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High Frequency Power Cycling of Three-Phase Inverters for Aircraft Applications

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ABSTRACT Accurate thermal cycle measurement is essential for estimating the lifetime of power modules, particularly those employing SiC MOSFETs characterized by extremely low thermal capacitance. This work presents a rigorous method for estimating the die temperature variation of SiC components within power modules utilized in three-phase inverters. The approach leverages high-speed thermal imaging to accurately characterize the individual thermal impedance of each die. The resulting thermal impedance model is coupled with high-fidelity loss calculations to predict dynamic SiC die temperatures during inverter operation. Experimental results obtained under conditions representative of a 540 V / 7.5 kW aeronautical inverter demonstrate the model's accuracy in tracking dynamic SiC die temperature variations.

KEYWORDS Power cycling; SiC MOSFET; thermal camera; thermal characterization; power losses.

I. INTRODUCTION

The aviation sector is currently undergoing a fundamental electrification, motivated by the need for a reduced environmental footprint, reduced cost, noise mitigation, and improved safety [1]. In response to these challenges, the aerospace industry is advancing two primary aircraft categories: the more electric aircraft (MEA), which involves the gradual replacement of secondary aircraft systems (e.g., hydraulic, pneumatic and mechanical) with electrical equivalents, and the electric propulsion aircraft (EPA), which fundamentally reconfigures the propulsion architecture through the integration of new electric technologies. In this context, power electronics technology plays a central role in realizing this transformation in transportation [1].

The electrical architecture of the aircraft requires power converters to manage power between ac and dc systems. Among the power converter topologies, inverters are present in both MEA, for driving actuators, and EPA, for propulsion motors. Power density of power inverters represents a critical design constraint for the overall effectiveness of aircraft electrification. The adoption of wide-bandgap (WBG) devices, such as silicon carbide (SiC) and Gallium Nitride (GaN) transistors, in inverters allows for greater efficiency and power density [1]. This technology enables an increase in switching frequency, which consequently results in a reduction of filtering weight and/or a decrease in semiconductor power losses.

Three-phase inverters are complex systems comprising power semiconductors, passive components (capacitors and inductors), thermal management systems, auxiliary supplies, control circuits, among others. References [2, 3] highlight the semiconductor power module as the most critical component

within power electronics systems regarding overall reliability. The lifetime of power modules is primarily affected by degradation in die attach and bond wires, typically induced by the power cycling experienced during operation that produces thermal cycling inside the module [4]. In fact, since power modules are composed of different materials with mismatched coefficients of thermal expansion, the thermal cycling induces significant thermomechanical stress at their joints [5]. In lifetime models, the thermal cycles are generally calculated by the mean junction temperature, junction temperature swing and heating time [5].

Furthermore, SiC dies within SiC-based power modules are subjected to higher thermomechanical stress compared to traditional Si-based power modules when the same voltage and current are considered. This phenomenon results from the fact that SiC dies are significantly smaller than their Si-based counterparts for an equivalent current rating. Consequently, SiC-based devices concentrate power losses within a smaller volume, resulting in a substantially higher loss density, which leads to higher thermal cycle amplitudes during operation [6].

Reference [7] investigates the power cycling reliability of SiC MOSFET modules under low junction temperature swing. It showed that SiC power modules have lower lifetime than Si-based power modules and they confirm some lifetime models from other works. However, none has been found for low-amplitude thermal cycles (10 to 40 K) and fast cycles (at frequencies from 10 to 100Hz) at the same time. Moreover, as discussed in reference [8], the lifetime can be overestimated by more than 10 times when fast power cycles are not taken into account. Thus, fast temperature variation must be precisely determined to accurately estimate the

lifetime of SiC power modules. This requires a high-fidelity instantaneous loss model coupled with a dynamic thermal model of the SiC dies within the module. Reference [9] presents an accurate instantaneous loss model for estimation of conduction and switching losses of SiC transistors in three-phase inverters. Nevertheless, the junction temperature is estimated considering this accurate loss model with the thermal model given in the datasheets of the components. Thus, this work does not take into account the variation of thermal impedance with the power dissipated by the die and its variation with the direction of current and the gate-source voltage of the die.

Reference [10] introduces a precise method for estimating the dynamic temperature of SiC transistors in three-phase inverters. This approach relies on a high-speed thermal camera to accurately characterize the thermal impedance of each die. This method was validated and coupled with the precise instantaneous loss model of reference [9]. Moreover, reference [10] demonstrates that while power losses have a minimal impact on the thermal impedance of the dies, the different direction of current flow (illustrated in Fig. 1) within the die can significantly affect it (by 10–20%). Nevertheless, the investigation of how thermal cycles in SiC dies used in three-phase inverters are significant at the frequency of the converter output current has yet to be conducted.

