



Fundamentals of Floating Measurements and Isolated Input Oscilloscopes

Our thanks to Tektronix for allowing us to reprint the following article.

This guide will provide you with a fundamental glossary of power measurement terms, explain the different options available for making floating measurements, and highlight the advantages and trade-offs of each option.

The most demanding floating measurement requirements are found in power control circuits, such as motor controllers, uninterruptible power supplies, and industrial equipment. In such application areas, voltages and currents may be large enough to present a hazard to users and/or test equipment. When measuring floating high voltage signals there are many options to consider. Each option has its advantages and trade-offs.

Differential vs. Floating Measurements

All voltage measurements are differential measurements. A differential measurement is defined as the voltage difference between two points. Voltage measurements fall into two sub-categories:

1. ground-referenced measurements
2. non-ground-referenced measurements (also known as floating measurements)

Traditional Oscilloscopes

Most traditional oscilloscopes have the "signal reference" terminal connected to the protective grounding system, commonly referred to as "earth" ground or just "ground". This is done so that all signals applied to, or supplied from, the oscilloscope have a common connection point.

This common connection point is usually the oscilloscope chassis and is held at (or near) zero volts by virtue of the third-wire ground in the power cord for AC-powered equipment. This means each input channel reference is tied to a single ground reference.

A traditional passive probe should not be used to directly make floating measurements on a ground referenced oscilloscope. Depending on the amount of current flowing through the reference lead, it can begin to get hot or, if the current is high enough, it will melt open similar to the way a fuse operates.

Floating Measurement Techniques

The different options available for making high voltage floating measurements are:

- Isolated-input Oscilloscopes

- Differential Probes
- Voltage Isolators
- "A minus B" Measurement Techniques
- "Floating" the Oscilloscope Techniques

Glossary

Common-Mode Signal

The component of an input signal which is common (identical in amplitude and phase) on both inputs.

Common-Mode Range

The maximum voltage (from ground) of a common-mode signal which a differential amplifier can reject.

Common-Mode Rejection Ratio

The performance measure of a differential amplifier's ability to reject common-mode signals. Because common-mode rejection generally decreases with increasing frequency, CMRR is usually specified at a particular frequency.

Differential Mode

The signal which is different between the two inputs of a differential amplifier. The differential-mode signal (VDM) can be expressed as:

$$VDM = (V+input)-(V-input)$$

Differential-Mode Signal

The signal which is different between two inputs.

Differential Measurement

The voltage difference between two points.

Differential Probe

A probe designed specifically for differential applications. Active differential probes contain a differential amplifier at the probe tip. Passive differential probes are used with differential amplifiers and can be calibrated for precisely matching the DC and AC attenuation in both signal paths (including the reference lead).

Floating Measurement

A differential measurement where neither point is referenced to ground (earth potential).

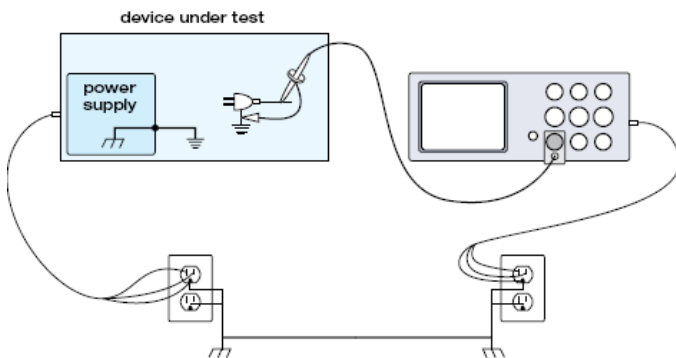
Glossary (continued)

Ground Loops

A ground loop results when two or more separate ground paths are tied 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 acts as 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 main 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 AC 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. 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.



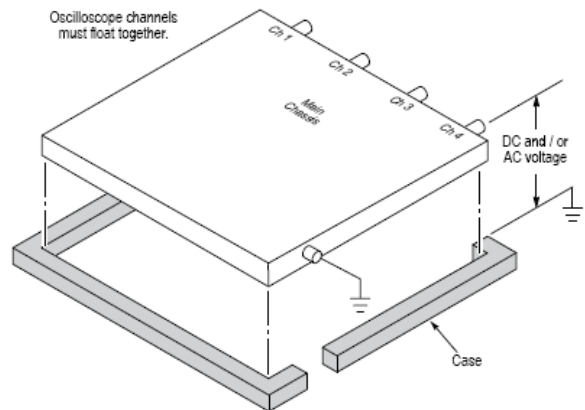
Connecting the ground lead of an oscilloscope probe to the ground in the circuit-under-test results in a ground loop if the circuit is "grounded" to earth ground.

