Condition Monitoring Approach of a SiC Power Semiconductor using Turn-Off Delay with an Integration in a SiC Driver

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Abstract

This paper deals with a condition monitoring approach based on the turn-off delay measurement and its integration in a SiC driver to measure the temperature-sensitive parameters in a continuous switching operation of a SiC power semiconductor. The presented approach requires a small area for integration and can be implemented with little effort.

Introduction

With the increasing demand for highly efficient power conversion systems, especially in the field of e-mobility and renewable energy, modern power semiconductors such as SiC and GaN are gaining in importance. Due to their small size, the modern semiconductors enable the development of high-speed switching and compact systems. This creates an additional demand for small state of health monitoring systems for wide bandgap semiconductors, which can significantly increase the operational reliability and reduce maintenance costs. The detection of a fault or the predicted service life of a power module can protect both higher-level systems from damage and the user from injury [2] [6]. In addition, it enables the user to perform predictive maintenance.

Often a higher working temperature is used as an indicator for a not optimal functioning semiconductor. Temperature changes are well known as an indicator of degradation processes in a power semiconductor. They are mainly caused by the thermomechanical effects in the layer assembly under the chips and the connections. The power cycling in a power module leads initiation and propagation of fractures in the solders and generate metallurgical damage to wire bonds and emitter metallization [7]. A common approach for condition monitoring systems is the measurement of the temperature of the semiconductor itself or dependent electrical parameters [3]. For common state of health monitoring systems of a semiconductor, various variables such as currents, voltages, resistances and temperatures are measured in real time. Other condition monitoring systems are using dynamic parameters such as switching gradients and time delays of a semiconductor which is a particular challenge [8][9]. The approach to determine a parameter is individual and requires technical effort which is depending on the method and the area of application. For example, high-resolution analog-digital-converter (ADC) and high-speed digital signal processor (DSP) are often used for condition monitoring based on the switching characteristics of the semiconductors. The cost for solutions of this kind can make such a system uneconomical.

This paper presents a possibility to detect the temperature changes of a semiconductor by integrating a turn-off-delay-based circuit into a SiC driver using a Time-to-Digital-Converter (TDC). The turn-off delay time is measured as a function of the chip temperature respectively of a switch and the drain current of a SiC semiconductor using a self-built driver. The main aspect of this measurement is the use of the TDC device, which measures the time between the input and the output of the turn-off edge of a semiconductor with a high resolution.

Basic Measurements

One possible dynamic method for monitoring the temperature change behavior of a semiconductor is the turn-off delay measurement [1]. It has been proven that the change in turn-off delay is directly related to the chip temperature and the drain current through the chip. This relationship arises from the temperature dependence of the parasitic capacitances of the SiC semiconductor. The main parasitic capacitances of a SiC semiconductor are C_{GD}, C_{DS} and C_{GS} (see fig. 1). The first two of the three parasitic capacitances are mainly responsible for the temperature dependence of the turn-off delay [4]. The following measurements in fig. 1 clearly show a correlation between the turn-off delay of a SiC semiconductor, the chip temperature and the drain current. The setup for the measurement of this experiment is based on a double-pulse experiment. The SiC semiconductors were heated from the outside using a heating plate. All signal traces were triggered to the same gate signal. A change in temperature of 150 °C causes a turn-off delay of 30 ns [1].
The effect described above can be used as a condition observer for online monitoring of a SiC-MOSFET. As already mentioned above, a significant change in the chip temperature is often an indicator for a degradation of the semiconductor.
The technical prerequisite for the use of the measuring system based on the effect described above is the temperature insensitivity of electrical components. Furthermore, the results achieved have no absolute reference point and can only be evaluated in reference-free systems. This is required because of the variation of values of the parasitic capacitances of such SiC MOSFETs depending on the manufacturer and the manufacturing processes.

