

Complete

ISOLATION

Extreme

COMMON MODE REJECTION



INTRODUCTION

This white paper describes the optically isolated measurement system architecture trademarked IsoVu™. IsoVu offers complete galvanic isolation and is the industry's first measurement solution capable of accurately resolving high bandwidth, high voltage differential signals in the presence of large common mode voltages. A stand out feature of IsoVu™ is its best in class common mode rejection across the entire bandwidth. This white paper will provide information on both TIVM Series and TIVH Series IsoVu products.

THEORY OF OPERATION

IsoVu utilizes an electro-optic sensor to convert the input signal to optical modulation, which electrically isolates the device-under-test from the oscilloscope. IsoVu incorporates four separate lasers, an optical sensor, five optical fibers, and sophisticated feedback and control techniques. The sensor head, which connects to the test point, has complete electrical isolation and is powered over one of the optical fibers. Figure 1 shows the block diagram.

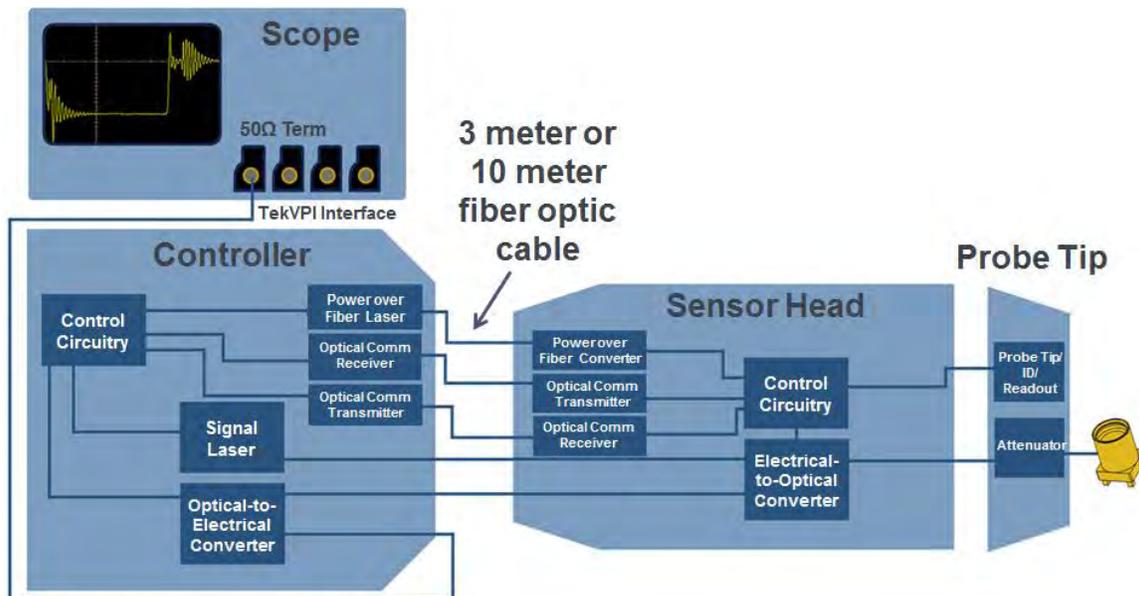


Figure 1: IsoVu Block Diagram

DIFFERENTIAL AND COMMON MODE SIGNALS BACKGROUND

Differential measurements are typically made with a differential probe. Differential probes are based on difference amplifiers which measure the potential difference between two test points. If the voltage at one input is 2 V and the voltage at the other input is 1 V, the output is the difference between the two inputs which is 2 – 1 or 1 V. However, there is typically a common mode component which must be considered.

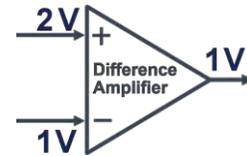


Figure 2: Differential Measurement

So, if the inputs to the amplifier are connected to the same source signal, what would you expect the output to look like? If this is an ideal amplifier, you would expect the output to be a completely flat line or 0 V because the amplifier should subtract the signals at both inputs. This signal that is "common" to both the non-inverting input and the inverting input is referred to as the common mode signal. An ideal difference amplifier would reject 100% of the common mode signal. If there is 100 V on both the non-inverting input and 100 V on the inverting input, an ideal differential probe would have an output of 0 V. It's 100 – 100.