"A Single"

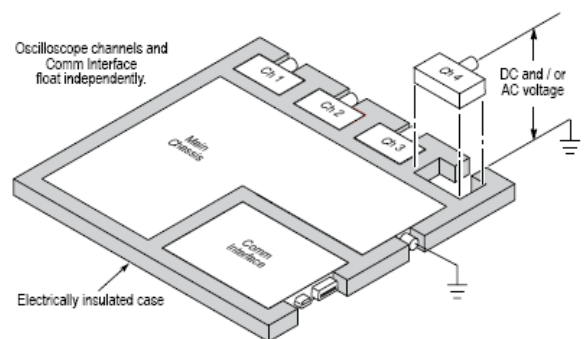
Battery-operated oscilloscopes with grounded input channels when operated from AC line power and using a standard 3 wire power cord, exhibit the same limitations as traditional oscilloscopes. However, when operating on battery power, these oscilloscopes allow you to make a single, safe floating measurement up to 30VRMS at a time. Remember that all input commons are tied together.

Shared Reference vs. Isolated Channel Architecture

Most bench-top oscilloscopes share the architecture shown below. With this architecture, all input signals must have the same voltage reference when taking multi-channel measurements and the shared default reference is "earth" ground. Without differential preamplifiers or external signal isolators, these bench-top oscilloscopes are not suitable for taking floating measurements.



Compared to the conventional bench oscilloscope architecture, voltage references in the isolated channel architecture are not connected together inside the instrument. Therefore, each reference of the used inputs must be connected to a reference voltage. Independently floating isolated inputs are still coupled by parasitic capacitance. This can occur between the input references and the environment, and between the input references mutually. For this reason, it is advisable to connect references to a system ground or another stable voltage. If the reference of an input is connected to a high speed and/or high voltage signal, you should be aware of parasitic capacitance.



Isolated Input Oscilloscopes Measurements

Oscilloscopes with IsolatedChannel™ input architecture, such as the TPS2000B or THS3000 Series, provide true and complete channel-to-channel and channel-to-power line isolation. Each channel is individually isolated from one another and other non-isolated components. When making floating measurements with an

IsolatedChannel™ oscilloscope, one must use specifically designed passive probes, such as the TPP0201 to float up to 30 V_{RMS}, the THP0301 to float up to 300 V_{RMS} or the P5122/P5150 probes to float up to 600 V_{RMS}. Unlike the passive probes used with most conventional oscilloscopes, these types of probes are insulated at the BNC connection for shock protection and the reference lead is designed to withstand the rated float voltage. (For more information please refer to the discussion entitled “Mind your CATs and Volts” later in this application note).

Differential Probe Measurements

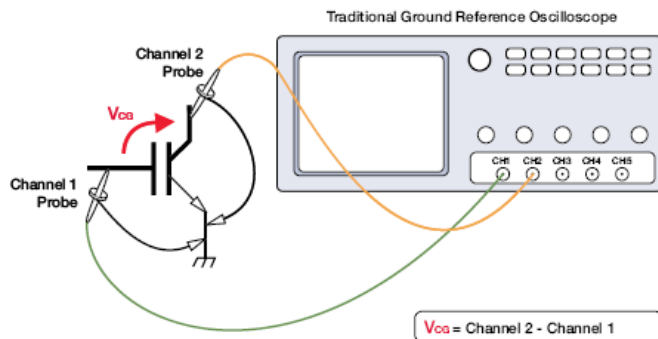
Differential probe systems enable floating measurements to be made with the Tektronix TDS/DPO/MSO and most other grounded oscilloscopes. Some differential probes such as the P6246, P6247, P6248, and P6330 are optimized for fast, lower amplitude signals. Others such as the P5200A, P5205A, and P5210A handle slower signals with higher voltage amplitudes. The ADA400A differential preamplifier provides the capability to display low frequency, very low amplitude differential signals even in high noise environments.

Voltage Isolator Measurements

As the name implies, isolators do not have direct electrical connection between the floating inputs and their ground-referenced outputs. The signal is coupled via optical or split-path optical/transformer means.