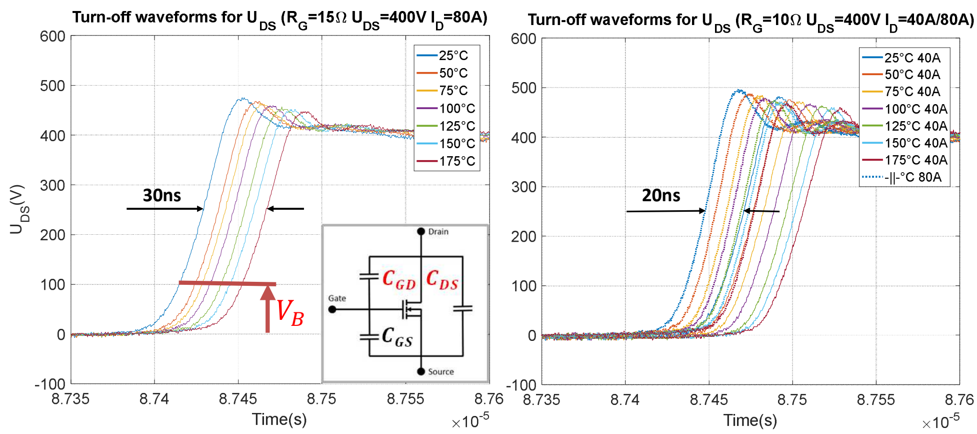

Fig. 1: Turn-off delay dependence on the temperature and drain current in the SiC semiconductor (C2M0025120D) [1]

It should be mentioned that the turn-off delay depends additionally on other parameters such as the gate resistance of the drivers, which are not always related to the chip temperature. Therefore, it is recommended to use gate resistors with a low temperature coefficient for such applications. In this way, the temperature drift can be reduced.
Another challenge to describe the temperature change of the semiconductor using the effect described above is the voltage and current dependence. The separation of these dependencies from each other in a practical application of the described effect is described in further chapters of this paper.

Measurement Circuit and Setup

This chapter describes the circuit for measuring the turn-off delay based on a TDC module. The TDC module measures the time between the turn-off edge of the trigger signal (driver) and the drain-source voltage. Most TDCs work with a Transistor-Transistor-Logic (TTL) and for this reason the level must be adjusted to the TTL level [5]. The main requirement for such a circuit is to transmit the measured drain-source voltage to the input of the TDC device without any loss of information. Therefore, the signal has to be reduced in the amplitude and protected against distortion.
The drafted interface circuit shown in the center block of fig. 2 consists of the following components:

- high voltage blocking diode circuit,
- filter
- impedance converter
- voltage divider

The high voltage blocking diode circuit with an integrated voltage source ensures that the high drain-source voltage of the switch is cut of at the level of the blocking voltage V_B. In fig. 1 we can see that not all positions of the switching edge signal are suitable for measuring the time delay because of the non- linear signal in the lower and upper areas. The blocking voltage should not be selected too small in order to remain in the linear range of the turn-off edge.
When the power semiconductor is switched on the diode D_1 conducts and the drain-source voltage is measured via the input impedance converter. It should be mentioned that the input impedance converter, used in the circuit, is made up of J-FETs. This is a cheaper approach for an alternative impedance converter based on an operational amplifier with a low input capacitance. The fig. 2 shows the schematic measuring principle of the system [1].