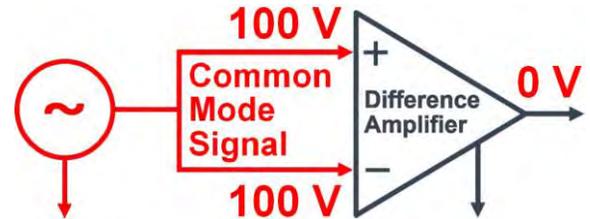


Figure 3: Common Mode Rejection

When you're making a differential measurement, the only thing you want to see is the difference between the two signals you're trying to measure. You shouldn't see the effects of the common mode voltage at the output of the amplifier. The ability to reject the common mode signal is the amplifier's common mode rejection ratio (CMRR). Ideally, an amplifier would have an infinite CMRR. The higher an amplifier's CMRR, the less impact the common-mode input voltage has on the differential measurement. Because it's impossible to perfectly match the two inputs of a differential probe, every differential measurement will include some common mode error; it is only a question of how much. It's important to note that an amplifier's common mode rejection ratio is frequency dependent. Differential probes typically have higher CMRR at DC and low frequencies but the CMRR degrades as the frequency increases.

Consider the simplified half bridge circuit shown in Figure 4. The differential voltage between the gate and source at the high-side transistor is 5 V. When there is 100 V of common mode voltage, the measurement system needs to display the difference between 105 V and 100 V. The measurement system's ability to accurately resolve the 5 V differential signal is dependent on the amplifier's common mode rejection capability.

