An Accurate Calorimetric Method for Measurement of Switching Losses in Silicon Carbide (SiC) MOSFETs

Anup Anurag[a], Sayan Acharya[a], Yos Prabowo[a], Ghanshyamsinh Gohil[b], Hulgize Kassa[a] and Subhashish Bhattacharya[a]
[a]Department of Electrical and Computer Engineering, North Carolina State University, Raleigh, NC, USA.
[b]Department of Electrical and Computer Engineering, University of Texas at Dallas, TX, USA.

***Abstract*—An accurate measurement of switching losses in SiC MOSFETs is necessary in order to design and evaluate the thermal performance of modern converter systems. Conventionally, electrical measurement methods, such as the double-pulse test (DPT) are used for calculating the hard-switching losses. However, with the advent of wide-bandgap devices, which have fast switching transients, it is rather difficult to capture the waveforms accurately during switching transitions, and consequently the measurement of switch loss suffers. This paper presents an accurate calorimetric method for measuring the switching losses. The conventional calorimetric measurement methods can accurately measure the device losses. However, the segregation of the conduction, turn-on and turn-off loss is not possible. This paper addresses this issue and proposes a method that can be used to determine individual loss components. The calorimetric test setup is described and a novel modulation scheme is introduced which enables the separation of turn-on and turn-off switching losses. The experimental test setup has been built and the method has been verified by measuring the losses of a Wolfspeed CMF10120D device.**

Keywords*—Calorimetric Methods, Conduction Losses, Hard Switching Losses, Semiconductor Devices, SiC MOSFET, Silicon Carbide, Switching Loss Measurement

I. Introduction

The efficiency of a power converter system is one of the critical criteria for modern converter systems. The losses in the devices acts as the main yardstick in determining the thermal solution and consequently, affects the cost and power density of the entire system. In addition, incorrect loss measurements (especially when the loss measurements are less than the actual losses) affects the reliability of the devices, thus, leading to premature failure [1], [2], [3], [4]. It is henceforth critical to accurately calculate the losses in the device, which comprises of conduction loss and switching loss. Several techniques have been proposed in the literature to accurately calculate the conduction losses in the devices [5], [6]. Calculation of the on-state resistance, and consequently the conduction loss is also provided in the literature [7], [8], [9] In order to calculate the switching losses, electrical measurement methods such as the double-pulse test (DPT) is widely used [10], [11], [12]. The DPT offers many advantages which includes short measurement times and eliminates the need for continuous operation. However, it is prone to measurement errors. The measurement errors arise primarily due to improper deskew between currents and voltages, limited bandwidth of the probes, from measurement distortion due to common mode, from the type of acquisition used by the oscilloscope etc. In addition, the post-processing of the measured waveforms is very critical [13], [14]. In addition, if the DPT is not done correctly, it leads to high inaccuracies in the measurements. Also, the DPT needs high-bandwidth measurements of the voltage and current waveforms of the device under test. This makes it necessary to add an additional current measurement circuitry (high bandwidth measurement) in the circuit which leads to additional inductance in the dc-link path and thus change the actual losses. The opposition method [15] eliminates the high bandwidth measurement issues by measuring the total losses in the system. However, the segregation of the losses still remains as a challenge.

In contrast to electrical measurements, calorimetric measurements determine the total losses in the device during continuous operation. The heat dissipated by the device (or the temperature) is measured and since the transient is very slow, higher measurement accuracies can be obtained [16], [13]. While the calorimetric method seems attractive for getting accurate results, post-processing of the results is required in this case also. In order to obtain the switching losses, the conduction losses needs to be subtracted from the total losses. This calls for accurate estimation of conduction losses too. In addition, it is difficult to separate turn-on and turn-off losses using calorimetric measurements. However, unlike the electrical measurement techniques, the post processing is done using exact data points and does not depend on time-dependent waveforms. Various calorimetric loss estimation methods have been discussed in the literature [13], [14], [16]. In [17], a calorimetric method is proposed in which a synchronous buck converter is operated continuously. The gate-driver units and the capacitors are enclosed inside the calorimeter. This adds extra complexity to the system since the power losses in the gate drivers have to be measured electrically and later subtracted from the total losses. The challenge of separating the conduction and switching loss still remains. In [13], a method is proposed to determine the soft-switching losses of 10 kV SiC MOSFETs. This method separates the conduction