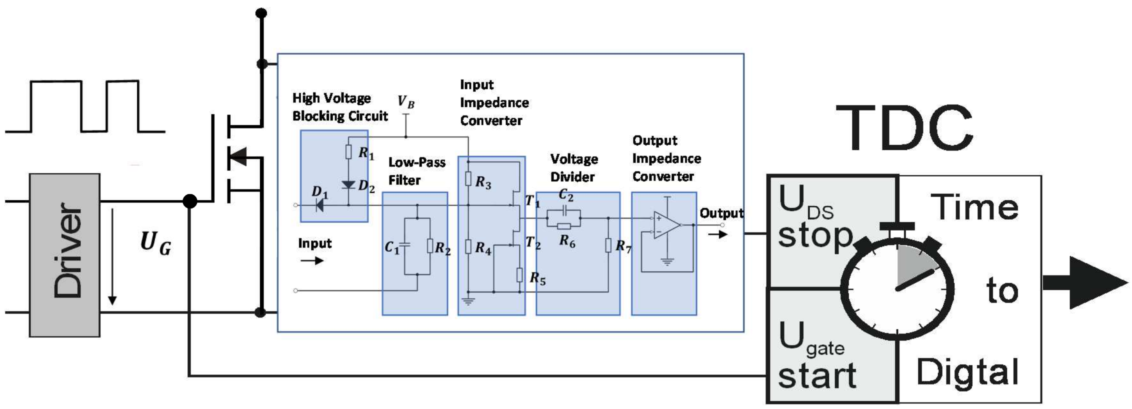

Fig. 2: Block diagram of the turn-off delay measuring system

The turn-off delay measuring system described above has been integrated into a SiC driver. A driver circuit is located on the top side of the board and the TDC measuring circuit is placed on the bottom side (see fig. 3c/b). The integration area of the TDC measuring circuit is approx. 2 cm^2 and is located directly at the high-voltage side. As shown in fig. 3, the circuit is decoupled from the low voltage side via a digital isolator. The communication with the TDC module is implemented via a serial interface. The power supply is also implemented with an isolated 2.5W DC/DC converter in a small package. The layout of the individual component groups can be found in fig. 3a.
The time to digital converter module TDC7200 from TI is used for the time measurement. This device has an internal self-calibrated time base which compensates the drift over time and temperature. Self-calibration enables the time-to-digital conversion accuracy in the order of picoseconds [5].
The driver itself is based on the UCC217100 chip and is a fully integrated SiC driver for a half bridge topology.

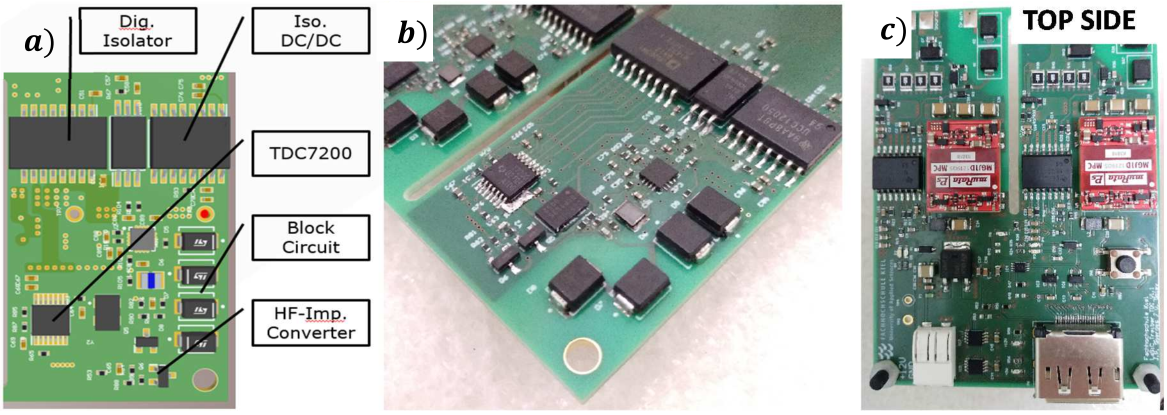

Fig. 3: Driver with TDC measurement circuit

The measurement tolerance with the presented TDC driver becomes smaller if the stop signal is interference-free and properly prepared for the measurement with TDC. In addition, the measurement tolerance increases proportionally with the increase of the drain-source voltage. For this reason, it is important to design the input of the interface circuit with as little capacitance as possible. The circuit shown in this paper was developed based on an active probe.
A SiC full bridge with power semiconductors has been set up to test the developed driver with the TDC-based measurement system. The complete measurement setup is shown in fig. 4. The central part of it consists of a heating plate which enables the heat up and cooling of the semiconductors independently of the drain current and the DC-link board which carries the SiC power modules. The setup has operated with an inductive load and the current has been measured by using a current probe (I-Prober 520). The turn-off delay time has been measured across of all four semiconductors by using two half-bridge drivers each with two TDC measuring circuits. The two SiC power modules are attached below the DC-link board and are thermally coupled to the heating surface via a heat-conducting pad. A phase shift control is implemented on a Aurix TC277 microcontroller board to control the semiconductors. The evaluation of the measurement results and reading out the TDCs is also done with the Aurix. In addition, a fan was used to cool the driver.
The Temperature measurement in this measurement setup is realized by several NTC resistors, which are placed close to the SiC semiconductors. The values of the read-out temperature are processed directly into the test rig software via the microcontroller.

