Precise Voltage Measurement for Power Electronics with High Switching Frequencies

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Abstract

In this paper different approaches in precise measurement of gate voltages as well as drain-source voltages of modern SiC and GaN transistors are compared. An approach to calculate the necessary bandwidth of a voltage probe to reproduce the voltage slope is presented. Furthermore, state-of-the-art voltage probes are compared in means of bandwidth, common mode reduction and response on EMI.

1. Introduction

With the ongoing development in wide bandgap power electronic switches leading to faster commutation processes and therefore higher possible switching frequencies, the precise measurement of the relevant voltages gets more challenging. At the same time, it becomes of greater importance as well because faster commutation most often comes hand in hand with bigger overshoot and more electromagnetic influence (EMI).

Precise measurement of voltage slopes that are very steep is demanding for the measuring equipment as well as the measuring technique. Because of the continuing efforts in developing more efficient, smaller and lighter power electronics the quality of the switching behavior comes more into focus. This is for example the case with soft switching modulation techniques that demand for a precise configuration of the oscillation process in order to achieve zero voltage switching or with the accurate characterization of hard switching processes in order to develop exact loss-models of power electronic switches. Reference [1] gives an overview of the main challenges.

This paper shall on the one hand present investigations on the voltage measurement of the gate-source as well as the drain-source voltage slopes of modern SiC MOSFETs. Particularly the interference of common mode and differential mode signals are of interest as they very often manipulate the measurement signal. On the other hand, an approximation shall be introduced, that gives an indication about what bandwidth actually is necessary to adequately reproduce a voltage slope with a certain given rise-time.

Measurements which are based on a double pulse test (DPT) setup will be presented that compare two different prototypes of voltage probes for practical purposes. High- and lowside switches are defined as depicted in Figure 1.

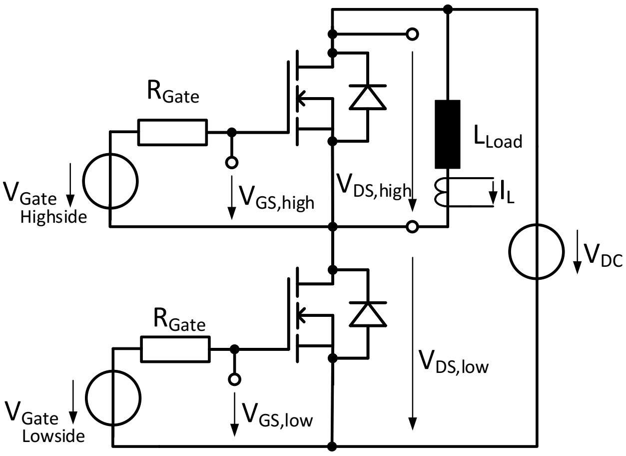


Fig. 1: Measurement setup

2. Voltage Measurement

2.1. Investigation on necessary bandwidth

The datasheets of common transistors generally give information about the rise time of the component. Most often it is measured between the 90% value and the 10% value of the drain-source voltage [2]. There exist several different formulas to approximate the necessary bandwidth in order to precisely measure the voltage slope. However, there are not many reliable explanations for these formulas. Usually they are based on the rise time t_r or the fall time t_f - depending on which is shorter.

For example:

$$f_{BW} \approx f_{knee} \cdot 1,4 \approx \frac{0,5}{min\,(t_r, t_f)} \tag{1}$$

$$f_{BW} = [3..5] \cdot f_{eff} \approx [3..5] \cdot \frac{0,25}{min\,(t_r, t_f)} \tag{2}$$

$$f_{BW} = [3..5] \cdot f_{eff} \approx [3..5] \cdot \frac{0,35}{min\,(t_r, t_f)} \tag{3}$$

Sources of equations (1): [3], (2): [4], (3): [1]

The f_{knee} is defined in [3] as the knee frequency of the rise or fall transients.

This paper shall present an approximation strategy by assuming the drain-source voltage pulse to be a trapezoid pulse as depicted in Figure 2.