978-1-5386-1180-7/18/$31.00

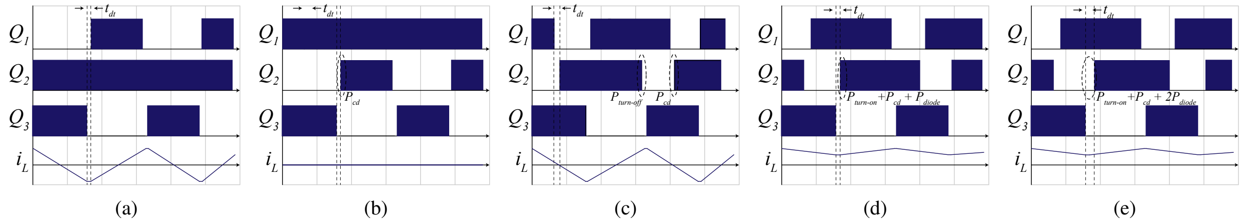

Fig. 1. Modulation Strategy used for calculating (a) Conduction Losses (b) Capacitor discharge losses (c) Turn-off losses and capacitor discharge losses (at half the dc-link voltage) (d) Turn-on losses along with capacitor discharge losses and diode losses. The configuration has a deadtime t_{dt} (e) Turn-on losses along with capacitor discharge losses and diode losses. The configuration has a deadtime $2 \times t_{dt}$.

and switching losses of the device. This has proven to be very accurate. However, it does not provide any information about the hard-switching losses. In [13], three calorimetric switching loss methods are presented namely measurement by thermal resistance, measurement by heat sink air flow temperature difference and measurement by air enthalpy increase. Some of the measurement techniques require additional air flow meters. Furthermore, no analysis for accurate measurements of conduction losses has been provided.

While it is observed that both electrical and calorimetric methods have certain drawbacks, it is found that the electrical methods have a higher chance of providing incorrect results as compared to the calorimetric measurement techniques [18]. This paper presents a method to separate the conduction, turn-on and turn-off losses in a device. This method employs a switch in series with the top leg of a half-bridge circuit similar to [13]. However, the modulation strategy is modified for calculating both the turn-on and turn-off losses.These losses can be obtained for different DC-link voltages, currents, temperature and gate-resistor values; which can be utilized in determining the switching losses and consequently, optimizing the thermal design. The separation of the capacitor discharge losses at various currents as shown in [19] has not been done in the current setup.

This paper is organized as follows. Section II discusses about the modified half-bridge topology and the modulation strategies used for the various loss calculations and the segregation of the losses. Section III provides the principle of the proposed topology including the hardware implementation and the practical design of the entire system. Section IV discusses some challenges observed while designing the calorimetric setup and accurately evaluating the switching losses. It is followed by the conclusion and the references.

II. Topology and Modulation Strategies Used for the Calorimetric Test Setup

In order to measure and segregate the conduction, turn-on and turn-off losses, a modified half bridge circuit is used as shown in Fig. 2. An additional device (Q_2), which is the device under test (DUT), is inserted in series to either the top switch or the bottom switch. In this paper, the analysis has been done assuming the switch Q_2 is connected in series with the top switch Q_1. In the modified half-bridge configuration, a novel modulation strategy is employed in order to calculate the losses of the device under test. In addition, the capacitor discharge losses can also be measured. Fig. 1 gives the various modulation strategies for measuring the losses in the DUT.