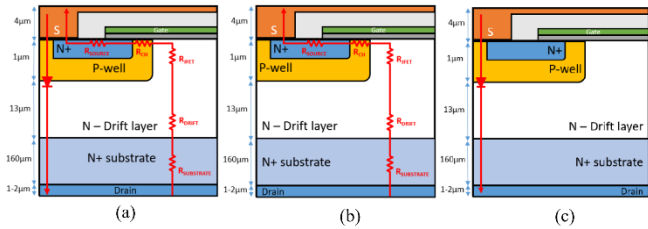


FIGURE 1 – Current flow path within the MOSFET during: (a) negative current operation with high gate-source voltage (V_{GS}); (b) positive current operation with high V_{GS} ; (c) negative current operation with low or zero V_{GS} . Adapted from [11].

Therefore, this work focuses on two main objectives:

- Show real SiC die temperature variation in a converter having ac current through it, such as three-phase converters, and the influence of different parameters on this variation (which reference [9] could only predict it by calculation, but not show it experimentally);
- Validate the electro-thermal model of SiC MOSFET for high-frequency power cycles, so it can be used in algorithms for lifetime estimation of a SiC power module. These algorithms, as well as lifetime models and calculations, are not the focus of this paper and will not be considered here.

Unlike reference [10], which validates one thermal model for SiC MOSFET dies, the work presented validated the entire thermo-electrical model, including switching and conduction losses on the dies, coupled with a more complete thermal model than the one presented in [10], taking into account either the highest or the average temperature in the SiC die surface.

This paper is organized as follows: first, the thermal impedance model for the SiC transistor in the power module using fast thermal camera measurements will be presented in Section II. Then, Section III experimentally shows SiC dies thermal cycling in a three-phase inverter under different

operational conditions. In Section IV, the thermo-electrical models are validated by experimental thermal measurements. Finally, the conclusions are given in Section V.

II. SiC DIE THERMAL MODEL

Most thermal models employ junction-to-case thermal impedance curves, which characterize the thermal response as a function of power pulse duration and duty cycle for a single switch. Furthermore, these models typically neglect the thermal cross-coupling between adjacent devices, since the thermal capacitance between dies is sufficiently high that loss fluctuations in the tens of Hz range do not induce significant temperature variations in neighboring dies. The thermal model presented below also neglects coupled thermal impedances between dies since the goal is to predict thermal cycles at the frequency range of sinusoidal currents in inverters. Indeed, given the distance between adjacent dies (around 10mm), experimental results in the setup described below showed that thermal cycles at 50Hz induced by one die in an adjacent dies were more than 80 times smaller, which demonstrates that thermal coupling between dies can be neglected.

A. Thermal impedance characterization

This work is based in thermal impedance characterization method first proposed in [10]. The experimental setup considered for acquisition of this model is shown in Fig. 2. The setup is based on a six-phase 540 V/15 kW power module. Only half of the six-phase was employed in the tests. Fig. 3 (a) presents the half-circuit, which consists of a direct-bonded copper (DBC) containing six 1200 V/80 mΩ SiC MOSFETs from CREE (part number CPM2–1200-0080B) to form three switching legs. A zoom-in of the six SiC dies is shown in Fig. 3 (b).

The surface temperature measurement was performed with a fast infrared thermal camera (FLIR X6900sc). To facilitate high-speed thermal imaging, a thin layer of black paint was applied to all six dies. The thermal camera was calibrated with a standard blackbody setup and the black paint emissivity compensation was set up to 0.95. The frame rate was modified to 1956 frames/s at a spatial resolution of 320x256 pixels, and the camera has a theoretical accuracy of ± 2 K.

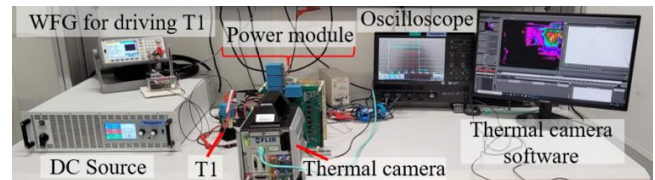


FIGURE 2 – Experimental setup for SiC die thermal impedance characterization.

Following conventional thermal impedance characterization methods, the die is subjected to constant, well-defined power losses while its transient temperature response is recorded over time. The circuit configuration is illustrated in Fig. 4. A current-limited dc power supply was employed to provide the excitation current in the circuit.

The thermal model is extracted from the transient temperature response measured by the thermal camera during the 1 s current pulse in the device under test (DUT). To

exemplify, Fig. 5 presents the experimental results of current, voltage, power and temperature considering a current pulse of 25 A applied to the DUT.

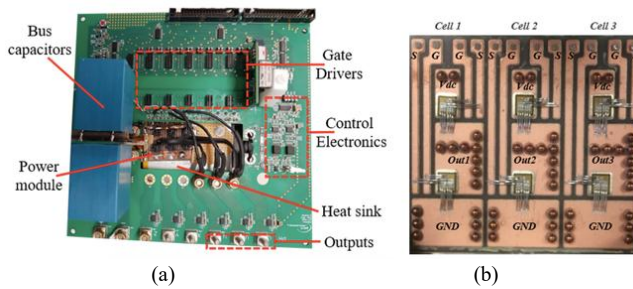


FIGURE 3 – SiC power module configuration featuring three switching cells with 1200V/80mΩ SiC MOSFETs.