“A minus B” Measurements

(Also known as the Pseudo-Differential Measurements) The “A minus B” measurement technique allows the use of a conventional oscilloscope and its passive voltage probes to indirectly make floating measurements. One channel measures the “positive” test point and another channel measures the “negative” test point. Subtracting the second from first removes the voltage common to both test points in order to view the floating voltage that could not be measured directly. Oscilloscope channels must be set to the same volts/division; the probes should be matched to maximize common mode rejection ratio.

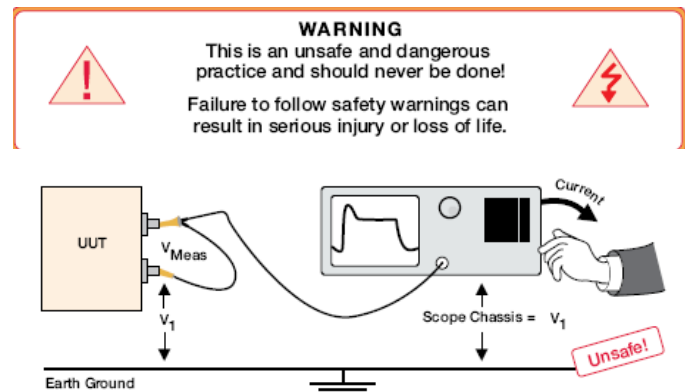


Example of two probes measuring ground reference voltages.

“Floating” a Conventional Grounded Oscilloscope

A common but risky practice is to float the oscilloscope through the use of an isolation transformer that does not carry the ground through to the secondary or by disconnecting the oscilloscope’s AC mains power cord grounding connector.

“Floating” a ground referenced oscilloscope puts all accessible metal including the chassis, casing, and connectors at the same voltage as the test point that the probe reference lead is connected.



A floating measurement in which dangerous voltages occur on the oscilloscope chassis. V1 may be hundreds of volts!

Advantages & Trade-Offs

Advantages

Isolated input channel oscilloscopes offer a safe and reliable way to make floating measurements. An obvious benefit of channel-to-channel and channel-to-ground isolation is the ability to simultaneously view multiple signals referenced to different voltages.

Another benefit is the ability to do this without the added cost of specialized probes or expensive and bulky voltage isolators. Channel-to-power line isolation eliminates the path between ground of the signal source and the oscilloscope.

Trade-Offs

Unlike a differential probe, an isolated input channel does not provide a balanced floating measurement. The impedance to earth ground is different in the tip (+) input and reference (-) input. Since the reference (-) input of the isolated channel does not have a default reference level like a grounded oscilloscope, you must connect the reference lead of the probe to the reference on the DUT.

There is no shunting to ground, therefore line frequency fields radiated from fluorescent lighting and building wiring can result in more baseline noise on the oscilloscope reading. Using averaging acquisition mode can mitigate this increase in baseline noise.

Advantages

Differential probes provide a safe method to adapt a grounded oscilloscope to make floating measurements. In addition to the safety benefits, the use of these probes can improve measurement quality. Differential probes provide balanced measurement input capacitance so any point in the circuit can be safely probed with either lead. Differential probes also typically have better CMRR performance at higher frequencies than voltage isolators.

Another benefit is the full use of the oscilloscope's multiple channels with the simultaneous viewing of multiple signals, referenced to different voltages.

Trade-Offs

The probes still have a resistive path to ground - so if a circuit is sensitive to leakage currents then differential probes may not be the best solution.

Other trade-offs include an added layer of cost - depending on the oscilloscope capability an independent power supply may be required, adding cost and bulk. The gain and offset characteristics must be factored manually into every measurement.

Advantages

Voltage isolators provide a means of safely measuring floating voltages. Because isolators have no resistive path to ground, they are a good choice for applications which are extremely sensitive to leakage currents.

Trade-Offs

Voltage isolators add a layer of cost. An independent power supply and isolation amplifier box must be used. The gain and offset characteristics must be factored manually into every measurement.

Advantages

The advantage of using the "A minus B" measurement technique is that it can be easily done with almost any oscilloscope and its standard probes. Keep in mind that both test points must be referenced to ground. Thus this method will not work if either test point is floating or if the entire system is floating.