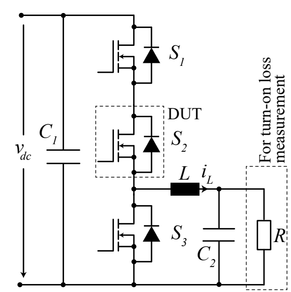

Fig. 2. Schematic of the modified half-bridge circuit. The additional switch Q_2 (DUT) is also shown. The load resistance is added across C_2 during turn-on loss measurements.

A. Modulation Strategy for Conduction Loss Measurement

Prior to the measurement of switching losses, the conduction losses are evaluated. Fig. 1(a) shows the modulation strategy used for measuring conduction losses. Switch Q_2 is kept ON and Q_1 and Q_3 are switched in complementary fashion (with a deadtime t_{dt}). This ensures that the DUT experiences only conduction losses and the switching/capacitor discharge losses are experienced by Q_1 and Q_3.

B. Modulation Strategy for Capacitor Discharge Loss Measurement

The capacitor discharge losses are calculated by using the modulation strategy shown in Fig. 1(b). It should be noted that the discharge losses are calculated at zero current only. This is done by disconnecting the inductor from the system. These losses can be evaluated for different voltage levels by providing different input voltages.

C. Modulation Strategy for Turn-off Loss Measurement

Fig. 1(c) shows the modulation strategy used for measuring the turn-off losses. In this case, it is ensured that only the turn-off losses are experienced by the DUT and the turn-on and the diode losses are experienced by Q_1.

D. Modulation Strategy for Turn-on Loss and Diode Loss Measurement

The turn-on losses are measured by adding a load to the system as shown in Fig. 2. The switches start to experience the turn-on losses. The modulation strategy (Fig. 1(d) and Fig. 1(e)) is modified such that Q_1 experiences the turn-off losses and the turn-on losses and the diode losses. In order to separate out the diode losses, the measurement is taken for two different deadtime intervals.

In all of these strategies, the effective duty cycle of the top side remains the same as in a half-bridge configuration. By inserting another switch in series with the top-side switch gives the flexibility to segregate the various losses.

III. Principle of the Proposed Methodology

The primary aim of the proposed methodology is to measure the losses calorimetrically and segregate them into conduction losses, switching losses, diode losses and capacitor discharge losses.

A. Hardware Implementation

Switch Q_2, which is considered as the device under test (DUT), is placed inside the calorimeter. It should be noted that all the devices are mounted on aluminum heatsinks which acts as a thermal capacitance. The calorimeter is modeled by a polystyrene box in order to minimize the effects of the ambient temperature, while providing adequate thermal resistance. A fan is placed inside the calorimeter in order to maintain equi-temperature conditions inside the calorimeter by having an airflow. A resistor is also placed inside the calorimeter to calibrate it with respect to temperature rise. Two K-type thermocouples are placed on either side of the heatsink to ascertain the temperature inside the calorimeter. The temperature is measured using Fluke 179 True RMS multimeter and also using Hioki Heat Flow Logger LR8432 (can measure temperature also). It should be noted that one of the two thermocouples is connected to the multimeter and the temperature sensors at different periods of time. In addition, the whole setup is placed inside a box in order to avoid additional air drifts from the ambient. The ambient temperature is constantly monitored with a thermocouple attached to one of the walls of the box. Care should be taken care of the fact that the calorimeter is not disturbed any time during the measurements. The parameters for the test setup are mentioned in Table I. A photograph of the experimental setup is shown in Fig. 4. The experimental waveforms for measuring the turn-off losses is shown in Fig. 3.