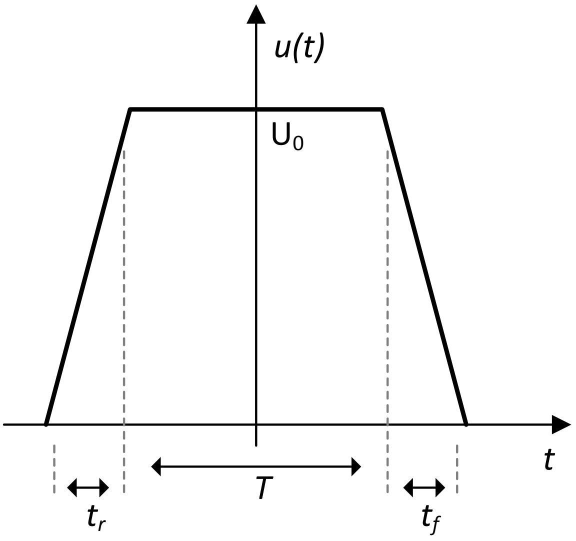


Fig. 2: Approximation of voltage pulse

Its parameters shall for example be supposed as $U_0 = 400\,\mathrm{V}$, $t_r = 10\,\mathrm{ns}$ and $T = 0.5\,\mu\mathrm{s}$ which comes close to a voltage pulse of 400 V at a switching frequency of 1 MHz. Comparable rise/fall times of transistors are for example $t_r = 8\,\mathrm{ns}$ with the Wolfspeed C3M0065100K SiC MOSFET and $t_{r,max} = 1.9\,\mathrm{ns}$ with the GaN Systems GS66506T GaN transistor. These are also the transistors which were characterized with the later introduced voltage probes probe 1 and probe 2.

With the voltage probe assumed to be a low-pass filter of a certain order, the influence of its cutoff frequency on its capability of reproducing the slope of the trapezoid is investigated in simulation.

The investigations result in a necessary bandwidth of about 130 MHz for a slope with the rise time of 10 ns and 700 MHz for a slope with the rise time of 1.9 ns. It results in an approximation formula for the necessary bandwidth as:

$$f_{BW} = 1,32 \cdot \frac{1}{min\,(t_r, t_f)} \tag{4}$$

As [1], [4] state, the necessary system bandwidth lies factor 3..5 higher than the maximum bandwidth of the measured signal. This is reflected in their suggested equations 2 and 3. The result of the proposed formula 4 matches this well.

2.2. Voltage probes

Basically there are two different approaches in measuring high voltages with an oscilloscope.

1. Use a high voltage passive probe, which connects the measured potential and the reference to the oscilloscope.
2. Use a high voltage differential probe, which makes the simultaneous measurement of voltages with different references at one oscilloscope possible.

Table 1 shows the parameters of several differential voltage probes taken from their respective datasheet. One can easily see that they vary in bandwidth, common mode voltage range and common mode rejection ratio. The parameters also correspond to the selected measurement range. This is explicitly not represented in this condensed table.

Tab. 1: Overview of the specifications of different state-of-the-art differential voltage probes

	Probe 1	Probe 2	Probe 3	Probe 4
Bandwidth	Up to 400 MHz	Up to 800 MHz	Up to 60 MHz	Up to 120 MHz
Risetime	Down to 875 ps	Down to 450 ps	Down to 7.5 ns	Down to 2.9 ns
Common Mode Voltage Range	2 kV	60 kV	35 kV	1.5 kV
Common Mode Rejection Ratio	DC: $>$80 dB 100kHz: $>$70 dB 1MHz: $>$62 dB 3.2MHz: $>$50 dB	DC-1MHz: 160 dB 100MHz: 100 dB 500MHz: 80 dB 800MHz: 70 dB	100Hz: 140 dB 1MHz: 120 dB 10MHz: 85 dB 60MHz: 60 dB	DC-60Hz: 85 dB 1MHz: 65 dB 20MHz: 30 dB 100MHz: 30 dB
Input Impedance	10 MΩ, 2 pF	40 MΩ, 2 pF	10 MΩ, 22 pF	10 MΩ, 2.5 pF
Gain accuracy	±0.35 %	±3 %	2 %	1 %

Especially the common mode rejection ratio has big influence on the precise measurement of highside gate-source signals. Because of the common mode voltage introduced by the drain-source voltage of the lowside transistor there often is large deviation in the measurement. The common mode voltage range itself states the ability to measure on high potentials and depends on the isolation technique. The input impedance describes the influence of the probe on the circuit. The gain accuracy is an expression of the deviation of DC voltage and measurement. Probe 2 has a noticeable higher gain accuracy stated in its datasheet than the others.

