How to measure MOSFET drain voltage and current

Chris Lee - August 13, 2013

As the primary switching device used in a broad range of power conversion applications, MOSFETs play a central role in power supply design. Defining their performance characteristics is crucial to reliable and predictable power supply operation. This article describes how to measure MOSFET drain voltage and current.

As part of that discussion it outlines how to use several types of current probes, how to identify the correct measurement points in a design, and how to measure and adjust voltage probe compensation. Along the way it also offers some helpful tips to minimize noise pickup and maximize measurement accuracy. While the examples used in this discussion are based on flyback converters using a Power Integrations device, the lessons learned are applicable to most topologies.

To implement these measurement techniques, you will need a functional power supply and a standard set of test equipment including a Variac, a programmable AC source, digital multimeters (DMMs), an electronic load, an oscilloscope, a wattmeter and AC/DC probes. Make sure to add a current probe to your lab setup. While the probe isn't always considered a typical piece of test equipment and will increase costs, it plays a crucial role in identifying faults and accelerating the design verification process. Ultimately, the current probe will save significant development time and greatly improve the quality of your design.

Those who don’t have a current probe may be tempted to connect a resistor in series with the Source pin and monitor voltage drop across it to determine drain current. This measurement method is not recommended because the resistor will modulate the controller ground and can prevent the device from functioning properly.

Selecting a current probe

Current probes are available from a variety of manufacturers. The two key factors to consider when purchasing a current probe are the required current rating and whether it requires an AC or DC probe. Select a current rating that is slightly higher than the peak currents you will need in your design. Power Integrations reference design RDR-91 offers a perfect example. In this 12-watt design you would expect to see peak currents of about 4 amps on the secondary side. Given that fact, you would need a standard current probe rated for 50 amps peak to measure most current waveforms. On the other hand if you’re measuring peak inrush current at startup or working with higher power designs, you might need a higher rated probe to achieve accurate results.

DC current probes are active devices that use a Hall Effect sensor to measure both AC and DC currents. They require a matching probe amplifier which may be either a standalone unit or built in.
AC currents probes, on the other hand, are simply current transformers and do not require a probe amplifier. However, they cannot be used to measure DC current levels. In a proper measurement is conducted both AC and DC current probe will give accurate result.

Since they can be used in a wider array of measurements, DC current probes are typically more useful for power electronics applications. As an example, a DC probe can be used to measure and characterize your load or to measure inductor currents in other topologies such as buck converters. However, that additional utility comes at a cost; AC probes typically run only about half the cost of a DC current probe and amplifier. If your test budget is limited, keep in mind that an AC current probe can be used for about 80 percent of all typical power supply measurements including the drain current waveform.

Begin the drain current measurement process by inserting a wire loop to place the current probe into the circuit. Insert the loop into the circuit so that only the drain current runs through it. Break the circuit in the printed circuit board drain node between the drain pin of the PI device and any component in the primary clamp circuit. This break can be easily made with a sharp razor blade and a hot soldering iron to lift the copper from the board. Solder a small wire loop across the break. To minimize noise coupling and leakage inductance, make sure the loop is just large enough to allow the current probe to clamp around it. Remember that the current loop must be removed before running EMI scans to prevent it from acting as a loop antenna, coupling high frequency noise which will result in poor EMI.

![Figure 1. Making the break in the PCB trace (Source: Power Integrations)](image)

Next, connect the current probe to the oscilloscope. If the bandwidth on the scope input is user selectable, set a range of 20 MHz or higher. Now we will take a look at the differences between setting up a DC and an AC probe.
If you’re using a DC probe, check the scope input impedance required by the probe amplifier. Most amplifiers require a value of 50 Ω. If your scope doesn’t have that setting, you can use an impedance-matching adapter. In most cases where the current probe interfaces directly with the scope, impedance-matching is automatically configured. Next, degauss the probe using the button or setting on the amplifier. To prevent induced currents from damaging your circuit, ensure the probe is disconnected from the circuit before degaussing.

Next, clamp the probe on the current loop and latch it closed. The arrow on the probe, which indicates the direction of the current flow, should be pointing towards the Drain pin. Set the scope gain to match the output of the probe amplifier and adjust the DC offset level on the probe amplifier to zero the current level on the scope.

If you’re using an AC probe, begin by verifying the input impedance of your scope matches that required for your probe. Typically AC probes have a 1 MΩ input and do not require an impedance-matching adapter. Clamp the probe around the current loop and latch it closed. As with a DC probe, make sure the arrow on the AC probe is pointed in the direction of the current flow, toward the Drain pin. Then set the scope gain to provide a readable waveform. The datasheet for the device you use in your design will indicate current limit. Select a scope channel gain which will supply about five divisions of resolution between ground and peak drain current. Once the supply is running, adjust the gain to make measurements. When the supply is running you will see that the output of the AC probe is an AC signal centered on ground.