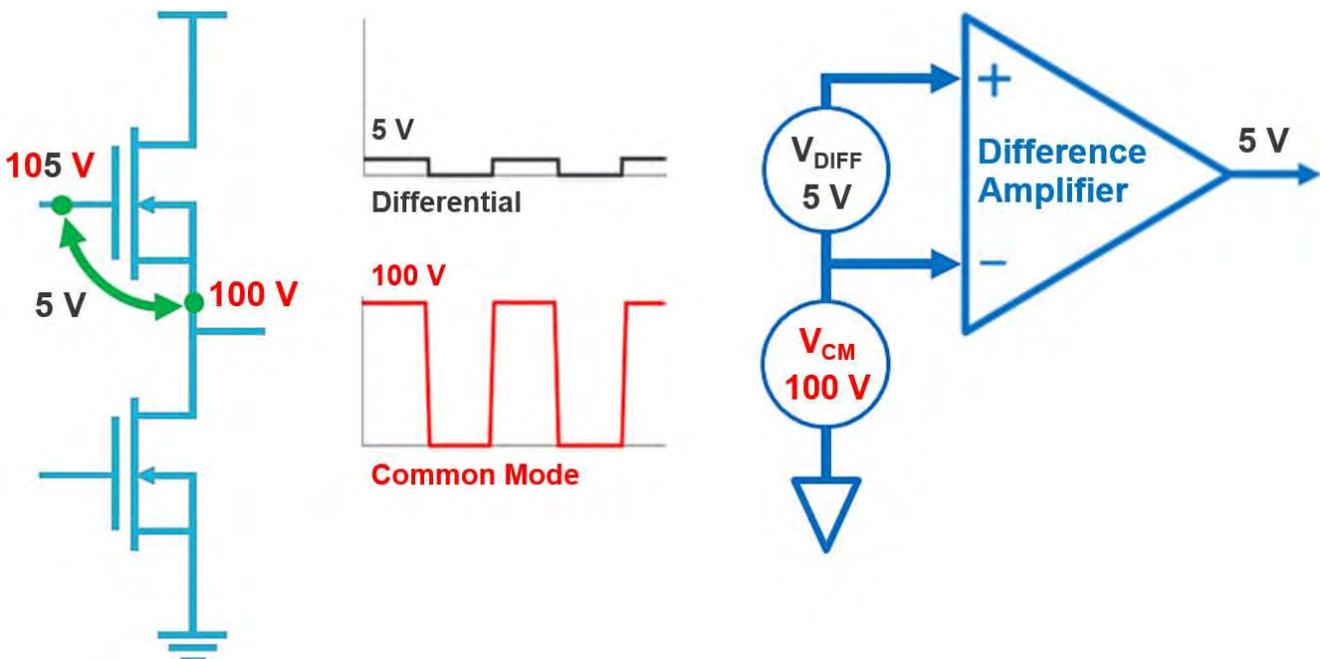


Figure 4: Simplified half-bridge circuit

HOW COMMON MODE REJECTION IS SPECIFIED

Because of the frequency dependence of CMRR, most differential probes only list the CMRR values at DC and low frequencies on the data sheet. Let's examine the data sheet of a high voltage differential probe shown in Figure 5. It's a 100 MHz probe, but when we zoom in on the numbers in the data sheet, it only specifies values at DC, 60 Hz, 1 kHz, and 1 MHz. It seems strange that the data sheet doesn't include the CMRR value for 100 MHz since that's the listed bandwidth of the probe. When you look at the CMRR plot in the manual in Figure 6, it becomes clear why the CMRR values at higher bandwidths are omitted. At 100 MHz, this probe only has ~27 dB CMRR which is about 22:1.

Product	
Bandwidth (-3dB)	→ ≥100 MHz probe bandwidth
DC CMRR	-70 dB at 500 VDC
AC CMRR	-80 dB at 50/60 Hz
	-50 dB at 1 kHz
	-50 dB at 1 MHz ←

Figure 5: High Voltage Differential Probe Data Sheet

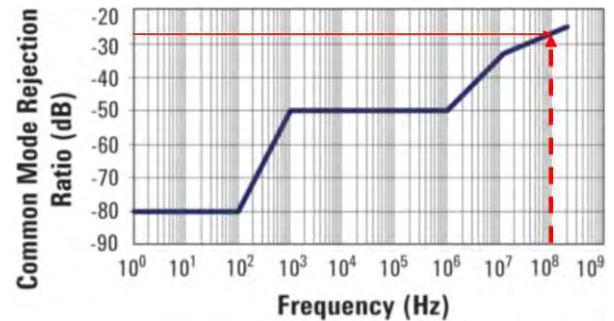


Figure 6: High Voltage Differential Probe CMRR Plot

Going back to the example of 100 V common mode voltage in Figure 4, the common mode error would be calculated as 100 V divided by 22 which is approximately 4.5 V of common mode error. With this amount of common mode error, it wouldn't be possible to resolve a 5 V differential signal in the presence of 4.5 V of common mode error. Given IsoVu's 1 Million to 1 rejection ratio at high bandwidth, the common mode error using an IsoVu probe would be calculated as 100 V divided by 1 Million. That's about 100 μ V of error.

In practice, a CMRR of at least 80 dB (10,000:1) will result in usable measurements. Most differential probes can easily obtain a CMRR of 80 dB or higher at DC and low frequencies where it's possible to tune the components accurately. As the frequency of the measurement increases, a differential probe's CMRR degrades because the mismatches become increasingly difficult to control. At 100 MHz, the CMRR capability of most measurement systems is 20 dB or less. Table 1 compares the CMRR specifications of an isolated measurement system (IsoVu) versus a traditional high voltage differential probe.

Probe	Bandwidth	CMRR @ DC	CMRR @ 1 MHz	CMRR @ 100 MHz	CMRR @ Full Bandwidth
Tektronix IsoVu	1 GHz	120 dB (1 Million:1)	120 dB (1 Million:1)	120 dB (1 Million:1)	80 dB (10,000:1)
Traditional High Voltage Differential	200 MHz	> 80 dB (10,000:1)	50 dB (316:1)	Not Listed in the data sheet. 27 dB from the manual's CMRR plot	Not Listed in the data sheet. 15 dB from the manual's CMRR plot

Table 1: Common Mode Rejection Ratio Comparison

A user may fall into the trap of thinking the 1 MHz specification is "fast enough" for their application. However, it's important to remember that while the repetition rate may not be fast, the rise time of the signal you're measuring may be quite fast, in the 1's or 10's of ns.