2.3. Measurements

To capture a switching process under specific conditions often the DPT is used. A half-bridge configuration with SiC C3M0065100K MOSFETs is applied (compare Figure 1) with two pulsed switching commands, see Figure 3. A large inductive load is charged by the first pulse (a). Therefore its duration as well as the DC voltage can be configured to achieve the desired current and voltage. The pause until the second pulse (b) is only chosen as long as necessary until all oscillation processes on the measured values have ceased. During this pause the load current commutates from the drain current (i_D) of the transistor to the forward current (i_F) of the freewheeling diode. Due to the large inductive load the current until the second pulse can be considered constant. Furthermore the junction temperature of the chip can be considered constant and is set to defined values. By applying this technique both the switching transition of the switch as well as of the internal freewheeling diode can be investigated.

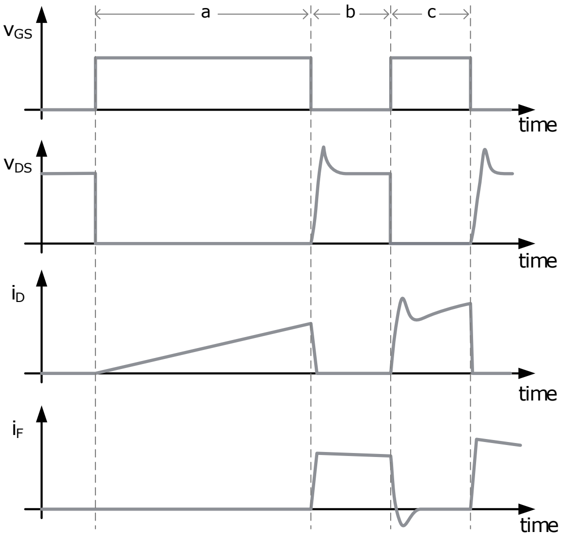


Fig. 3: Time sequence of double pulse test

The following measurements shall compare the introduced voltage probes 1&2. A 1 GHz and 8-channel oscilloscope MSO58 from Tektronix with 12bit ADCs was used. By these means full support of the probes maximum bandwidth was ensured.
As the bandwidths of probe 3 and probe 4 do not fulfill the precondition by equation 4 for the considered devices they are not evaluated in practice.
In order to be able to synchronize measurements in post-processing a full galvanically isolated trigger source was used. The switching command is transmitted via fiber-optic cable to a battery powered logic device which is directly connected to the

oscilloscopes trigger unit. Therefore switching processes can be compared in different configurations and with different measuring devices. The propagation delay of the probes is not compensated hereby. For analysis of e.g. switching losses this would be essential, compare [1].

Drain-source voltage measurement

Figure 4 shows a comparison of the falling edge of the drain-source voltage pulse of a lowside MOSFET measured by the probes 1&2. The 22 V/ns slope is reflected by both probes equally. Probe 1 shows a slightly larger undershoot. The fall time of approximately $t_f = 7.8$ ns results in a necessary bandwidth of 170 MHz according to the introduced formula 4. The DC offset of probe 2 has to be noted.

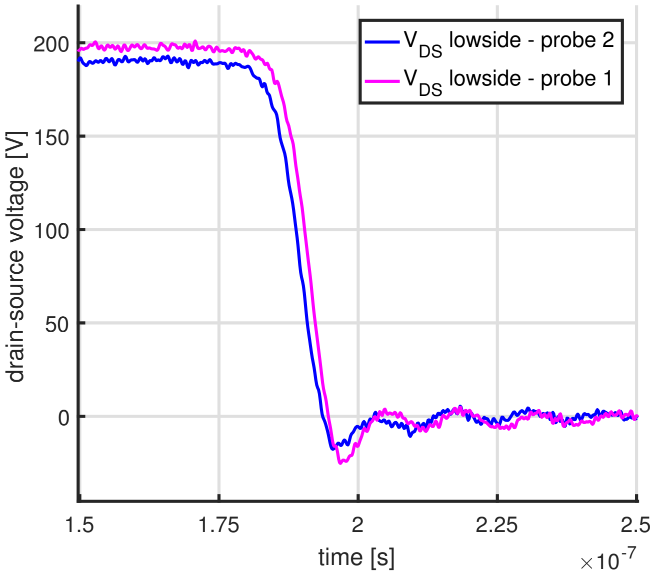


Fig. 4: Drain-source voltage comparison of the lowside MOSFET - falling edge. $V_{DC} = 200$ V

Figure 5 shows a comparison of the rising edge of the drain-source voltage pulse of a lowside MOSFET measured by the probes 1&2. The 19 V/ns slope is reflected by both probes equally. The oscillation of the drain-source voltage is captured with the same frequency, only the amplitude seems to be different due to differing DC gain between both probes.