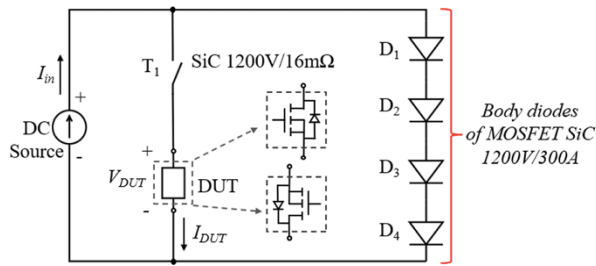


FIGURE 4 - Circuit configuration for SiC dies for thermal impedance characterization based on constant current excitation (near-constant losses).

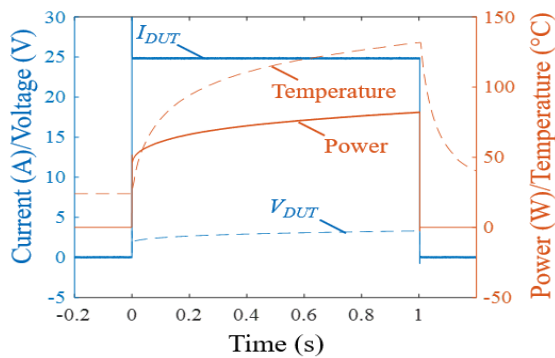


FIGURE 5 - Current, voltage, power and temperature results considering a current pulse of 25 A applied to the DUT.

For the junction-to-case thermal impedance modeling, this work considers the Foster model configuration with six parallel RC elements connected in series. To tune the model parameters, a curve fitting based on the method of least squares was performed. A lower number of RC elements induces higher error between real and fitted curves. A higher number increases calculation time. Six RC elements were a good compromise and resulted in least-squares errors for all different fitted thermal impedance curves below 0.7%.

To exemplify, the thermal resistances and respective time constants for current applied in positive and negative directions to the DUT, at different gate-source voltages (V_{gs}), are presented in Table 1.

Note that all the thermal impedance models were created from tests with 1 s pulses. Consequently, the thermal impedance model is accurate for predicting only “high frequency” power cycles (with frequencies higher than 1Hz). This model cannot predict average temperature. Currents of different values were applied to the DUT in the positive direction (drain to source) and in the negative direction

(source to drain), when the DUT was driven with $V_{gs} = 20$ V. To cover certain cases of converter operation during the dead time of a switching leg, or when the transistor is blocked but used as a diode, tests were also carried out applying a current in the negative direction (source to drain), when the DUT was blocked with $V_{gs} = 0$ V. The idea was for the tests to be conducted with the same losses in each situation; however, they were not exactly the same in practice, yet close enough for the experiment to be carried out. The instantaneous power for current applied in positive and negative directions to the DUT, and at different V_{gs} are shown in Fig. 6.

TABLE 1 - Thermal resistances and time constants of the Foster model of the SiC die in a power module, estimated considering average temperature measured in the square area the size of the die [10].

RC elements (k)	Positive current		Negative current		Negative current	
	$V_{gs} = 20$ V		$V_{gs} = 20$ V		$V_{gs} = 0$ V	
	R_k [K/kW]	τ_k [ms]	R_k [K/kW]	τ_k [ms]	R_k [K/kW]	τ_k [ms]
1	207	803.4	97	10.3	21	10.1
2	367	128.8	365	198.2	258	9.8
3	404	47.3	261	55.6	304	362.7
4	257	8.7	836	10850.4	534	73.7
5	620	295.1	198	10.3	132	35.2
6	39	188.5	325	55.6	37	33.2

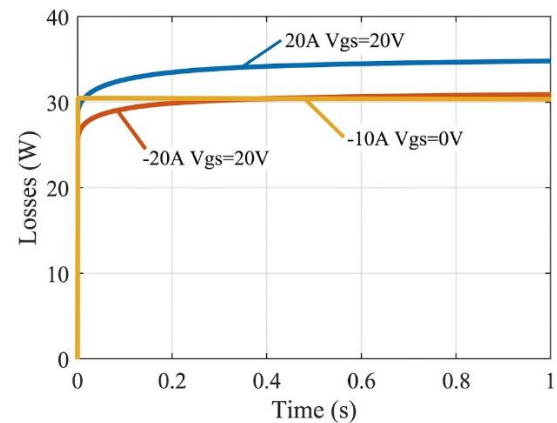


FIGURE 6 - Instantaneous power for current applied in positive and negative directions to the DUT, and at different V_{gs} .

B. Challenge in choosing the thermal model

The thermal camera measures the surface temperature of the SiC die, which is influenced by the bonding wires covering the metallization surface. These wires, made of aluminum, conduct heat differently, affecting the measured temperature. To analyze the impact of measurement regions, five regions of interest (ROIs) were tested: two squares and three single-pixel cursors, as shown in Fig. 7 (on the right). Each ROI provided different temperatures and heating dynamics for the same current, as can be seen in Fig. 7.