If the differential signal you're measuring is in the presence of 500 V common mode voltage, how much error should you expect? Again, it depends on the signal's rise time. Table 2 describes how much common mode error the user should expect in the presence of 500 V common mode voltage across bandwidth.

Probe	Common Mode Error for 500 V Common Mode Voltage across Bandwidth			
	DC	1 MHz (35 ns rise time)	100 MHz (3.5 ns rise time)	Full Bandwidth (≤ 1 ns rise time)
Tektronix IsoVu	500 μ V	500 μ V	500 μ V	50 mV
Traditional High Voltage Differential	50 mV	1.6 V	22.3 V	89.3 V

Table 2: Error due to Insufficient Common Mode Rejection Ratio

CHARACTERIZE THE ENTIRE SWITCHING CIRCUIT

When evaluating signals such as V_{DS} or V_{GS} at the high-side transistor where the switch node voltage is rapidly switching between “ground” and the input supply voltage, a measurement solution with the following characteristics is required:

- High bandwidth: > 500 MHz
- Large common mode voltage: > the input supply voltage
- Large common mode rejection ratio: > 60 dB at 100 MHz
- Large input impedance: > 10 M Ω || < 2 pF

Tektronix launched the TIVM Series products squarely aimed at measurements such as the high-side V_{GS} where the measurement system needed high performance, high common mode voltage, and large common mode rejection ratio across bandwidth. Tektronix followed the TIVM Series with the TIVH Series products which significantly increased the differential voltage range and input impedance, allowing measurements such as high-side V_{DS} to be possible.

	IsoVu TIVM Series	IsoVu TIVH Series
Bandwidth	Up to 1 GHz	Up to 800 MHz
Rise Time	Down to 350 ps	Down to 450 ps
Differential Voltage Range	± 50 V	> 1000 V*
Common Mode Voltage Range	60 kV	60 kV
Common Mode Rejection Ratio	DC – 1 MHz: 160 dB (100 Million to 1) 1 MHz – 100 MHz: 120 dB (1 Million to 1) 1 GHz: 80 dB (10,000 to 1)	DC – 1 MHz: 160 dB (100 Million to 1) 1 MHz – 100 MHz: 120 dB (1 Million to 1) 800 MHz: 80 dB (10,000 to 1)
Input Impedance	Up to 2.5 k Ω < 1 pF	Up to 40 M Ω * As low as 2 pF*
Fiber Cable Length	3 meters or 10 meters	3 meters or 10 meters
Power Over Fiber	Powered over the fiber connection – no batteries required	Powered over the fiber connection – no batteries required
Input Offset	± 100 V	Up to > 1000 V*
AC Input Coupling	No	Yes

Table 3: Tektronix TIVM and TIVH Series Specifications

*Note: Specifications are dependent upon the probe tip cable

ISOVU MAKES HIDDEN SIGNALS VISIBLE

The benefits of a design such as a half-bridge circuit can only be achieved when the half-bridge circuit, the gate drive circuit, and layout, are all properly designed and optimized. It's impossible to tune and optimize this circuit if you cannot measure it. Completing this design requirement involves characterizing the waveforms shown in the ideal case in Figure 7.