B. Calorimeter Calibration

The calorimeter is first calibrated for calculating its thermal resistance and/or thermal capacitance. The fan, placed inside the calorimeter is turned on and the input power is noted. It is assumed that the power consumed by the fan is dissipated inside the calorimeter. A known amount of power is provided to the resistor and the temperatures are noted. Simultaneously, the

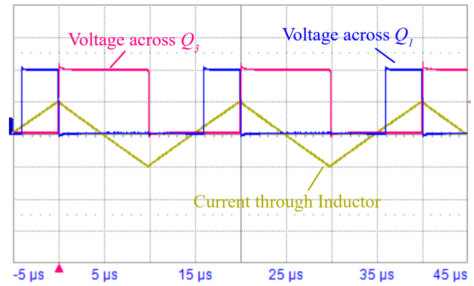

Fig. 3. Operation of the modified half bridge circuit for measuring turn-off losses. The voltage of the DUT is not measured since it is inside the calorimeter. The operation of this circuit is shown at a input voltage of 400 V and a switching frequency of 50 kHz. Scale: Voltage across Q_1: 200V/div; Voltage across Q_2: 200V/div; Current through Inductor: 5A/div)

TABLE I. Parameters of the Test Setup

Parameter	*Values*
Operating Voltage	400V
Switching Frequency	20 kHz - 75 kHz
Duty Cycle	50%
Gate Resistance	20 Ω total
Switches Used	Wolfspeed CMF10120D
Input Capacitance	28 μF
Output Capacitance	22 μF

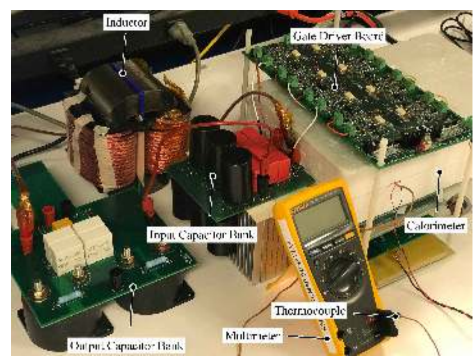

Fig. 4. Photograph of the experimental setup used for calculating the switching and the conduction losses.

ambient temperature is also measured. The thermal resistance can therefore be calculated by

$$R_{th} = \frac{T_{cal} - T_a}{P_{diss}} \quad (1)$$

where R_{th} is the thermal resistance of the calorimeter, T_{cal} is the temperature inside the calorimeter, T_a is the ambient temperature and P_{diss} is the total power dissipated inside the calorimeter. The measurements are taken at a time interval of two minutes till the calorimeter reaches a steady state temperature.

The calibration can be done based on the thermal capacitance (C_{th}) of the calorimeter also, as shown in Fig 5.

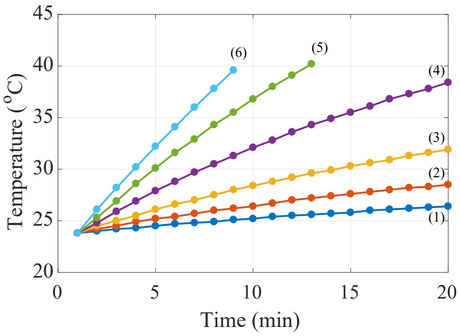

Fig. 5. Calibration Results for the calorimeter (polystyrene box). A known amount of power is supplied to the box and the temperature rise is noted with respect to time. The thermal capacitance of the box can therefore be estimated. ((1): P = 1.1W; (2): P = 2.5W; (3): P = 5.1W; (4): P = 8.5W; (5): P = 12.6W; (6): P = 17W)

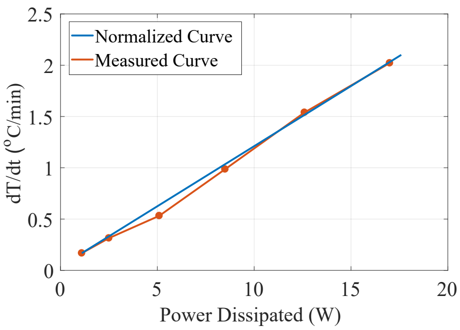

Fig. 6. Estimation of the thermal capacitance of the polystyrene box. The slopes of the calibration results are plotted against the power dissipation to calculate the thermal capacitance. It is seen that the thermal capacitance of the box varies slightly with the amount of power dissipated inside it.

$$C_{th} = \frac{P_{diss}\Delta\tau}{T_{meas} - T_a} \quad (2)$$

where P_{diss} is the power dissipated in the calorimeter and $\Delta\tau$ is the measurement time. This serves as a faster method to calculate the power dissipated inside the calorimeter. However, the sensitivity is lower as compared to the calibration done through the thermal resistance. In this paper, the thermal capacitance is taken as the calibration reference for all measurements.