The estimated thermal impedance of Table 1 is based on the average temperature measured using a square area the size of the die, as indicated by the green box in Fig. 7. On the other hand, Table 2 presents the estimated thermal impedance considering the temperature measurement from a single point on the metallization surface of the SiC die, only when V_{gs} is 20 V.

As observed by comparing Tables 1 and 2, the estimated thermal impedance will differ depending on how the temperature information of the power module obtained from the thermal camera is used. Usually, researchers and engineers use this information to calculate a temperature either for protection or for lifetime estimation. For protection, the highest temperature on the die surface is more appropriate to be calculated and estimated. For lifetime estimation, the average temperature on the die surface is more representative of the average temperature in the MOSFET die channel, which is usually the parameter used when researchers create lifetime models.

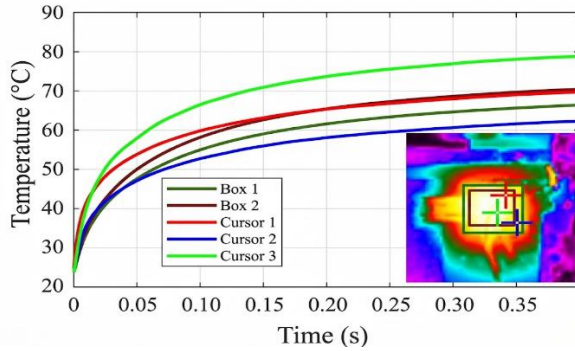


FIGURE 7 - Thermal image of SiC die and die temperatures measured by the camera for different ROIs.

TABLE 2 - Thermal resistances and time constants of the Foster model of the SiC die in a power module, estimated considering the temperature measured in a single pixel on the top metallization of the SiC die.

RC elements (k)	Positive current		Negative current	
	$V_{gs} = 20 \text{ V}$		$V_{gs} = 20 \text{ V}$	
	$R_k \text{ [K/kW]}$	$\tau_k \text{ [ms]}$	$R_k \text{ [K/kW]}$	$\tau_k \text{ [ms]}$
1	252	419.1	384	5.0
2	403	75.0	199	508.6
3	289	14.7	410	103.7
4	379	3.4	40	515.0
5	78	42.1	333	26.3
6	48	261.7	77	26.3

III. SiC DIE POWER CYCLING IN THREE-PHASE INVERTERS

This section presents how the thermal cycles in SiC dies used in three-phase inverters are significant at the frequency of the converter output current. For that, tests were carried out on half of the six-phase 540V/15kW power module in a real three-phase inverter operation. The circuit configuration is shown in Fig. 8.

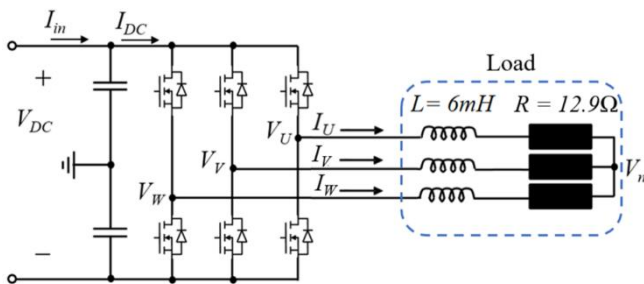


FIGURE 8 - Three-phase inverter circuit configuration.

The module is composed of three legs of identical SiC MOSFETs connected to a variable RL load emulating an electrical actuator. Switches are controlled by pulse-width

modulation (PWM) through a gate driver with a variable gate resistor. Tests were conducted under operating parameters designed to meet the requirements of aircraft applications. The operating parameters are presented in Table 3.

TABLE 3 – Nominal parameters of the three-phase inverter based on requirements of aircraft applications.

Parameter	Value
Switching frequency (f_{sw})	50 kHz
Fundamental frequency (f_n)	50 Hz
Gate driver resistance (R_g)	10 Ω
Dc-link voltage (V_{dc})	540 V
Rated active power (P)	7.5 kW

Fig. 9 shows the thermal image of the six SiC dies captured by the camera for the inverter, operating with 21.11 A of output rms current (I_{out}), sinusoidal pulse-width modulation (SPWM) method and a modulation index (M_i) of 0.9. Notably, the dies exhibit significantly higher temperatures compared to the copper traces. It is also evident that the bond wires maintain a lower temperature than the die source metallization. Furthermore, each die displays a distinct thermal signature, reflecting the converter operation as the alternating current flows through the individual dies at different intervals.

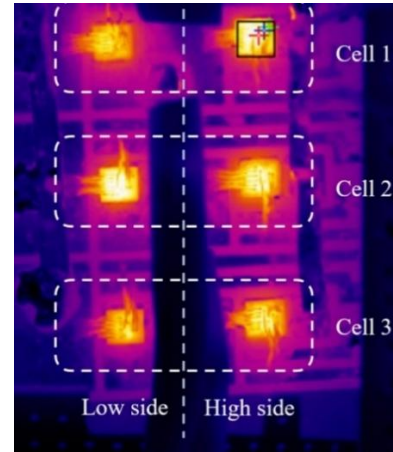


FIGURE 9 - Thermal image of SiC power module and temperature measurement (on the right) with the operating parameters of Table 3, $I_{out} = 21.11 \text{ A}$, $M_i = 0.9$ and SPWM method.