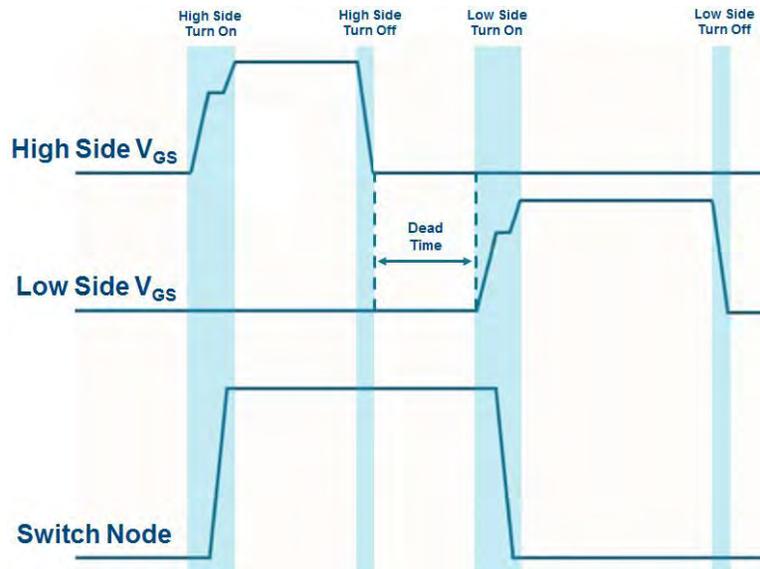


Figure 7: Example Ideal Half-Bridge Switching Waveforms

In general, there are three characteristic regions of the turn on waveform that are of interest. The first region is the C_{GS} charge time. This is followed by the Miller Plateau which is the time required to charge the gate-drain Miller capacitance (C_{GD}), and is V_{DS} dependent. This charge time increases as V_{DS} increases. Once the channel is in conduction, the gate will charge up to its final value. The ideal representation of these regions is shown in Figure 8.

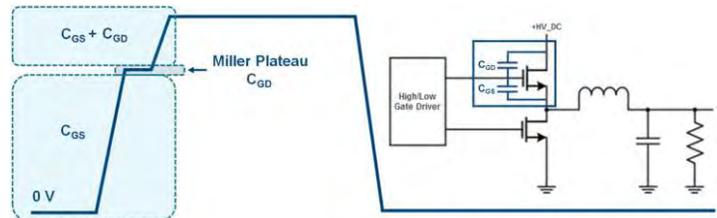


Figure 8: High Side Turn On Characteristics

The high side V_{GS} is riding on top of the switch node voltage which is switching between “ground” and the input supply voltage. Because of this rapidly changing common mode voltage, the gate-source voltage is impossible to measure without adequate common mode rejection.

Comparing this actual output to the ideal transition, it's difficult to extract any meaningful details regarding what is happening in each of the regions referenced above and make design decisions based on this measurement. It's worth noting that the waveform shown below changes dramatically based upon position of the probe's input leads making a repeatable measurement impossible.

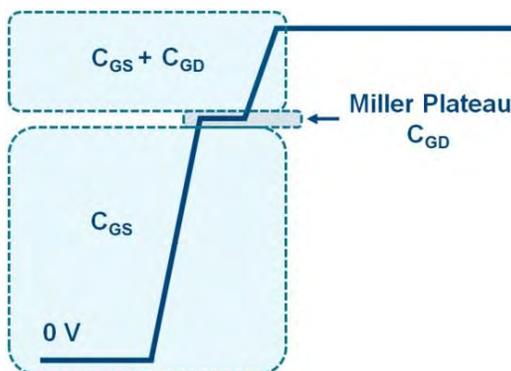


Figure 9: V_{GS} Measurement using a probe with inadequate CMRR



Until now, a traditional high voltage differential probe has offered the most insight into these kinds of measurements. With this measurement system, the user may have been tempted to optimize their design based on the waveform information. After all, it does seem to show some of the expected characteristics. However, the IsoVu system shows a very different story. Figure 10 shows a comparison of these two measurement systems and reveals how optimizing based on a measurement system with limited CMRR and bandwidth can cause users to severely mis-tune their design.

