Gate-Driver with Full Protection for SiC-MOSFET Modules

Karsten Fink, Andreas Volke, Power Integrations GmbH, Germany
Winson Wei, Power Integrations, China
Eugen Wiesner, Eckhard Thal, Mitsubishi Electric Europe B. V., Germany

Abstract

This paper is presenting an advanced method of full protection by the gate driver unit for a SiC-MOSFET module using its sense terminals. The presented test results are including features like an adjustable overcurrent and short-circuit detection together with a Soft Shut Down function and Active Clamping, which is reducing the occurring over-voltage spikes at turn-off actively.

1. The SiC-MOSFET Module

Today the need for highly efficient power energy conversion facilitates the introduction of full SiC-MOSFET modules, which consist of parallel-connected SiC-MOSFET and -diode chips. In [1, 2, 3, 4] a full 1200V/800A SiC-MOSFET module FMF800DX-24A by Mitsubishi Electric is presented, which is designed for high power applications in the range of several 100 kW. With this power module designers should be able to realize applications with high switching frequencies up to 100 kHz, high efficiency or high density, respectively.

Compared to Si-IGBTs today's SiC-MOSFETs offer a limited short-circuit endurance of only a few microseconds. Therefore the FMF800DX-24A offers the feature of a *Sense Output*, which provides information on the actual drain current and can be used for an adjustable detection of overcurrent or short-circuit events. Due to this function high overcurrents or short-circuits can be turned-off safely by reducing the dissipated switching energy considerably as shown in the following.

The MOSFET part of the FMF800DX-24A consists of eight paralleled 100A-chips, which are able to withstand a maximum short-circuit time of t_{SC} = 2 µs as per datasheet. For a gate driver design it might be difficult to turn-off a short-circuit safely within this limited time without being too sensitive triggering falsely a short-circuit shut-down during normal switching operation. With this motivation an advanced method for overcurrent and short-circuit detection was derived.

The FMF800DX-24A offers a separate source area which acts like a current-mirror to the main source terminal and provides a sense current i_{Sense}, which is proportional to the drain-current i_D. The equivalent circuit is given in Figure 1. The characteristics of the sense output can be taken from [4]. This sense current can be transformed via a shunt resistor R_S to a voltage signal, which is ready to be be evaluated back into the information of the actual current value. This can be used to realize an overcurrent or short circuit protection.
The gate of the FMF800DX-24A can be controlled with +15V/-10V, which are commonly used voltage levels to control IGBTs.

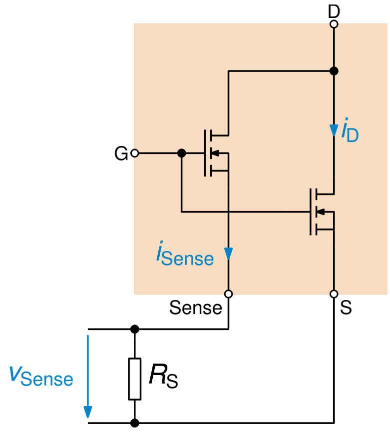
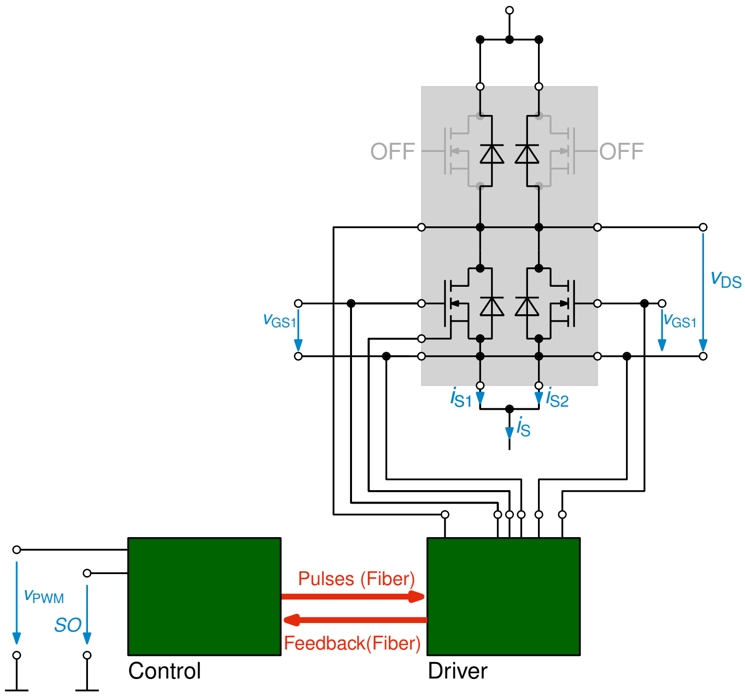