Instead of taking a normalized thermal capacitance (which might lead to inaccuracies, an interpolation function is taken to form a lookup table between the temperature-rise and the time elapsed. The initial seven readings for each measurement is taken to form a linear fit and the interpolation is shown in Fig. 6.

C. Measurement of Conduction Losses

The conduction loss in the device is found using various methods in order to get an accurate estimation. First, a static measurement technique is used to measure the conduction losses. The switch is kept ON using a constant gate-source voltage and the on-state resistance is measured at different temperatures (30^{o}C to 40^{o}C) using a LCR meter. This method does not take the dependency of the on-state resistance with current into account. However, it gives a fair estimate of the on-state resistance, and consequently, the conduction losses.

Secondly, using the modulation strategy explained in the previous section, the conduction loss can be calculated. By changing the switching frequency, the current through the DUT changes and the losses are recorded. This method serves to be more reliable since the dependence of the on-state current on the conduction losses are taken into account. Fig. 7 shows gives the on-state resistance (calculated from the conduction losses) for different values of peak drain current. The on-state resistance change is attributed to the fact that the $I-V$ curve of MOSFETs are not exactly linear, but vary slowly at regions of low currents.

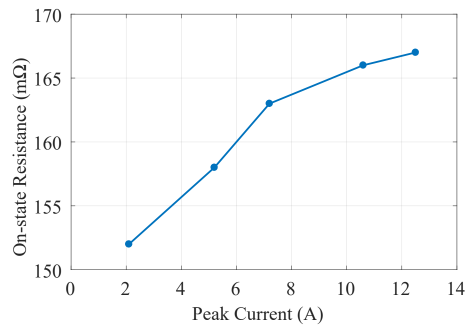

Fig. 7. Variation in the on-state resistance of the device with respect to the drain current. It should be noted that the LCR meter shows a constant value of 153 mΩ since it measures using a very small drain current.

D. Measurement of Capacitor Discharge Losses

The capacitor discharge losses is an integral part of the losses seen by SiC MOSFETs. However, designers generally eliminate capacitor discharge losses while measuring the losses in a switch. Since the capacitor discharge losses can be very low, it is difficult to estimate these through electrical methods. Using the modulation strategy described, the capacitor discharge losses are estimated for two different voltage levels. The device is switched at 75 kHz (without any current) in order to generate considerable losses. This is important since the sensitivity of the measuring equipment does not allow it to capture really low losses. Table II shows the capacitor discharge losses at two different voltage levels (200V and 400V).

TABLE II. CAPACITOR DISCHARGE LOSSES

Voltage Level (V)	*Capacitor Discharge Loss (μJ)*
200	6.5
400	30

E. Measurement of Turn-off losses

The measurement of turn-off losses are carried out using the modulation strategy as explained in Section II. For measuring the turn-off energy, using the modulation strategy, the power loss is given by

$$P_{Q2,off} = P_{cond} + P_{turn-off} + P_{cd}(V_{dc}/2) \quad (3)$$

where P_{Q2} represents the total losses in the switch, P_{cond} is the conduction loss, $P_{turn-off}$ gives the turn-off loss and P_{cd} gives the capacitor discharging loss. The capacitor discharging loss for this case is the loss at 200 V, since, the DUT blocks half the dc-link voltage before turning ON. The conduction losses and the capacitor discharging losses are accounted for, from the previous measurements. The turn-off loss can thus be evaluated from

$$P_{turn-off} = P_{Q2,off} - P_{cond} - P_{cd}(V_{dc}/2) \quad (4)$$

The losses provided by this measurement reflects just the turn-off losses.