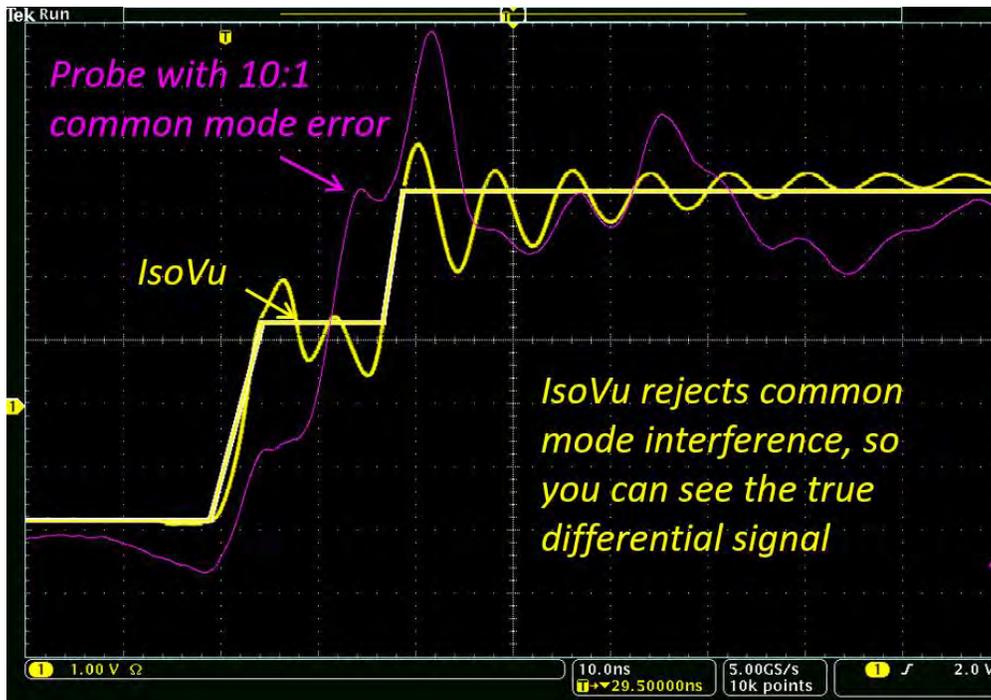


Figure 10: High Side Turn On Characteristics

Although the low side switch is supposed to be “ground” referenced, it’s also interesting to see the actual waveform and how it may affect the high side performance. Figure 11 shows the low side switch has ringing due to parasitic coupling between the low side switch, the high side gate and the switch node.

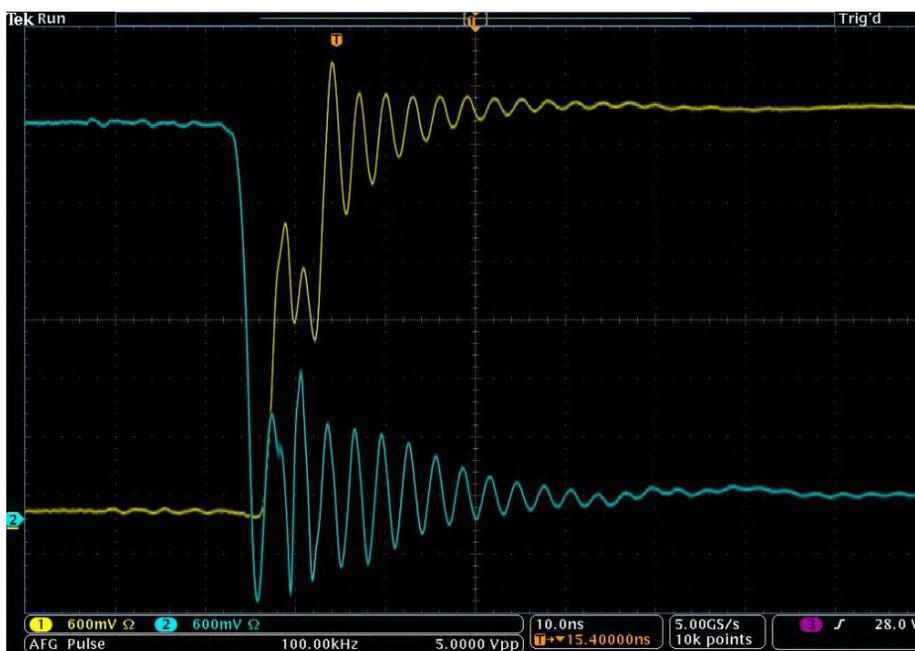


Figure 11: Interaction of the High Side and Low Side Switches

Many of the same characteristics are apparent during the high-side turn-off/low side turn on transitions. As shown in Figure 12, the Miller plateau on the low side V_{GS} is clearly visible. The coupling due to parasitics between the switch node and the high and low side FETs is apparent, and the IsoVu measurement system has more than adequate bandwidth to measure the dead time.