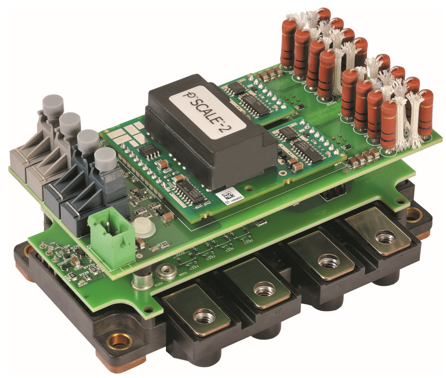
Fig. 1: Sense Output

2. Gate Driver for FMF800DX-24A

The proposed driver circuit as depicted in Fig. 2(b) provides - besides the well known condition of the Gate-Source voltages, an *Active Clamping circuit* and dv/dt-*Feedback* as described in [5, 6] - a circuitry for evaluating the sense output between the connectors *Sense* and *S* of the SiC-module (Fig. 1). By this the driver is able to measure the actual value of the drain current and thus shut-down overcurrents. The overcurrent limit is programmable by selecting the appropriate values of the sense resistor R_S. Thus a combination of power module and driver is obtained, which virtually can't be damaged by electrical parameters such as overcurrent and over-voltage.



(a) ESB



(b) Assembly of Driver board on module

Fig. 2: SiC-Module with attached Driver

The equivalent circuit of the FMF800DX-24A and the relevant parameters for testing the bottom switch of this setup are shown in Fig. 2(a). The block *Control* converts the PWM voltage signals into optical signals for the fiber-optic interface of the driver. On the other hand the status feedback fiber-optic signal is converted into the electrical signal *SO*. The main function of the block *Driver* is explained with Fig. 3. Here the *Over-Voltage Detection* is realized with a chain of TVS diodes that feeds into the gate and additionally gives a feedback to the ACL-pin of the gate driver core 2SC0435 in case of drain-source-voltages higher than a static value of approximately 900V during the turn-off transient. The dynamic peak value of the resulting drain-source voltage during turn-off is always a bit higher due to the response time of the TVS chain. A chain of capacitors in series connection are provided for a dv/dt-feedback from Drain to Gate. For the following measurements it is not used but can be helpful to reduce the maximum drain-source-voltage slope for instance in case of the over-voltage detection is not responding fast enough. As a dv/dt-feedback implies additional losses it should only be implemented if needed.