Fig. 10 shows the SiC die temperature (T) in the low-side dies in each cell (leg) of the inverter for an operating point with low current compared to the one from Fig. 9. Even at lower instantaneous losses (due to lower current), the temperature tracks the current dynamics, exhibiting a 120 degrees phase-shift between the respective dies. The temperature analysis performed employing the thermal camera can be conducted in different manners, depending on the area being considered. For example, a single point on the surface or different area sizes can be considered, as exemplified in Fig. 11 (a), where the black line represents a square and the other marks represent different points of measurement. As observed in Fig. 11 (b), each point or area has a different average and amplitude temperature. The temperature considered was the average of the temperatures of each pixel within the square placed around the perimeter of the die.

The measured die temperature for different modulation indexes, PWM methods and fundamental frequencies is shown in Fig. 12 (a)-(c), respectively.

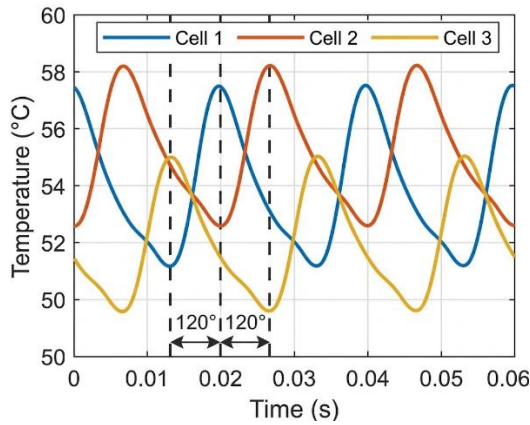


FIGURE 10 - Temperature measurement of SiC dies of the low side in three different legs (cells 1 to 3) of the inverter with the operating parameters of Table 3, $I_{out} = 14.73$ A, $M_i = 0.85$ and SPWM method.

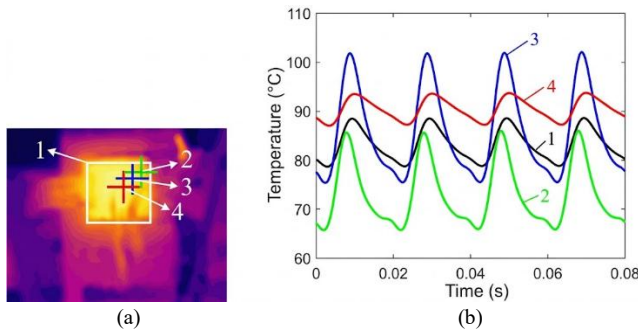


FIGURE 11 - Temperature measurement of different locations in the same SiC die considering the operating parameters of Table 3, $I_{out} = 21.11$ A, $M_i = 0.9$ and SPWM method: (a) location of measurements; (b) SiC die temperature.

As observed in Fig. 12 (a), the temperature amplitude (ΔT) increases as the modulation index rises, since conduction losses become more uneven between the positive and negative half-cycle currents.

The literature presents several different PWM methods [12]. For the PWM methods variation tests, this work considers six PWM techniques: space vector PWM (SVPWM), sinusoidal PWM (SPWM) and discontinuous PWM methods (DPMIN, DPMAX, D0 and D1). Fig. 12 (b) presents the measured temperature for these six PWM techniques. Small temperature variations among each one of the PWM methods can be observed. In addition, DPMIN presents the lowest temperature swing amplitude because it induces lower switching and total losses in the LS die (in which the measurement was made). As a result, the temperature variation is also minimized. Fig. 12 (c) presents the temperature measured for different fundamental frequencies. As observed, ΔT is inversely proportional to the fundamental frequencies. Indeed, the temperature variation changes from 23°C at 10 Hz to 0.9°C at 200 Hz.

IV. TEMPERATURE ESTIMATION FOR THREE-PHASE INVERTERS

In this section, the temperature estimated with the SiC die thermal model in a three-phase inverter is compared with the experimental temperature measured with the thermal camera.

In this context, estimation of instantaneous temperature in the SiC die surface can be achieved by applying the time

signal of the losses in each component to the Foster thermal model of the SiC die. For this reason, an accurate instantaneous loss model, combined with a thermal model, is essential for die temperature and lifetime estimation of a die. Most of the losses in a three-phase inverter are due to the losses in power transistors, which depend on conduction and switching losses. Accurate models for estimating losses of SiC transistors in three-phase inverters have already been widely studied in [9] and will be briefly presented.