You can make an AC probe signal look like the output from a DC probe by simply modifying a few oscilloscope settings. First, set the scope input to DC coupling. Next, adjust the offset level on the scope until the current level when the MOSFET is off is seen as scope ground. Then, examine the current waveform you get when the supply is running. Gradually adjust the gain of the probe amplifier and the time base of the scope to obtain a clear, measurable waveform. If you’re using an AC probe, adjusting the gain will adjust the entire waveform and require you to re-center the ground by re-adjusting the DC offset.
Figure 2. Waveform resulting from incorrect placement of current loop (Source: Power Integrations)

Figure 3. Expected drain current waveform (Source: Power Integrations)
Please note that some devices, such as Power Integrations’ TinySwitch™-III IC used in the design example RDR-91, employ on/off control. Instead of manipulating the duty cycle to control power transfer as PWM products do, these devices use on/off control to skip entire cycles. Keep in mind that while this characteristic can appear as instability in a design, it is actually operating normally.

If the waveform you see is inverted, than the arrow on the current probe is pointed in the wrong direction. Simply switch the orientation of the current probe on the loop.

When the probe is connected and properly configured, the drain current waveform in a flyback design should fall to zero within approximately 100 ns. If the current fall takes far longer, verify that the current loop is inserted at the correct point in the design. If the loop is placed between the transformer pin and the clamp components, the probe will properly measure current that flows into the clamp network.

Use of a current probe will introduce a delay in the current waveforms you view. Typically you can expect about a 10 to 15 ns delay for a probe with a 50 MHz bandwidth. You must keep this delay in mind when measuring switching losses or making time-sensitive comparisons between the current waveform and other waveforms on the screen.

Now you are ready to measure drain current.

**Measuring Drain Voltage**

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We begin the drain voltage measurement process by first reviewing equipment requirements. To measure switching voltage across the MOSFET, you will need a 100x voltage probe rated for at least 1000 V. The bandwidth of both the scope and probe used to view the drain voltage waveform should be 100 MHz or higher.

It is important to check probe compensation before connecting it to your circuit. First, connect the voltage probe to the scope. Hook the probe to the compensation terminal on the scope and adjust the scope voltage and time base settings so that the rising and falling edges of the test signal fill the screen. Next, use the probe’s non-metallic adjustment tool to modify the compensation capacitor until any undershoot or overshoot on the waveform is minimized.
Time spent optimizing probe compensation pays off in more accurate measurements. The screenshots below offer an excellent illustration. The three screenshots (Figure 5.) show the same drain voltage with a correctly compensated probe (on left) and an undercompensated and overcompensated probe (on right). In both improperly compensated probes, the difference between the measured peak drain voltage and the correct peak drain voltage is more than 50V. In one, the under-compensated probe, the difference is greater than 100V.
Figure 5. Different scope bandwidths result in different voltage measurements (Source: Power Integrations)

It is also crucial to check the calibration of the oscilloscope by measuring a fixed DC voltage using both a calibrated digital multimeter and the scope. Since high-voltage probes tend to be somewhat inaccurate when measuring low voltages, we suggest you use a high-voltage source. If a high-voltage source is not available, you can create a fixed, high-voltage DC level by rectifying high-voltage AC and filtering it with a large value capacitor. In the example schematic below, a 265 VAC input is rectified and then filtered using a 22 µF capacitor. In this example, the multimeter reads a voltage of 374 VDC while the scope reads 376 VDC that indicates a high likelihood the measurements will be accurate. Don’t forget to safely discharge the capacitor after completing this test.
Next, connect the scope probe to the drain mode and clip the ground to the Source pin. To minimize noise pick-up, wrap the ground wire around the probe to reduce its loop area before connecting it to the board.

After you turn on the supply, adjust the vertical gain and time base of the scope to allow the drain voltage waveform to be seen clearly. For the most stable measurements, trigger the scope on the falling edge of the voltage waveform. Finally, to ensure high accuracy set the digitizing sample rate of the scope to the highest possible non-repetitive value. At the same time set the scope and input channel to the maximum bandwidth and turn off all additional filtering provided by the scope.

When measuring peak drain voltage, a high scope bandwidth is crucial to ensuring highly accurate measurements. The graphic below illustrates how different scope bandwidths can result in highly different voltage measurement results. Here three peak voltage measurements were made with bandwidths of 20 MHz, 100 MHz and 250 MHz. Note that the difference in peak voltage between the 20 MHz and 250 MHz measurements is more than 3V.

For critical measurements of drain voltage, such as where absolute value of peak voltages is important, you can achieve better results by replacing the scope tip with a ripple probe. Using a ripple probe minimizes loop area of the probe ground and reduces noise pickup. Typically this strategy will result in a peak measurement that is 5 to 10 volts lower.

At this point you are now ready to measure drain voltage.

Conclusion

As power supply design evolves and becomes increasingly complex, the ability to accurately and quickly measure MOSFET performance characteristics promises to become a highly valuable skill. By following the strategies and procedures outlined above, you can accurately perform this task and use it to evaluate and troubleshoot your power supply designs effectively.
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