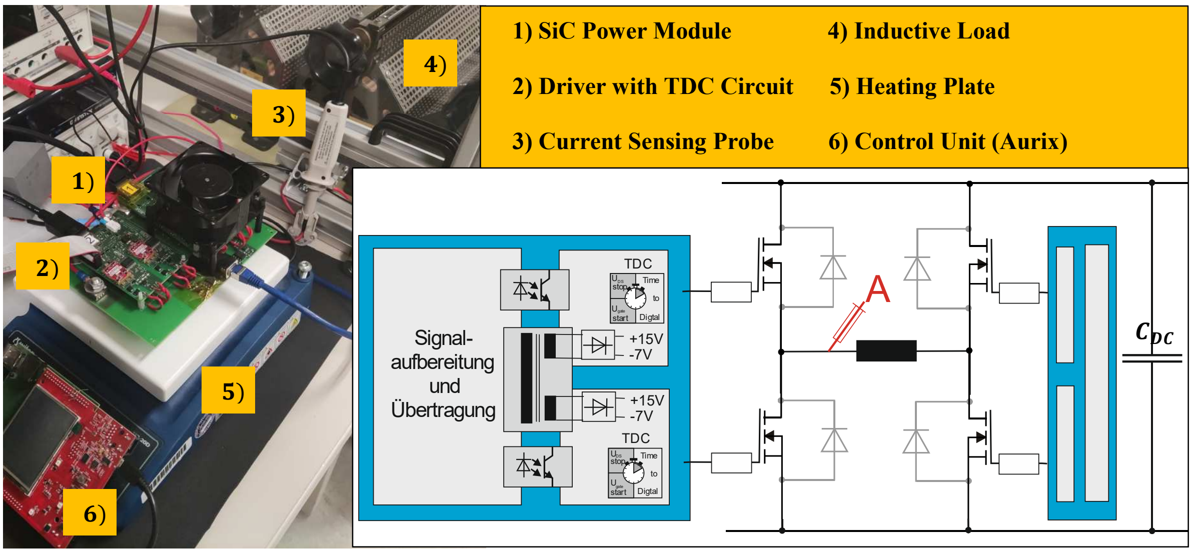

Fig. 4: Turn-off-delay measurement setup realized using the SiC full bridge with the delf-developed driver

The measuring process on the measurement setup is as follows.
The value of the current value which flows through the measured object (semiconductor) is set via the adjustable load or phase shift between two half-bridges. If the phase shift and the load remain the same for several periods, the same current remains the same for every turn-off edge. In this way, the temperature can be adjusted with the heating plate independently of the current. This TDC measurement setup can record the turn-off time delay either continuously on every turn-off edge or on demand.

Measurements

This chapter analyses the results of the measurement. The TDC driver is tested on two different systems. The measurements on the full bridge are made over several periods with a constant current and a small amplitude of up to 5 A_{PK}. In this way, the self-heating of the power module was minimized by the losses. The driver was then put into operation on a frequency converter system.

Validation of the system on a full bridge

The fig. 5 shows the turn-off delay recorded with the developed driver in the measurement setup on the full bridge as described above. The temperature measured by the NTC resistor with uniform heating over a longer time period correspond to a mean chip temperature and is not the junction temperature. Temperature measured in this way is nevertheless directly related to junction temperature. The diagrams in fig. 5 show the dependency of the turn-off delay to the chip temperature with variation of the current in the range from 1 A_{PK} to 5 A_{PK}. Here, the variant a) shows the nearly linear temperature dependency and variant b) shows the non-linear dependency on the current. This means that the current and the temperature have different influences on the turn-off delay time in terms of linearity.
This measurement has been recorded with a measurement accuracy of $\pm 250\ ps$. Changing the temperature by 10 °C causes a turn-off delay of approx. 4 ns. This results in a measurement tolerance of approx.1 °C.
In contrast to the temperature dependency, the current dependency is more significant, especially with small currents. As the current increases, the turn-off delay saturates. For the practical application of the effect, this means that the temperature-dependent measurement should be carried out at a high current. In this case the temperature dependence will dominate over the current dependence. In this way, the measurement accuracy of the turn-off delay can be increased as a function of the chip temperature.