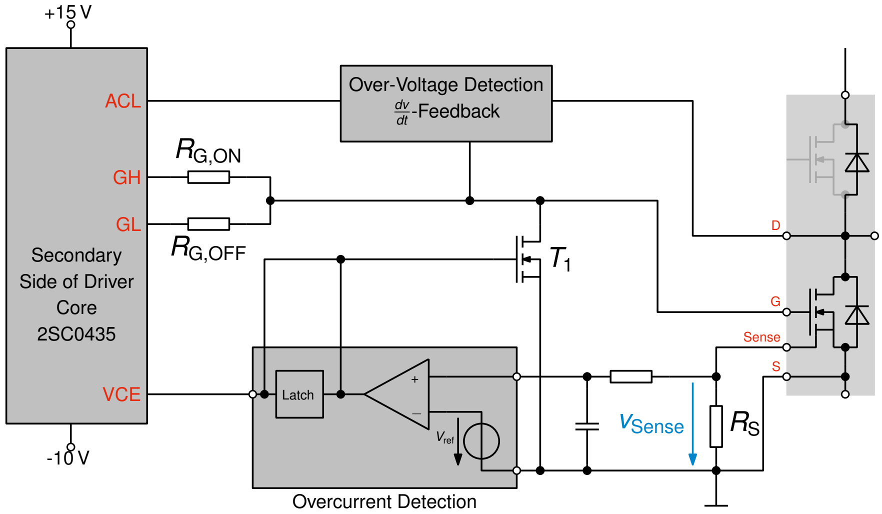


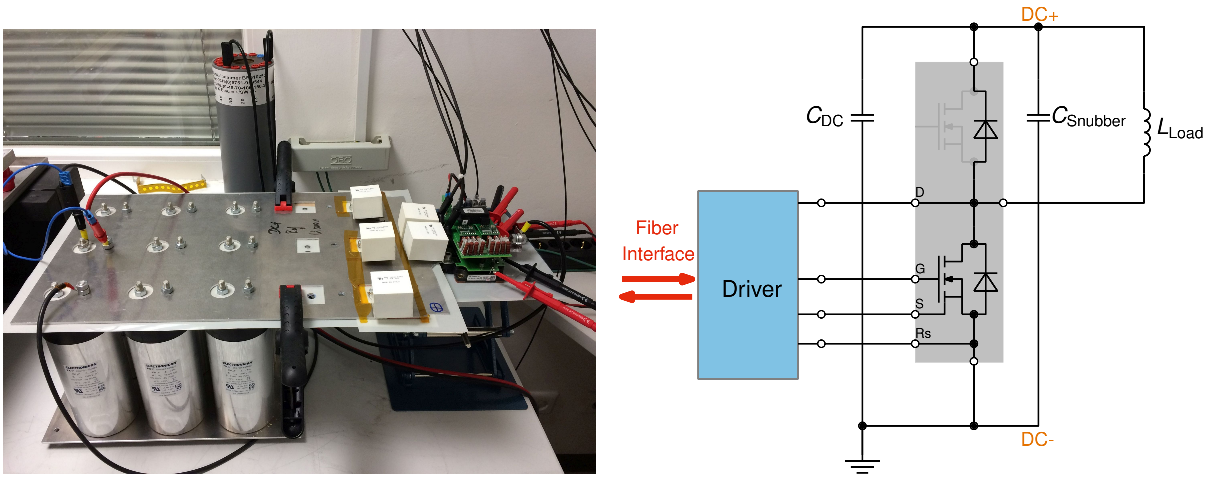
Fig. 3: Equivalent Circuit of the Gate Drive for the Bottom Channel of a PI Driver Core

The proposed overcurrent-protection is measuring the voltage across the shunt resistor R_S and compares it with a constant reference value. If the actual value is higher than the reference, the MOSFET T_1 between Gate and Source of the FMF800DX-24A is turned-on over a large gate resistor value, which keeps the level of the turn-on resistance of the MOSFET relatively high. Thus a *soft* discharge or *Soft Shut Down* (SSD) of the SiC-Gate is realized. By this the drain-current slope is reduced and thus the over-voltage peak during turning-off over- or short-circuit currents. In order to avoid an turn-on/turn-off oscillation of the transistor T_1 the output signal of the comparator is additionally latched. The constantly existing noise in power electronic circuits is filtered by a low-pass at the shunt resistor R_S. With this circuitry an adjustable over-current protection is realized.