F. Measurement of the Turn-on Losses

The turn-on losses can be measured in a similar manner. However, a load needs to be added in order to have the DUT experience the turn-on loss. The modulation strategy is adapted in such a way that the turn-off losses are experienced by Q_1. This is critical since higher losses in the DUT leads to a higher change in temperature and all the losses combined takes the DUT to more than 40^{o}C, which is not desirable. In this case, however, before the turn-on, the diode of the DUT conducts which leads to additional diode losses. In addition, the turn-on of the device makes the output capacitor discharge through its channel. This adds the capacitor discharge losses to the total measured losses.

For measuring the diode losses, two different measurements are taken (M_1 and M_2) for two different deadtime intervals (t_{dt1} and $2 \times t_{dt1}$). Since, the diode loss is linearly proportional to the deadtime interval, for the two different measurements, the diode loss can be found.

$$P_{Q2,on}(M_1) = P_{cond} + P_{turn-on} + P_{cd}(V) + P_{diode}(M_1) \quad (5)$$

$$P_{Q2,on}(M_2) = P_{cond} + P_{turn-on} + P_{cd}(V) + P_{diode}(M_2) \quad (6)$$

Subtracting (5) from (6),

$$P_{Q2,on}(M_2) - P_{Q2,on}(M_1) = P_{diode}(M_2) - P_{diode}(M_1); \quad (7)$$

Also, since the deadtime interval for M_2 is twice that of M_1

$$P_{diode}(M_2) = 2 \times P_{diode}(M_1) \quad (8)$$

From (7) and (8), the diode losses are evaluated. The turn-on loss along with the capacitor discharge losses can therefore be calculated by

$$P_{turn-on} + P_{cd}(V) = P_{Q2,on} - P_{cond} - P_{diode} \quad (9)$$

It should be noted that the capacitor discharge losses happens for the full dc-link voltage. This is because of the fact that the DUT blocks the full voltage before turning-on. However, these losses occur at non-zero current and hence the measurement done earlier is not valid. The current setup does not allow a separation of the turn-on losses and the losses due to the discharging of the output capacitor. The turn-on losses along with the capacitor discharge losses are thus evaluated. Fig. 8 shows the turn-off and turn-on switching energies for the DUT for different load currents.

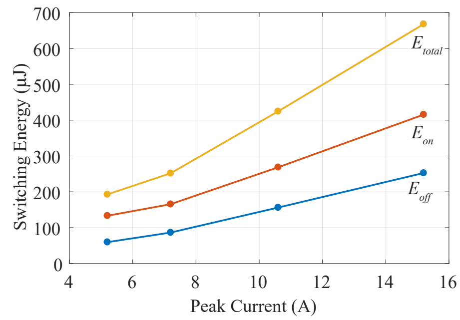

Fig. 8. Turn-off and turn-on switching energy for the DUT. This loss is the actual turn-off loss in the device and does not include the energy stored in the output capacitor of the device. In case of the turn-on losses, the output energy of the capacitor is also added to the losses.

IV. Challenges in Designing and Testing a Calorimetric Test Setup

Though a calorimetric measurement of the switching losses offers a lot of advantages over conventional electrical methods, it brings along a lot of challenges also. In this paper, the modified half-bridge circuit has the disadvantage of having a switch in series with the top device in the half bridge configuration. This introduces an additional element in the dc-commutation path which leads to pessimistic loss measurements as compared to the actual system. In [14], this is avoided since a conventional full-bridge circuit is employed to measure the switching losses.

In addition, the DUT is placed inside the calorimeter where as the gate driver is mounted outside it in order to avoid having additional losses inside the calorimeter. This results in long leads from the gate driver to the device. This is particularly a problem for devices with a high dv/dt like GaN based devices. Also, higher lead lengths in the gate-source path does not allow testing at lower gate resistances. In [13], the gate driver is placed directly on the device, but the device itself is not enclosed in the calorimeter. This might lead to changes in the calibration due to changes in the environment. A small air draft introduces errors in the measurement.