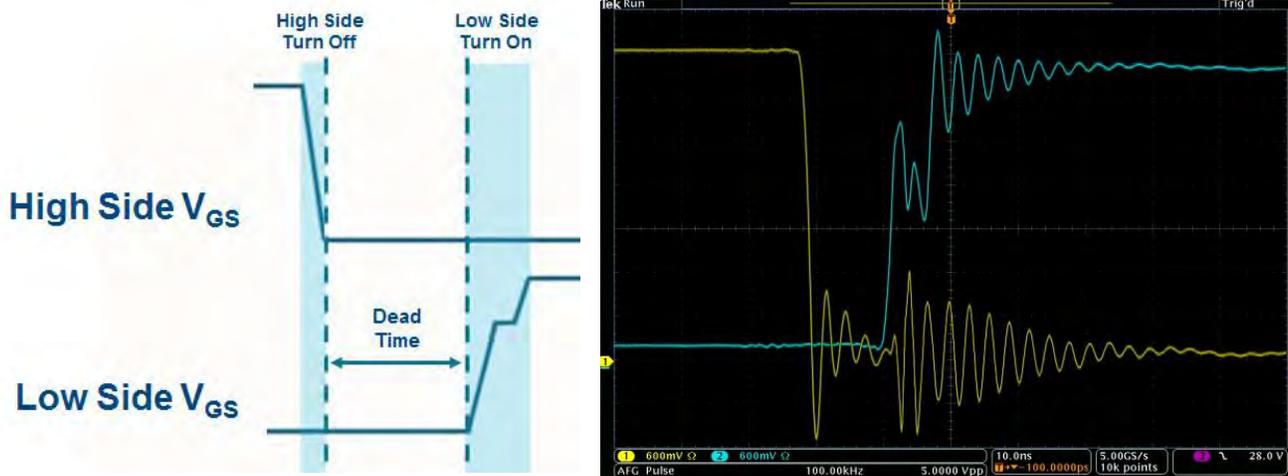
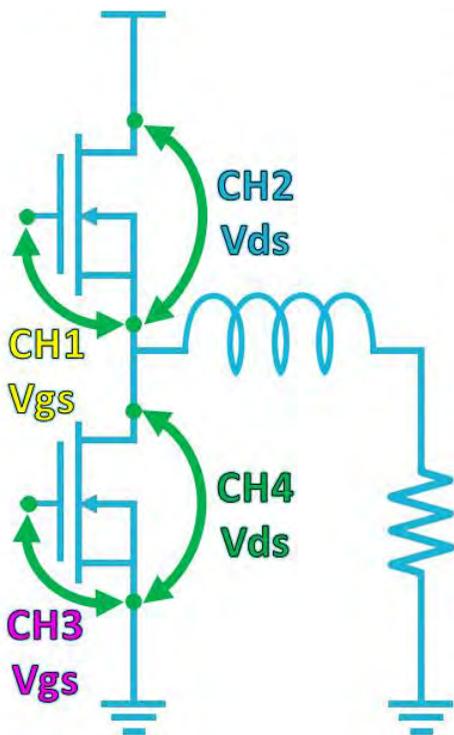


Figure 12: High Side Turn Off, Low Side Turn On, and Dead Time

With the TIVM Series and TIVH Series of products, the entire circuit can be completely characterized as shown in Figure 13.



- Characterize the gate voltages, V_{ds}, and I_s
- Characterize the time alignment of high and low side events
- Optimize and tune switching characteristics (edge rates, overshoot, ringing and dead time)