3. Measurements

3.1. Test Setup

In order to prove the switching behavior of the gate-drive unit in combination with the FMF800DX-24A the bottom MOSFET is double-pulse tested in a well known buck-converter topology as shown in Fig. 4(b). Turning constantly off the top switch of the half-bridge, provided by the FMF800DX-24A, the built-in diode gives the freewheeling path for the load inductor $L_{Load} \approx 30\,\mu H$. For an optimized stray inductance value of the commutation loop additional snubber capacitors are mounted between DC+ and DC- as close as possible to the SiC-module. The measurement signals depicted in Fig. 2(a) are measured with differential probes and current transducers, respectively. For the half-bridge configuration of the FMF800DX-24A gives no access to the drain current i_D the source currents $i_S = i_{S1} + i_{S2}$ are measured instead. Fig. 4(a) shows a photograph of the setup with attached measurement equipment.



(a) Photo (b) Equivalent Circuit

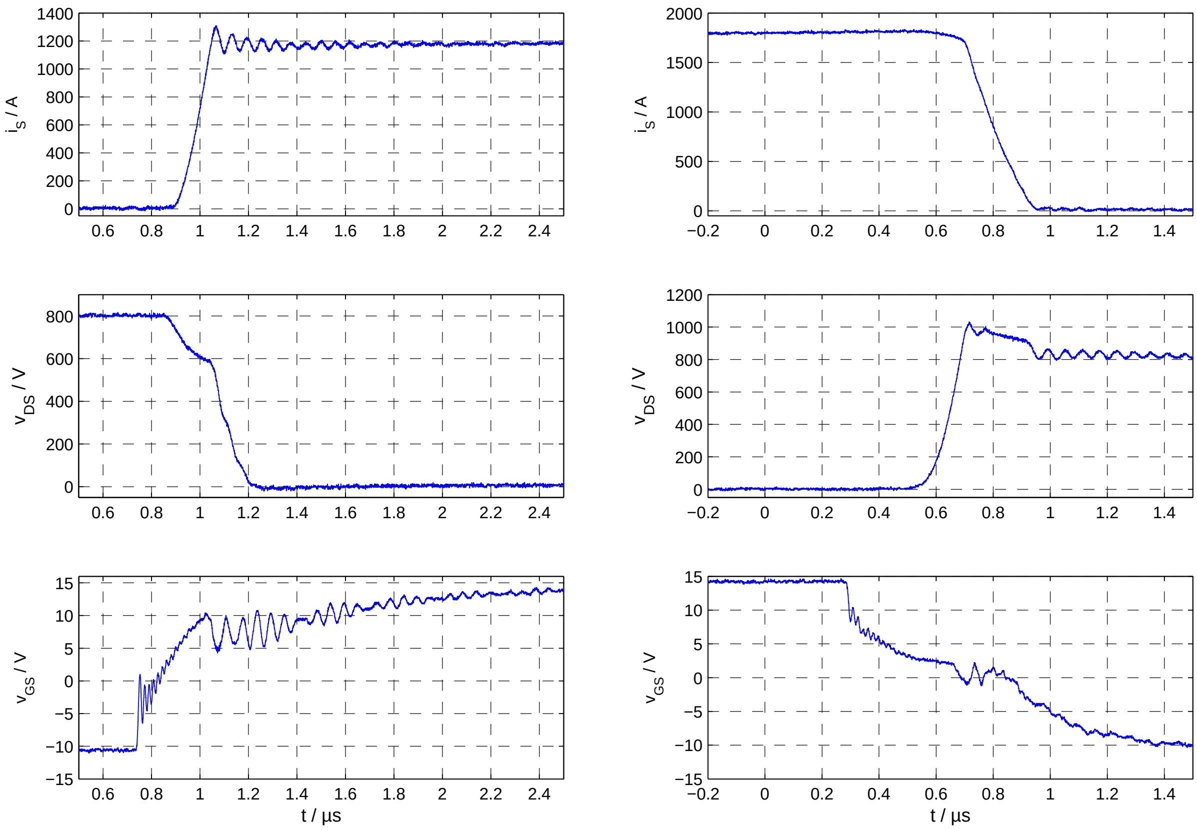
Fig. 4: Setup for measurement of switching transients