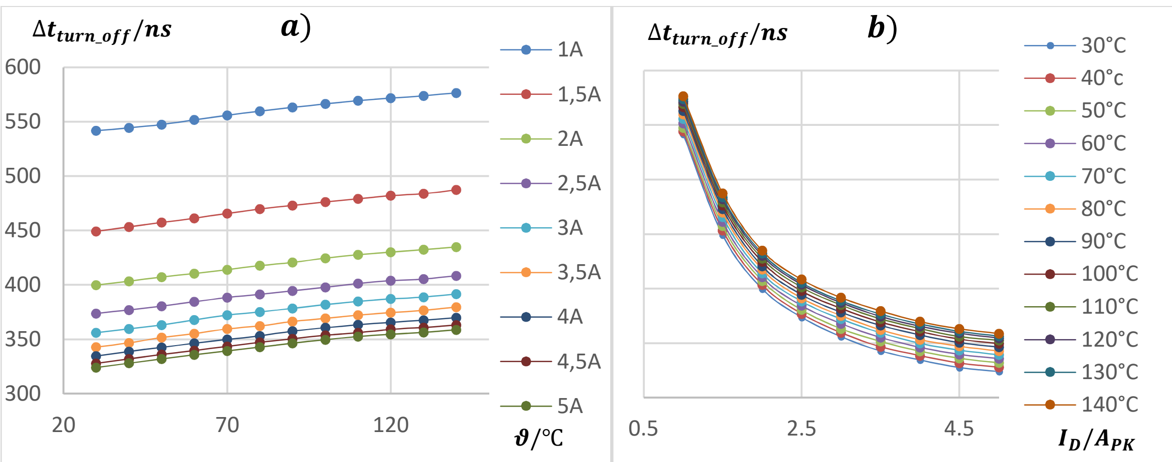

Fig. 5: Turn-off delay measurement on a H-bridge made of SiC power semiconductors with an inductive load (V_{ds} = 100 V)

Revalidation of the system in a 3-phase frequency converter

A 3-phase SiC frequency converter was used to test the measurement electronics on the frequency converter during operation. This measurement setup is designed for the use of the designed drivers with the TDC measuring system. To process the measurement data, a software has been developed and implemented on the microcontroller (Aurix) together with a software for the control of the converter.

The converter system has been operated with an inductive load and a ventilated heat sink. The drivers were also cooled with a fan. In the ideal case, the control electronics should be thermally decoupled from the semiconductors to minimize the thermal feedback into the driver circuit. Such a decoupling cannot be realized in a practical application. To minimize this effect, heat-insulating materials have been used in combination with a thermal management.
The following measurement in fig. 6 has carried out on converter system under load. The measurement was recorded at a current switching frequency of 1 kHz over 2.5 periods. The measured values cannot be recorded with every switching process. This is because the current does not flow through the same switch with every switching process in a half bridge operation. The current flows through different switches every second period or, due to the dead time, the current flows through the body-diode. In these cases, the turn-off delay of the measured switch is constant or not defined.

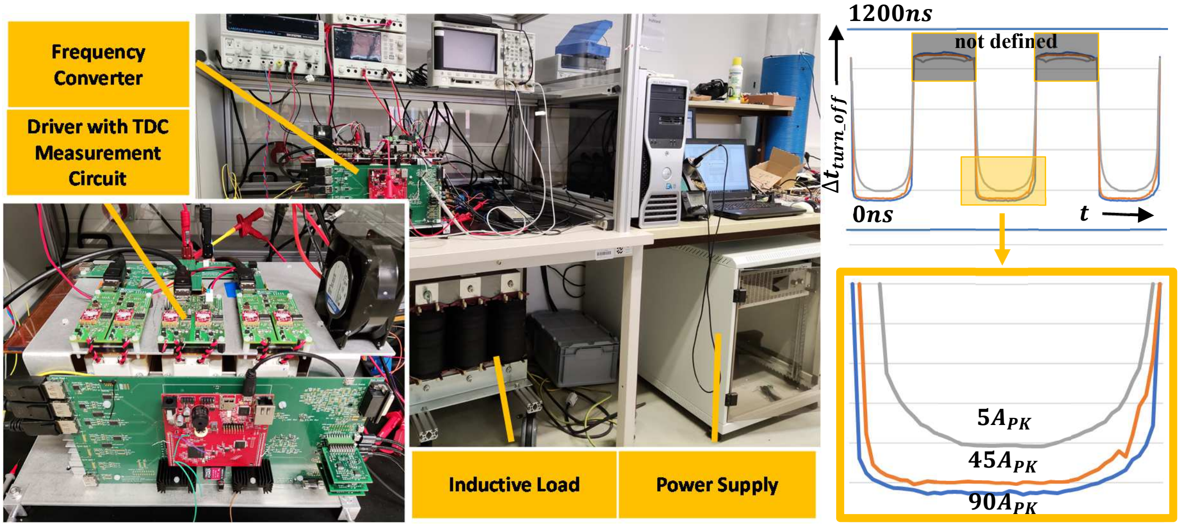

Fig. 6: Turn-off-delay measurement and measurements setup in frequency converter operation

For technical reasons, it was not possible to record the temperature during this measurement. However, the results do correlate with the measurements in a full bridge. It can be seen, that the turn-off delay saturates with large currents. It must be considered that large flowing currents cause additional heating of the SiC semiconductor due to losses at the on-resistance. Therefore, it is assumed that the current has a quadratic dependency on losses [10].