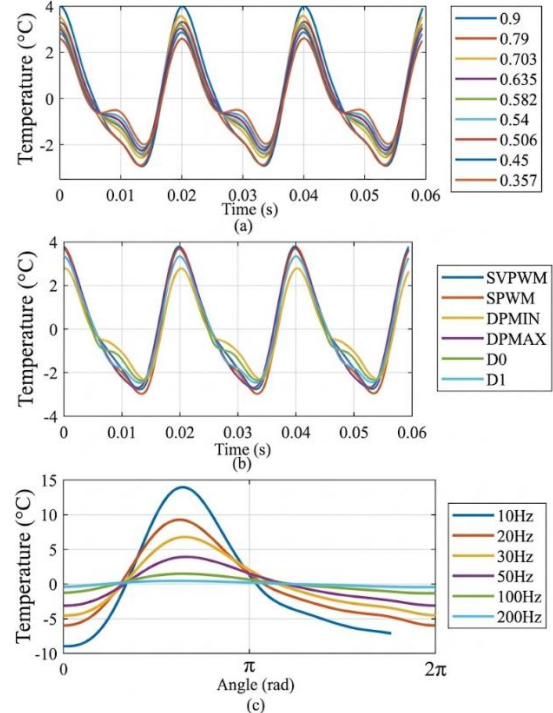


FIGURE 12 - Temperature measured for variation of parameters: (a) modulation index; (b) PWM method; (c) fundamental frequency.

A. Precise loss estimation in three-phase inverters

The primary source of power losses into a three-phase inverter is the power modules. The semiconductor power losses are divided in conduction and switching losses. This work considers the precise loss calculation approach of [9], which will be partially recalled below. The conduction losses in a switching leg can be calculated as:

$$P_{cond} = R_{DSon} \cdot I_{ORMS}^2, \quad (1)$$

where I_{ORMS} is the RMS value of the current in each leg (composed of fundamental value and harmonics) and R_{DSon} is the on-state resistance of a MOSFET. R_{DSon} is computed as a function of the junction temperature T_j and can be computed as [9]:

$$R_{DSon}(T_j) = \frac{T_j - 25}{125} [R_{DSon,150} - R_{DSon,25}] + R_{DSon,25}, \quad (2)$$

where $R_{DSon,150}$ is the on-state resistance at 150°C and $R_{DSon,25}$ is the on-state resistance at 25°C.

Manufacturer data is often insufficient or fails to reflect the actual switching losses within a real converter. Consequently, estimating switching losses is considerably more complex than conduction losses, necessitating the characterization of switching energies to achieve accurate results. The double pulse method [13] is often used in datasheets. Nevertheless, this method has some drawbacks, as it requires current measurement in the component. To

overcome this, a more accurate method for fast components, the modified opposition method, was proposed in [14] to characterize the switching energies. In this approach, the switched current can be determined by using the waveform of the output current for each duty cycle of a fundamental period. By analyzing the current direction relative to the output voltage commutation, turn-on and turn-off energy dissipations can be identified. This allows the precise calculation of switching energy for each switching event throughout the fundamental cycle, enabling the estimation of switching losses.

B. Validation of the Thermal Model by Experimental Measurements

The precise loss estimation considering the three-phase inverter of Table 3 is performed. The waveforms of instantaneous conduction, switching and total losses (averaged in each switching period) in the power module for the high-side (blue line) and low-side (red line) transistor in a leg of the inverter are shown in Fig. 13, considering $I_{out} = 15$ A, $M_i = 0.9$ and SPWM method. As observed, power losses are uniformly distributed between the high-side and low-side components of the inverter.

Estimation of instantaneous die temperature can be achieved by applying the time signal of the estimated losses in each component to the Foster thermal model of the SiC die. For this operation, Fig. 14 (a) shows the temperature variation in the SiC die measured by the thermal camera, considering the average surface temperature and estimated with the thermal model of Table 1. As observed in Fig. 14 (a), ΔT measured by the thermal camera is 6.3 K and ΔT estimated by the thermal model is 5.6 K. Consequently, a relative error of 11.1% is achieved when the thermal model is considered, resulting in an underestimation of the temperature variation. Fig. 14 (b) shows the temperature variation in the SiC die measured by the thermal camera, considering the temperature at a single point of the die and estimated with the thermal model of Table 2. As observed in Fig. 14 (b), ΔT measured by the thermal camera is 12.5 K and ΔT estimated by the model is 14.4 K. Consequently, a relative error of 15.2% is achieved when the thermal model is considered, resulting in an overestimation of the temperature variation.

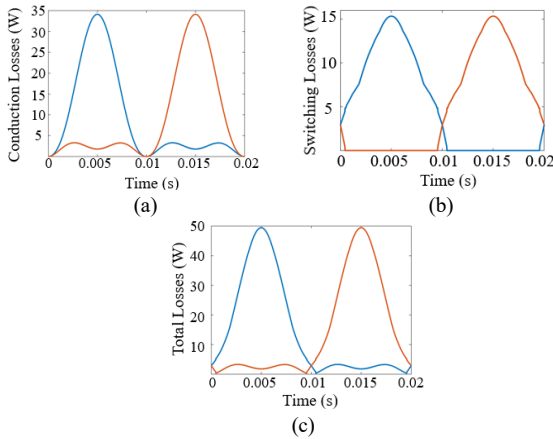


FIGURE 13 - Instantaneous (a) conduction, (b) switching and (c) total losses (averaged in each switching period) in SiC dies in a switching leg of a three-phase inverter with $I_{out} = 15$ A, $f_n = 50$ Hz, $f_{sw} = 50$ kHz, $M_i = 0.9$ and SPWM method.