Similar to having high accuracies of currents and voltages in the electrical measurements, a high accuracy is necessary for temperature measurement in calorimetric methods. An error analysis provided in [19] shows that up to 15% error can be seen in these methods. However, if the experiments are done carefully and using precise temperature measurement techniques, it is less likely to have the worst case scenario.

The placement of the thermocouple inside the calorimeter is also a critical parameter and care should be taken to ensure that the thermocouple is not disturbed during the measurements. The thermocouple can be glued to the calorimeter using a thermal adhesive such as Arctic Silver to avoid this issue. In devices, which has a high dv/dt, capacitive coupling between the device and the thermocouple might lead to inaccuracies and incorrect temperature measurements. It is advisable to use optical fiber based temperature sensors to avoid such issues.

Compared to the electrical measurement techniques, this method is slow, since after each measurement, the temperature inside the calorimeter needs to drop down to the ambient before the next measurement is taken. If the measurement is taken before the temperature comes down, it leads to inaccuracies in the measurement since the temperature inside the calorimeter does not actually reflect the power loss on the DUT.

V. Conclusion

As shown in the literature, electrical methods for measuring switching losses can lead to inaccuracies in their measurements and also need high bandwidth current and voltage sensors (which adds to the cost). In this paper, an accurate calorimetric method to measure the switching and conduction losses is presented. This method is based on a modified half-bridge configuration where the DUT is inserted in series with one of the devices in the half-bridge topology. Different modulation strategies are employed to segregate the switching losses from the conduction losses. In addition, this method is able to separate the turn-on and the turn-off losses. Based on the proposed method, the losses in a 1200V, 24 A devices is measured. The future work includes separating the capacitor discharge losses from the turn-on losses and having a detailed error analysis of each measurement inaccuracy. In addition, a comparison between the losses observed in this method and in a DPT circuit is also essential to evaluate the differences in both the techniques. Additional measurements for different values of voltage and current levels can be done in a similar manner. Accurate measurement of the losses is necessary in order to help designers optimize the converters based on size and cost. This is helpful, especially in high-switching frequency applications.

References

[1] N. C. Sintamarean, F. Blaabjerg, H. Wang, and Y. Yang, "Real Field Mission Profile Oriented Design of a SiC-Based PV-Inverter Application," *IEEE Transactions on Industry Applications*, vol. 50, no. 6, pp. 4082–4089, Nov 2014.

[2] A. Anurag, Y. Yang, and F. Blaabjerg, "Impact of reactive power injection outside feed-in hours on the reliability of photovoltaic inverters," in *2015 IEEE 6th International Symposium on Power Electronics for Distributed Generation Systems (PEDG)*, June 2015, pp. 1–8.

[3] Y. Yang, H. Wang, and F. Blaabjerg, "Reduced junction temperature control during low-voltage ride-through for single-phase photovoltaic inverters," *IET Power Electronics*, vol. 7, no. 8, pp. 2050–2059, August 2014.

[4] A. Anurag, Y. Yang, and F. Blaabjerg, "Thermal Performance and Reliability Analysis of Single-Phase PV Inverters With Reactive Power Injection Outside Feed-In Operating Hours," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 3, no. 4, pp. 870–880, Dec 2015.

[5] S. Madhusoodhanan, K. Mainali, A. K. Tripathi, A. Kadavelugu, D. Patel, and S. Bhattacharya, "Power Loss Analysis of Medium-Voltage Three-Phase Converters Using 15-kV/40-A SiC N-IGBT," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 4, no. 3, pp. 902–917, Sept 2016.

[6] G. Feix, S. Dieckerhoff, J. Allmeling, and J. Schonberger, "Simple methods to calculate IGBT and diode conduction and switching losses," in *2009 13th European Conference on Power Electronics and Applications*, Sept 2009, pp. 1–8.