3.2. Switching without SSD

The normal switching behavior of the FMF800DX-24A with the proposed gate driver is shown in Fig. 5, where Fig. 5(a) shows the turn-on transient at V_{DC} =800V, I_D =1200A with a turn-on resistor value of $R_{G,ON}$ = 2.5Ω. Here the very fast reverse-recovery behavior of the SiC-Diode is obvious. The turn-off transient at V_{DC} =800V, I_D =1850A in Fig. 5(b) shows the functionality of the incorporated Active-Clamping circuitry, which works properly even for SiC-MOSFETs. The drain-source voltage is limited to approximately 1000V. In the time interval t = 0.7 µs ... 0.8 µs the driver keeps the SiC-gate within the active region thus it is reducing the drain-current slope. If a lower limitation of the drain-source voltage is needed the on-board provided dv/dt-feedback can be activated taking into account that it will lead to higher turn-off and turn-on switching losses.

3.3. Soft Shut Down (SSD)

Activating the SSD functionality makes it possible to reduce the maximum switchable current for the FMF800DX-24A. In Fig. 6 the behavior during turn-off and turn-on at V_{DC} = 800V with R_S = 33Ω is documented. In order to check the current-limit value for each value of the shunt resistor R_S the load current is increased step by step. In Fig. 6(a) the reference trigger (t = 0 µs) is provided by the PWM-input signal and kept constant for better comparison. The blue lines are showing the normal switching behavior without SSD. If the current is slightly increased the driver starts detecting the programmed overcurrent of approximately 1400A and initiates the SSD. Thus the green lines compared to the original blue ones are shifted to the left. Here the