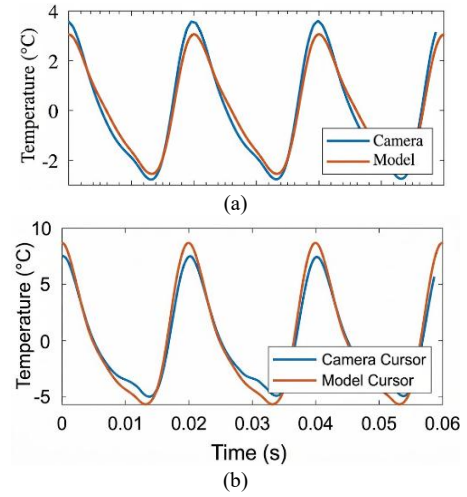


FIGURE 14 - Temperature on the SiC die surface: a) average surface temperature estimated with the thermal model of Table 1, and b) single point of the die estimated with the thermal model of Table 2 measured and calculated using the developed thermal model with $I_{out} = 15$ A, $f_n = 50$ Hz, $f_{sw} = 50$ kHz, $M_i = 0.9$ and SPWM method.

Waveforms of instantaneous conduction, switching and total losses (averaged in each switching period) in the power module for high-side (blue line) and low-side (red line) transistors in a leg of the inverter are shown in Fig. 15, considering $M_i = 0.357$ and the SPWM method. As observed, the power losses are uniformly distributed between the high-side and low-side components of the inverter.

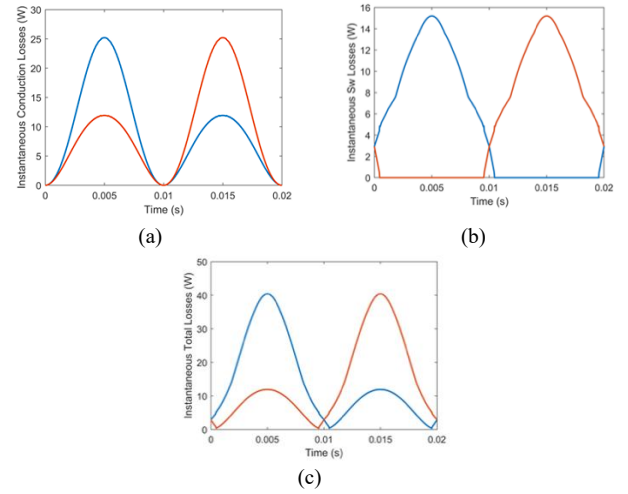


FIGURE 15 – Instantaneous (a) conduction, (b) switching and (c) total losses (averaged in each switching period) in SiC dies in a switching leg of a three-phase inverter with $I_{out} = 15$ A, $f_n = 50$ Hz, $f_{sw} = 50$ kHz, $M_i = 0.357$ and SPWM method.

Fig. 16 shows the temperature variation in the SiC die for this operating point. Fig. 16 (a) shows the temperature variation in the SiC die measured by the thermal camera, considering the average surface temperature and estimated with the thermal model of Table 1. As observed in Fig. 16 (a), ΔT measured by the thermal camera is 4.6 K and ΔT estimated by the thermal model is 4.2 K. Consequently, a relative error of 8.7% is achieved when the thermal model is considered, resulting in an underestimation of the temperature variation.

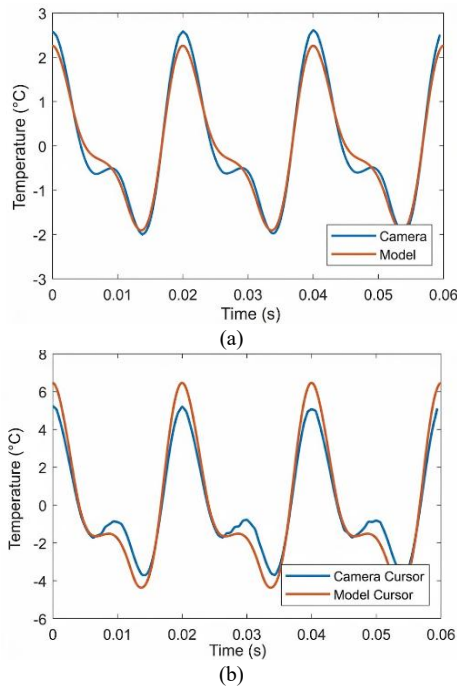


FIGURE 16 – Temperature in SiC die surface: a) average surface temperature estimated with the thermal model of Table 1, and b) single point of the die estimated with the thermal model of Table 2 measured and calculated using the developed thermal model with $I_{out} = 15$ A, $f_n = 50$ Hz, $f_{sw} = 50$ kHz, $M_i = 0.357$ and SPWM method.