[7] A. Marzoughi, R. Burgos, and D. Boroyevich, "Characterization and performance evaluation of state-of-the-art 3.3 kV 30 a full-SiC MOSFETs," in *2017 IEEE Energy Conversion Congress and Exposition (ECCE)*, Oct 2017, pp. 1350–1357.

[8] A. Anurag, G. Gohil, S. Acharya, K. Han, K. Vechalapu, B. J. Baliga, S. Bhattacharya, E. VanBrunt, S. Sabri, B. Hull, and D. Grider, "Characterization and Evaluation of a 3.3 kV, 45 A 4H-SiC MOSFET," in *International Conference on Silicon Carbide and Related Materials (ICSCRM 2017)*, Sept. 2017.

[9] U. Raheja, G. Gohil, K. Han, S. Acharya, B. J. Baliga, S. Battacharya, M. Labreque, P. Smith, and R. Lal, "Applications and characterization of four quadrant GaN switch," in *2017 IEEE Energy Conversion Congress and Exposition (ECCE)*, Oct 2017, pp. 1967–1975.

[10] A. P. Arribas, M. Krishnamurthy, and K. Shenai, "Accurate characterization of switching losses in high-speed, high-voltage Power MOSFETs," in *2015 IEEE International Workshop on Integrated Power Packaging (IWIPP)*, May 2015, pp. 95–98.

[11] Z. Zhang, B. Guo, F. Wang, L. M. Tolbert, B. J. Blalock, Z. Liang, and P. Ning, "Methodology for switching characterization evaluation of wide band-gap devices in a phase-leg configuration," in *2014 IEEE Applied Power Electronics Conference and Exposition - APEC 2014*, March 2014, pp. 2534–2541.

[12] S. Hazra, S. Madhusoodhanan, G. K. Moghaddam, K. Hatua, and S. Bhattacharya, "Design Considerations and Performance Evaluation of 1200-V 100-A SiC MOSFET-Based Two-Level Voltage Source Converter," *IEEE Transactions on Industry Applications*, vol. 52, no. 5, pp. 4257–4268, Sept 2016.

[13] D. Rothmund, D. Bortis, and J. W. Kolar, "Accurate transient calorimetric measurement of soft-switching losses of 10kV SiC MOSFETs," in *2016 IEEE 7th International Symposium on Power Electronics for Distributed Generation Systems (PEDG)*, June 2016, pp. 1–10.

[14] J. A. Anderson, C. Gammeter, L. Schrittwieser, and J. W. Kolar, "Accurate Calorimetric Switching Loss Measurement for 900 V 10 m Ω SiC Mosfets," *IEEE Transactions on Power Electronics*, vol. 32, no. 12, pp. 8963–8968, Dec 2017.

[15] J. Brandelero, B. Cougo, T. Meynard, and N. Videau, "A non-intrusive method for measuring switching losses of GaN power transistors," in *IECON 2013 - 39th Annual Conference of the IEEE Industrial Electronics Society*, Nov 2013, pp. 246–251.

[16] D. Bortis, O. Knecht, D. Neumayr, and J. W. Kolar, "Comprehensive evaluation of GaN GIT in low- and high-frequency bridge leg applications," in *2016 IEEE 8th International Power Electronics and Motion Control Conference (IPEMC-ECCE Asia)*, May 2016, pp. 21–30.

[17] A. Tüysüz, R. Bosshard, and J. W. Kolar, "Performance comparison of a GaN GIT and a Si IGBT for high-speed drive applications," in *2014 International Power Electronics Conference (IPEC-Hiroshima 2014 - ECCE ASIA)*, May 2014, pp. 1904–1911.

[18] "Accurate Calorimetric Switching Loss Measurement of Ultra-Fast Power Semiconductors," https://www.pes.ee.ethz.ch, accessed: 2010-07-26.

[19] D. Rothmund, D. Bortis, and J. W. Kolar, "Accurate Transient Calorimetric Measurement of Soft-Switching Losses of 10kV SiC MOSFETs and Diodes," *IEEE Transactions on Power Electronics*, vol. PP, no. 99, pp. 1–1, 2017.