Trade-Offs

Two oscilloscope channels are used to make one "A minus B" measurement. The primary limitation of this technique is the rather small common-mode range, which results from the oscilloscope's vertical channel dynamic range. Generally this is less than ten times the volts/division setting from ground. Whenever common mode voltage is greater than differential mode voltage, the "A minus B" technique can be thought of as extracting the small differences from two large voltages. This technique is suitable for applications where the common-mode signal is the same or lower amplitude than the differential mode signal, and the common-mode

component is DC or low frequency, such as 50 or 60 Hz power line. It effectively eliminates ground loop voltages from the measurement when measuring signals of moderate amplitude.

Advantages

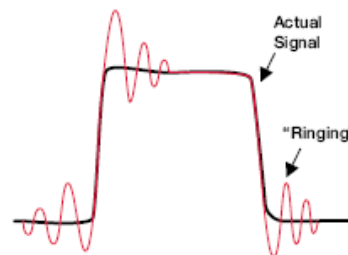
Although floating equipment is a method that uses existing equipment to make floating measurements and remove ground loops on lower frequency signals, it is an unsafe and dangerous practice and should never be done.

Trade-Offs

This technique is dangerous, not only from the standpoint of elevated voltage present on the oscilloscope (a shock hazard to the operator), but also due to cumulative stresses on the oscilloscope's power transformer insulation. This stress may not cause immediate failure but can lead to future dangerous failures (a shock and fire hazard), even after returning the oscilloscope to properly grounded operation.

At higher frequencies, severing the ground may not break the ground loop as the line-powered instrument exhibits a large parasitic capacitance when floated above earth ground. The floating measurement can be corrupted by ringing. Floating oscilloscopes 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. Connecting the oscilloscope 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 by a miniature fireworks display right on your bench.

Yet another trade-off is that only one measurement may be made at a time - remember all the input references are tied to each other. Once you have floated one input references, all input references are now floating at the same level.



Ringing caused by parasitic inductance and capacitance distorts the signal and invalidates measurements.

Tektronix TPS2000B and THS3000 Series IsolatedChannel™ Oscilloscopes

The TPS2000B Series combines the proven Tektronix bench oscilloscope performance with a four isolated channel architecture designed for making measurements on products operating on industrial power. Paired with the optional power bundle (TPS2PBND2), which includes four passive, high voltage probes (P5122) and the power measurement and analysis software package (TPS2PWR1), this instruments sets the standard for advanced floating measurements in its class. The power measurement and analysis software package offers power analysis measurements (true power, reactive power, true power factor, phase angle), waveform analysis measurements (RMS, crest factor, frequency), harmonic measurements, and switching loss measurements.

The THS3000 Series is designed for engineers requiring a higher degree of mobility in their oscilloscope usage without sacrificing bench-level performance or the ability to perform floating measurements. The instrument's ruggedized, light-weight and handheld form factor, 7hr single-battery performance and automated measurement capability offers a large degree of versatility in both lab and field operations. The instrument's isolated channels, high voltage acquisition (up to 1000 V_{RMS} CAT II) and advanced waveform recording capability allows for safe floating measurements and is therefore highly suitable for users who frequently need to correlate measurement taken in the lab to those taken in the field.

Mind your CATs and Volts

Selecting the proper voltage probe for making floating measurements

How to select probe and oscilloscope combination:

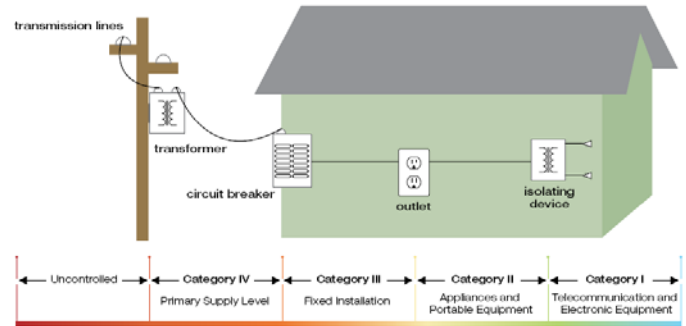
1. Determine measurement (or overvoltage) category

The IEC 61010-1 international standard defines four overvoltage categories for voltage-measuring instruments. The overvoltage categories I through IV are defined by how much electrical energy could be present during a transient.

Based on IEC 61010-1, voltage-measuring instruments are rated on their ability to withstand a voltage transient.

Summary Description of Categories	
CAT IV	For measurements performed at the source of a low voltage installation (<1,000 V).
CAT III	For measurements performed in the building installation.
CAT II	For measurements performed on circuits directly connected to the low voltage installation.
CAT I	For measurements performed on circuits not directly connected to MAINS.