Figure 6 shows the drain-source voltage of the lowside MOSFET during a complete double pulse. As probe 2 shows deviation in steady state from the DC voltage in all measurements an offset analysis with different voltages was done. Figure 7 displays the difference between measured and applied voltage referenced to (a) the applied voltage and (b) the sensor measurement range (500 V).

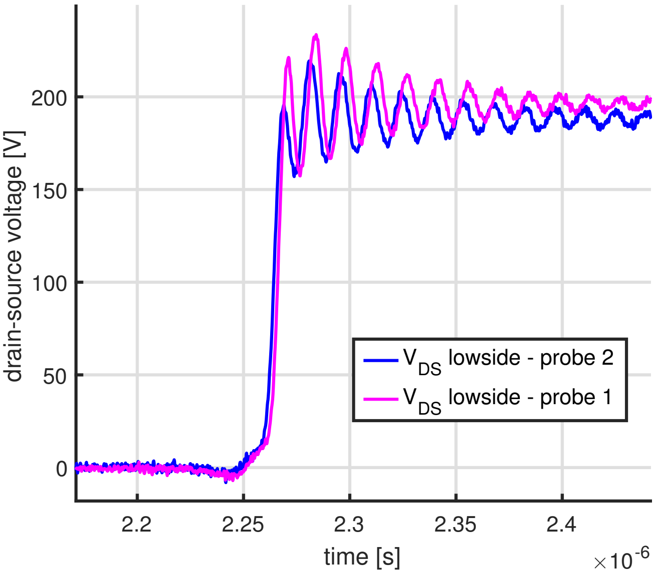


Fig. 5: Drain-source voltage comparison of the lowside MOSFET - rising edge. $V_{DC} = 200$ V

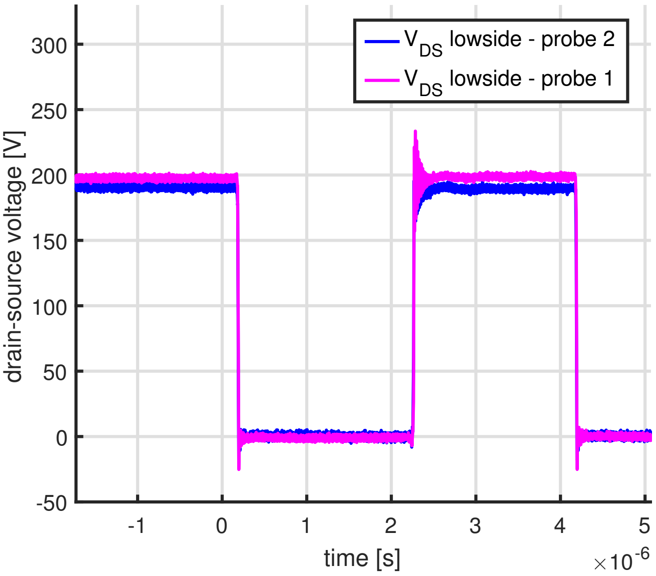
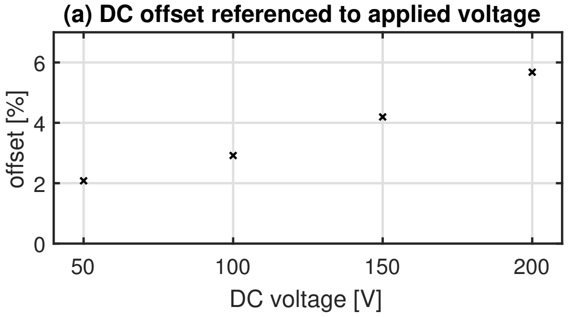
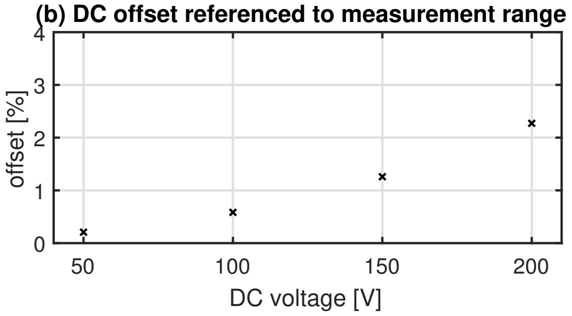


Fig. 6: Drain-source voltage comparison of the lowside MOSFET - complete pulse. $V_{DC} = 200$ V

The offset, i.e. deviation if referenced to the sensor measurement range of this prototype lies within the gain accuracy as presented in Table 1 when not exceeding 200 V DC voltage.