(a) Turn-On at V_{DC} = 800V

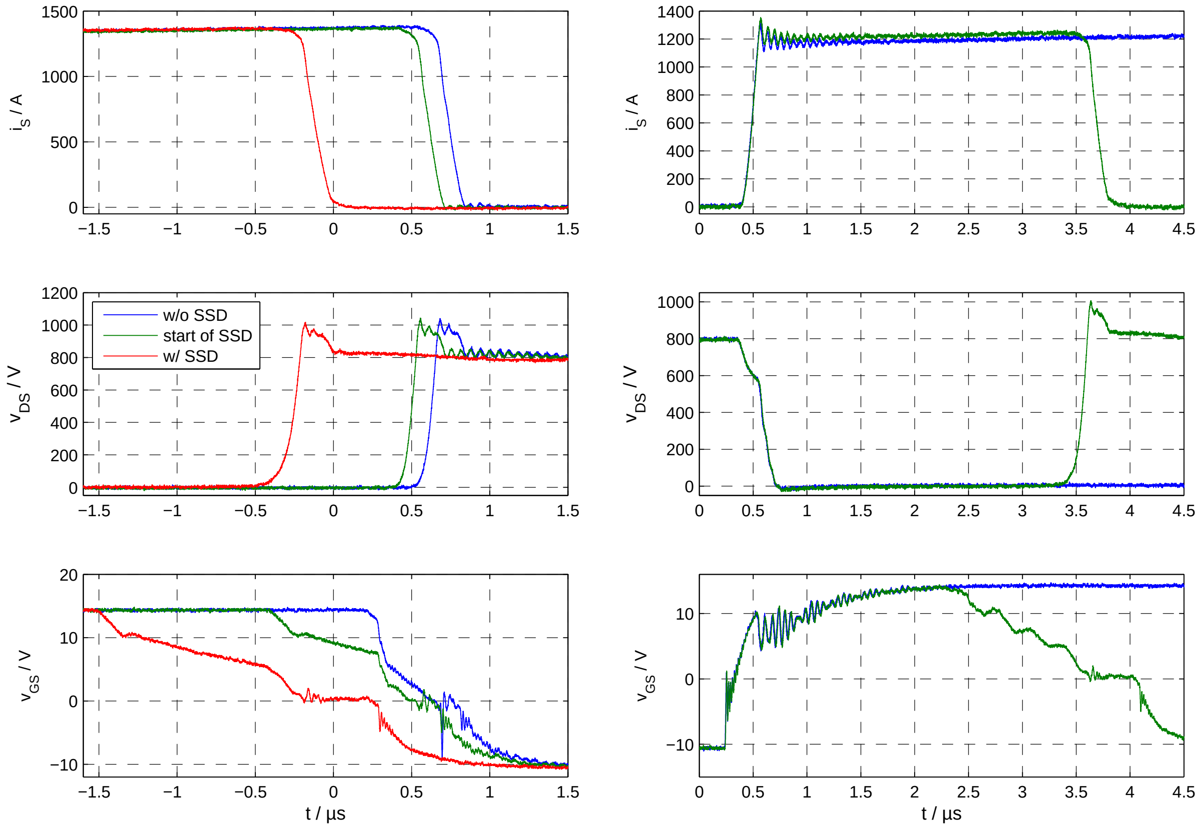
(b) Turn-Off at V_{DC} = 800V

Fig. 5: Waveforms of switching transients without SSD

gate voltage v_{GS} starts to show a soft turn-off behavior that is obvious in the reduced slope between the +15V-level to the Miller-Plateau. An even higher current that is detected by the sense circuit leads to the behavior shown with the red lines. Here the driver itself turns-off the current 1.5 µs before the original turn-off signal at t = 0 µs. The SSD-MOSFET is discharging the gate very slowly. The Active-Clamping functionality is needed to keep the over-voltage withing the desired limit of 1000V. Active Clamping can however be omitted if the SSD MOSFET behavior is slowed down.

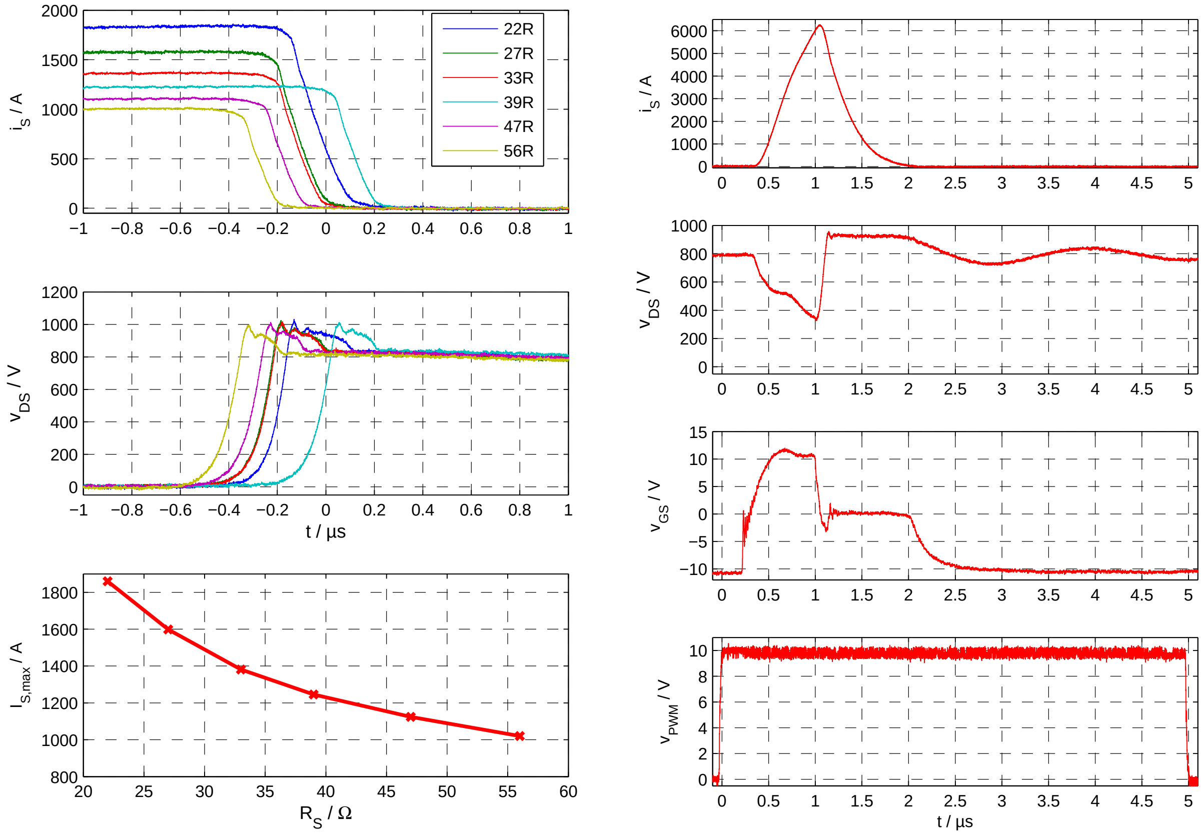
In Fig. 6(b) the driver turns on normally but close to the programmed limit. The blue line shows the normal behavior without SSD whereas the green line shows that the driver interrupts the turn-on command by itself because of the reached overcurrent limit at approximately 2.5 µs. This indicates that the SSD functionality works independently from the driver logic state and is permanently at guard protecting the SiC MOSFET in an overload situation.