Fig. 16 (b) shows the temperature variation in the SiC die measured by the thermal camera, considering the temperature at a single point of the die and estimated with the thermal model of Table 2. As observed in Fig. 16 (b), ΔT measured by the thermal camera is 8.7 K and ΔT estimated by the model is 10.8 K. Consequently, a relative error of 24.1% is achieved when the thermal model is considered, resulting in an overestimation of the temperature variation.

Temperature variation ΔT in one fundamental frequency cycle was calculated for each test performed, in order to demonstrate the impact of each inverter parameter on this temperature variation.

Fig. 17 shows the relationship between the temperature variation ΔT and the RMS current value, using both measured values and those calculated by the developed models. Note that the difference between the values calculated using the model and the measured values is very small, and that this difference is greater at high currents when losses and temperature are higher. The higher the current, the greater the losses, and consequently, the greater the temperature variation (or thermal cycles).

Fig. 18 shows the values of ΔT changing with the fundamental frequency of the inverter current. The model accurately reproduces the measurements. The higher the fundamental frequency, the lower the ΔT , which is consistent with the thermal impedance curves of semiconductors. The amplitude of the thermal cycles has significant values (> 10 K) for frequencies lower than 30 Hz.

Results shown in this section validate the thermal and loss models shown in this study. These models can be used to determine the temperature variation of each SiC die in an inverter or rectifier application, and these temperature

variations together with the SiC module lifetime models could be used for estimating the lifetime of these modules.

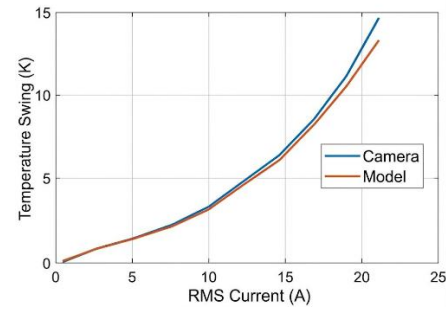


FIGURE 17 – Temperature variation in a fundamental cycle, measured with the thermal camera and calculated with the model as a function of the RMS current with $f_n = 50$ Hz, $f_{sw} = 50$ kHz, $M_i = 0.9$ and SPWM method.

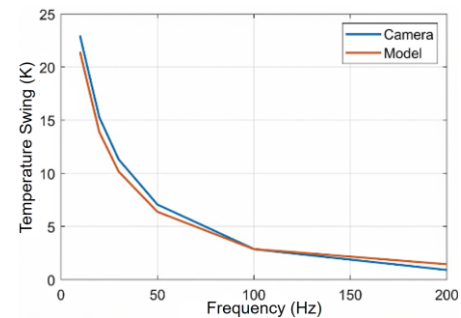


FIGURE 18 – Temperature variation in a fundamental cycle, measured with the thermal camera and calculated with the model as a function of the fundamental frequency.

However, lifetime models of semiconductor dies are created based on virtual junction temperature, measured with a TSEP, which gives an average temperature of the channel. For that reason, the relationship between “virtual junction temperature” and the die temperature measured with a thermal camera (either at a point on the die surface or an average in the die surface) must be further investigated.

An advantage of measuring temperature variation in each part of the die surface is that lifetime models could be applied differently for each part of the die (or for each bond wire), if the model takes into account the mechanical stresses due to temperature variation in the bond wire and die metallization around the bond wire.

V. CONCLUSIONS

This paper presented thermal analyses and modelling of a real three-phase inverter operating at different output currents, fundamental frequencies, PWM methods and modulation indexes. It was also presented a comparison between the measured temperature and the temperature estimated by a thermal impedance model, one made with the average temperature of the SiC and the other with the measured temperature of a single pixel in the die. Results show that the model estimates temperatures in the SiC die surface with accuracy and could be used for lifetime reliability studies.

AUTHOR'S CONTRIBUTIONS

A.H.T.SILVA: Data Curation, Formal Analysis, Investigation, Methodology, Validation, Visualization, Writing – Original Draft. **B.COUGO:** Conceptualization,

Data Curation, Formal Analysis, Funding Acquisition, Investigation, Methodology, Project Administration, Resources, Software, Supervision, Validation, Visualization, Writing – Original Draft, Writing – Review & Editing. **G.SEGOND:** Conceptualization, Investigation. **M.V.T.ANDRADE:** Data Curation, Formal Analysis, Investigation, Validation, Visualization. **D.TRAN:** Data Curation, Investigation, Methodology, Software, Supervision, Visualization. **R.O.SOUSA:** Formal Analysis, Investigation, Visualization, Writing – Review & Editing. **L.M.F.MORAIS:** Conceptualization, Formal Analysis, Investigation, Supervision, Writing – Review & Editing.

PLAGIARISM POLICY

This article was submitted to the similarity system provided by Crossref and powered by iThenticate – Similarity Check.

DATA AVAILABILITY

The data used in this research is available in the body of the document.

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