$$P_{loss} = P_{sw} + {I_{D(on)}}^2 \cdot R_{DS(on)} \cdot D_{Duty\ Cycle} \qquad (1)$$

Another aspect that influences the turn-off-delay measurement in a converter system is the cooling system. This means that such a curve as in fig. 5a for the temperature dependency is not possible with a conventional converter due to the cooling capacity of the cooling system and the AC current. The heating and cooling process of a cooled semiconductor are different in their slope. Based on the difference in the slope of the warm-up and cool-down phases the influence of the thermal capacity of the cooler becomes visible in the measurement (see fig. 6) [11].

Evaluation of the measurement Results

The main idea of this paper is to realize a state of health monitoring of a power module. The practical application of the measurement system presented to determine the absolute chip temperature is

difficult by various factors such as current dependencies. The application of the turn-off delay measurement system to a power module or a half-bridge due to the same manufacturing and operating conditions as the same cooling system or the use of the same chips minimizes the effects that cause the scattering of the measurement results. The temperature drift of electrical components such as the gate resistor also has an impact on the charging time of the parasitic capacitances in a power module. In a power module both switches are usually controlled by the same driver board with the same gate resistors. This allows a direct comparison between the high- and the low-side switches with regard to the temperature-sensitive switching characteristics.
The turn-off delay time must be measured and evaluated for high-und low side switches periodically at the same current level. A significant difference between two values indicates the malfunction of a switch respectively a power module. The method can also be applied to a full bridge, half bridge, B6 module or multi-level converter systems. These values must be recorded for all semiconductors within a system and compared with each other. The accuracy of the measurement increase with the number of observed switches and the failure of a single switch can be predicted more accurate.

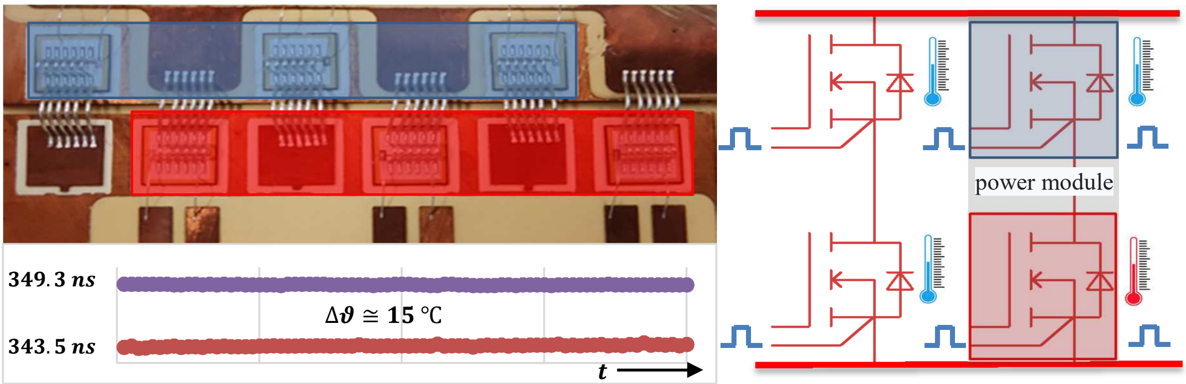

Fig. 7: Temperature comparison between the upper and the lower semiconductor inside a SiC power module

To prove the function of the method, the switches in a half-bridge of a power module were heated to different temperatures. This represents the same effect which would occur during an error state. In this case, both switches had a temperature difference of 15 °C. The tests were carried out in the measurement setup shown in fig. 4. The tested power module consists of a half bridge with 3 chips in parallel per switch. The results for such a measurement can be found in fig. 7. The set the temperature difference of 15 °C between the high- and low-side switch has been measured and validated in continuous mode of operation in the full bridge setup.

Conclusion

As part of this work, a measurement system based on the TDC module was presented. In addition, the measuring circuit was implemented in a SiC driver and tested on two different systems. The measurements have shown that the measuring principle as well as the measuring system itself represent a functioning condition observer for a temperature-sensitive parameter while the converter is in operation. It was metrologically demonstrated that the system can measure temperature differences between two switches within a power module. Using this measurement method can be developed within a frequency converter or energy converter. Malfunctions of a switch can be detected based on turn of delay time differences for example between switches in a half bridge configuration.
The measuring circuit itself is compact and inexpensive and can be implemented in small areas without great effort.

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