(a) DC offset referenced to applied voltage



(b) DC offset referenced to measurement range

Fig. 7: Offset analysis of probe 2

Gate-source voltage measurement

Figure 8 shows a comparison of the rising edge of the gate-source voltage, i.e. the switching on of the highside MOSFET. Furthermore the drain-source voltage slope of the highside MOSFET is plotted which indicates the common mode voltage introduced by the potential step.

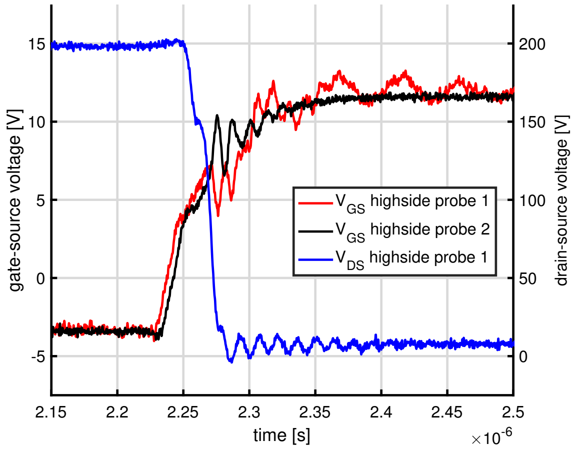


Fig. 8: Gate-source voltage comparison of the highside MOSFET - rising edge. $V_{DC} = 200\,\mathrm{V}$

Both probe 1 and probe 2 react to the potential step, however it seems like inverse behavior. Probe 1 afterwards has an overlying oscillation that ceases only slowly.

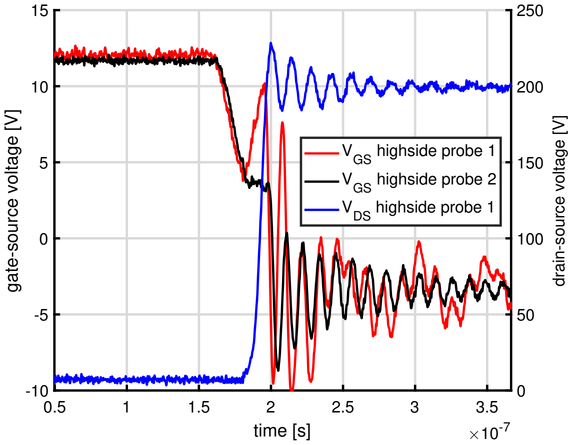


Fig. 9: Gate-source voltage comparison of the highside MOSFET - falling edge. $V_{DC} = 200\,\mathrm{V}$

Figure 9 depicts a comparison of the falling edge of the gate-source voltage, i.e. the switching off of the highside MOSFET. Furthermore the drain-source voltage slope of the highside MOSFET is plotted again which indicates the common mode voltage introduced by the potential step.

Noticeable is the strong reaction of probe 1 to the potential step which is not reflected by probe 2. As this concerns especially the Miller plateau which indicates the switching transition a precise voltage measurement is important. After the voltage has completely commutated to the highside transistor both probes show oscillation. However, probe 2 reflects the physically more probable course.

3. Conclusion

Precise voltage measurement for power electronics with high switching frequencies poses big challenges for the measurement equipment. With increasing switching frequencies and therefore steeper voltage slopes sophisticated probes are necessary. Optical isolation from the oscilloscope can bring advantages in common mode rejection ratio. There are only few voltage probes available that allow precise measurement of the steep slopes of state-of-the-art GaN transistors. The practical comparison of two state-of-the-art differential probes shows that there are significant differences in the reproduction of measured voltages. The bandwidth of the tested probes was sufficient in both cases. The significantly larger common mode rejection ratio of probe 2 resulted in less influence by potential steps, in particular when measuring highside gate-source voltages.

This paper shall give users who investigate switching processes closely an idea of the difference in the reproduction of voltage slopes by probes with similar constraints as the proposed.

References

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