The overcurrent detection can be programmed by selecting the shunt resistor R_S. Fig. 7(a) shows the waveforms and the resulting maximum current as a function of the value of R_S. For the waveforms the point in time t = 0 µs is again the trigger point of the PWM input signal. Evaluating the maximum of the drain current waveforms i_S leads to the graph of $I_{S,max} = f(R_S)$ at 25 ℃. In comparison to [4] here the response time of the SSD-circuit is incorporated. For resistor values higher than 56Ω the signal-noise ratio of the detection circuit becomes very small. Thus the SiC-module might not be switchable anymore as every noise is detected as overcurrent.



(a) Stepwise SSD before Turn-Off (b) Turn-On with and without following SSD

Fig. 6: Waveforms of switching transients with SSD at V_{DC} = 800V with R_S = 33Ω



(a) Turn-Off with various R_S at V_{DC} = 800V (b) Short-Circuit at V_{DC} = 800V, R_S = 33Ω

Fig. 7: Behavior of SSD

Switching on a hard short-circuit (type I) realized by a short metal connection leads to the waveforms in Fig. 7(b). Here the shunt resistor value is 33Ω. The current rises to a maximum value of around 6 kA before it is shut down successfully by the overcurrent-detection circuit. The overall short-circuit time[1] is 1.2 µs and thus below the limit of 2 µs. During the negative slope of the source current the Active Clamping circuit is additionally protecting the SiC-MOSFET against over-voltages by keeping its gate in the active region. The slight oscillation after t = 2 µs is caused by the snubber capacitors, which exchanges energy with the main DC-link capacitors. The input PWM signal v_{PWM} shows that the driver ignores the switching command of the superior control, which is 5 µs long, in order to protect the SiC-MOSFET.

4. Conclusions

The presented gate driver design offers a full control of the SiC-MOSFET module FMF800DX-24A with features like overcurrent/short-circuit detection and shut-down and an overvoltage protection with Active Clamping. With this the FMF800DX-24A is safely operating under nearly any electrical condition. Measurement results of a double-pulse test at room temperature were presented. The proposed gate driver will be part of the upcoming reference design RDHP-1417 by Power Integrations.

5. References

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[1] Determined from 10% to 10% of the maximum short circuit current.