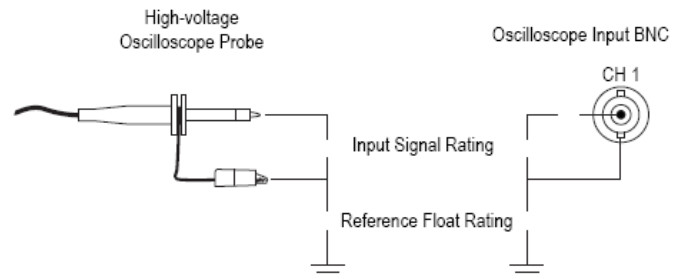
2. Determine maximum floating voltage.
3. Determine maximum tip to ground voltage.
4. Determine the maximum voltage from probe tip to the reference lead.
5. Determine maximum peak to peak reading desired on screen.



IEC Installation Categories.

Selecting the proper voltage probe for your TPS2000B and THS3000 Series Oscilloscopes

	Probe Name			
	TPP0201	THP0301	P5150	P5122 ¹
Maximum probe tip to ground voltage	300 V _{RMS} CAT II	300 V _{RMS} CAT III	1000 V _{RMS} CAT II	1000 V _{RMS} CAT II when DC coupled
Maximum reference to ground (floating) voltage	30 V _{RMS}	300 V _{RMS} CAT III	600 V _{RMS} CAT II	600 V _{RMS} CAT II
Attenuation settings	10x	10x	50x	100x
Bandwidth	200 Mhz	300 Mhz	500 Mhz	200 Mhz
Probe type	passive	passive	passive	passive
On-screen Peak-to-Peak Voltage ²	TPS	400 V _{p,p}	400 V _{p,p}	2000 V _{p,p}
	THS	849 V _{p,p}	849 V _{p,p}	2828 V _{p,p}
On-screen RMS Voltage ²	TPS	141 V _{RMS}	141 V _{RMS}	707 V _{RMS}
	THS	300 V _{RMS}	300 V _{RMS}	1000 V _{RMS}
¹ P5122 probe should not be used for AC-coupled measurements on signals with DC > 300 V on the TPS2000				
² Limited by instrument's vertical resolution (TPS = 5V/div, THS = 100V/div)				



Example:

Need to measure peak-to-peak voltages on Line-to-Line 240 V_{RMS} 3-phase wye Active Harmonic Filter.

1. Determine maximum rated input voltage for desired installation category: CAT III

- The maximum allowed input voltage for a certain CAT rating generally applies to lower CAT environments as well. E.g., if the instrument is rated 300 V_{RMS} CAT III, it would be safe to work with the instrument at 300 VRMS in a CAT II environment.
- Instruments are often additionally rated at a lower CAT category for higher voltage levels, e.g. 300 V_{RMS} CAT III and 600 V_{RMS} CAT II simultaneously. This is not always the case and therefore such ratings across multiple CAT categories must be explicitly verified by the user in the instrument's documentation.

2. Determine maximum floating voltage required (ground to reference voltage)

- This example has 240 V_{RMS} measurement requirements.
- Therefore, only the THP0301, P5150 and P5122 probes would be suitable.

3. Determine maximum probe tip to ground voltage requirements

- In this example, the engineer determined this to be approximately 140 V_{RMS}.
- All four probes fulfill this requirement.

4. Determine maximum voltage from probe tip to the reference lead

- The maximum expected voltage is the 240 V_{RMS} of the signal to be measured.
- This limits the probe selection to the THP0301, P5150 and P5122 probes.

5. Determine attenuation needed

- Calculate maximum peak-to-peak voltage corresponding to 240 V_{RMS}.
- Desired viewable voltage range is therefore: $240 V_{RMS} \times \sqrt{2} \times 2 = 679 VP-P$.
- TPS2000B Series has maximum vertical setting of 5V/div and 8 divisions on the screen.
- THS3000 Series has maximum vertical setting of 100V/div and 8 divisions on the screen.
- Probe attenuation needed = viewing voltage / max vertical / # of divisions.
- TPS2000B: $679 VP-P / 5 / 8 = 17x$, only the P5150 and P5122 offer enough attenuation.
- THS3000: $679 VP-P / 100 / 8 = 1x$, all available probes offer enough attenuation.

6. Select probe fulfilling minimal requirements

- For the TPS2000B, the P5150 and P5122 would be suitable probes for this test scenario
- For the THS3000, the THP0301, P5150 and P5122 would be suitable probes.

