a higher impedance in series with the common mode signal (floating the scope). The differential amplifier deals with the common mode signal by algebraically subtracting it from the measured differential signal. The measure of how well the differential amplifier can remove or reject the common mode signal is specified similarly to the differential bandwidth and gain, except now we want attenuation instead of gain. Common mode bandwidth is measured by simultaneously applying exactly the same signal (frequency, amplitude and phase) to both inputs of the differential amplifier. With these input signals, an ideal differential amplifier would have no signal at its output. Since real world limitations apply to real amplifiers, there will be an output that is a function of amplitude and frequency of the input signal. If we put a 1 volt, 10 MHz signal into both inputs (same phase) and we measure a 1 mV signal at the output, the differential amplifier can reject 1MHz signals by a factor of 1,000. How well the differential amplifier can reject a common mode signal is usually stated as a ratio of the output signal's magnitude divided by the differential input signal's magnitude, or Common Mode Rejection Ratio (CMRR). In this case the CMRR is 1,000 to 1 at 10MHz. It is also

commonly given in dB's of attenuation, but it is always the ratio of the output magnitude over input magnitude. It should be specified as a function of attenuation ratio versus frequency since it is a function of frequency. CMRR is highest at DC and declines as the frequency increases.

Common Mode Range

The next most important characteristic of the differential amplifier that we need to know about is its common mode range. This lets us know how large the amplitude of v_{COMMON} can become before the amplifier can no longer tolerate it. This value is usually at least several times larger than the differential input range and is specified as a DC value, but it applies to the peak magnitude of an AC signal as well. How much common mode range a differential amplifier should have depends on the measurement requirements. If the common mode voltage is a small signal caused by ground loop currents then a volt or two of range will be sufficient. However, if the differential signal we are trying to measure is riding on top of a large common mode voltage, the range will have to be large. As an example, let's assume v_{A-B} is the voltage waveform across a current monitoring resistor in the primary of a switching power supply. In this example, v_{COMMON} is 400 volts (DC+peak AC) and the v_{A-B} waveform is a voltage ramp with a 1 volt peak. By using probes and attenuators that have a combined divide by 100 attenuation factor, v_{COMMON} will be attenuated to 4 volts and v_{A-B} will be attenuated to a 10mV signal. The differential amplifier must have at least 4 volts of common mode range.

If the amplifier's CMRR is 10,000 to 1, then the differential amplifier will attenuate the 4 volt v_{COMMON} down to a 400 μ V level at its output. In this case, when the CMRR of the amplifier is combined with the attenuation of the probes and the amplifier's internal attenuator, the common mode signal is attenuated by a factor of 1,000,000 to 1 while the differential signal is attenuated by a factor of 100. This output can be easily and safely displayed on a standard ground referenced scope.

Obtaining Good CMRR

Good common mode rejection performance is obtained by carefully matching all attributes of the paths for the + and - signals into and through the differential amplifier. This matching is as important for the probes as it is for the amplifier.

Some scopes provide methods of algebraically subtracting one input from another (commonly referred to as A-B). In analog scopes, this is accomplished by inverting one channel and adding it to another in the scope's input section. Digital scopes (DSO's) provide math functions that allow one acquired waveform to be subtracted from another. CMRR is not normally specified for this type of operation, but a figure for DC can be derived by taking into account the accuracy specifications of each channel. If the DC gain accuracy of each channel is $\pm 1\%$ then the CMRR could be as low as 50 to 1 and is seldom better than 100 to 1. When AC signals are taken into account, the CMRR deteriorates even further. In our earlier example of the 1 volt signal riding on a 400 volt common mode signal, the output would be 10mV of differential signal and 40mV of common mode signal. It is also unlikely that the inputs could tolerate the 4 volt offset level.

To obtain optimum CMRR, the probes used with the differential amplifier should be designed to maximize CMRR. The user needs to make sure the probes are optimally compensated.