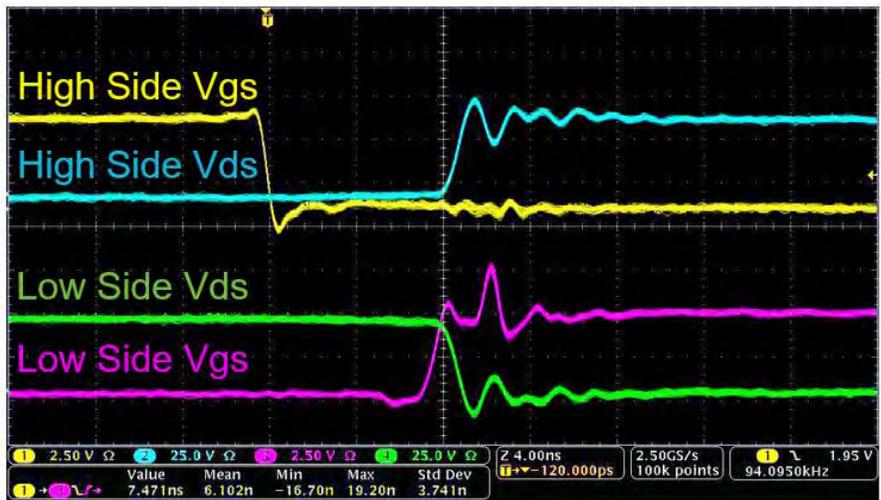


Figure 13: High Side Turn Off, Low Side Turn On, and Dead Time

DIFFERENT TIP CONNECTORS

DESIGNED FOR OPTIMAL PERFORMANCE AND CONVENIENCE

MMCX Style Sensor Tip Cables (high performance up to 250 V applications)

The best performance from the IsoVu measurement system is achieved when an MMCX connector is inserted close to the test points. MMCX connectors are an industry standard and are available from many electronic component distributors. These connectors offer high signal fidelity. The solid metal body and gold contacts provide a well-shielded signal path. The mating MMCX interface offers a snap-on connection with a positive retention force for a stable, hands free connection. The disengage force provides a safe, stable connection for high voltage applications. MMCX connectors are available in many configurations as shown below and can be adapted to many designs, even if the connector was not designed into the board. Information for soldering these connectors into your design can be found at www.tek.com/isolated-measurement-systems.



Figure 14: MMCX Connectors

Square Pin to MMCX Adapters

When an MMCX connector cannot be used, the tip cable can be adapted to fit onto industry standard square pins. Tektronix provides probe tip adapters to connect the sensor tip cables to square pins on the circuit board. Two adapters with different pitches are available, MMCX-to-0.1-inch (2.54 mm) and MMCX-to-0.062-inch (1.57 mm).

The adapters have an MMCX socket for connection to an IsoVu tip cable. The other end of the adapter has a center pin socket and four common (shield) sockets around the outside of the adapter. Notches on the adapters can be used to locate the shield sockets. The best electrical performance is achieved when the probe tip adapter is close to the circuit board.

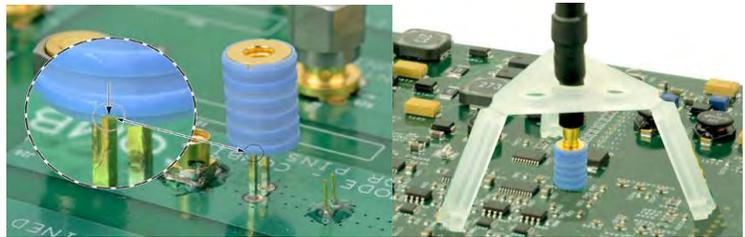


Figure 15: MMCX to Square Pin Adapter

Square Pin Style Sensor Tip Cables

The TIVH Series products also include square pin style sensor tip cables to achieve higher input differential voltage capability. These tip interfaces offer both ease of connectivity and a secure connection for safe, hands free operation in high voltage environments. The square pin style sensor tip cables are available in both 0.100" (2.54 mm) pitch which can be used in applications up to 600 V and 0.200" (5.08 mm) pitch which can be used in applications up to 2500 V.



Figure 16: Square Pin Style Sensor Tip Cables

CONCLUSION

Accurate differential measurements rely on a measurement system's bandwidth, rise time, common mode voltage range, common mode rejection capability, and the ability to connect to smaller test points to characterize devices that are shrinking in size and increasing in performance. While differential voltage probes have had modest performance gains in bandwidth, these probes have failed to make any substantial improvements in common mode rejection and connectivity. The IsoVu measurement system is a leap forward in technology and is the only solution with the required combination of high bandwidth, high common mode voltage, and high common mode rejection to enable modern differential measurements.

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