Letters

Lumped Thermal Coupling Model of Multichip Power Module Enabling Case Temperature as Reference Node

Mengqi Xu, Ke Ma, *Senior Member, IEEE*, Xu Cai, *Senior Member, IEEE*, Gongzheng Cao, and Yalin Zhang

***Abstract*—Insulated gate bipolar transistor (IGBT) modules with multiple chips have wide range of applications, and the correct estimation for the thermal behaviors inside IGBT modules is becoming crucial. Thermal impedance matrix is one of the most adopted approaches to describe the thermal-coupling effect of IGBT module. For simplicity of analysis, the heatsink or ambient temperature is typically chosen as the reference node for the thermal-coupling impedance term, while the case temperature is simplified or ignored. This letter provides a thermal coupling model enabling case temperature as reference node. This proposed model decouples the thermal coupling impedances of IGBT module itself and external cooling condition, so that the modeling of cooling conditions outside device and inside the power module, can be separately considered. The characterization method and advantages of the proposed model are verified by an experimental demonstration, and the potential applications are further discussed.**

***Index Terms*—Curve fitting, multichip power devices, power semiconductor device, thermal modeling, thermal network.**

I. Introduction

INSULATED gate bipolar transistor (IGBT) modules with multiple chips, have been widely used in many important applications such as motor drives, renewable energy generations, transportations, and power transmission [1]–[3]. It is known that the thermal stress is one of the major causes of failure [4]–[6], thereby the correct prediction of thermal behaviors for IGBT modules is getting critical. But there are two challenges: First, more chips are integrated in compact area to increase power density [7], leading to the complexity of thermal dissipation and propagation inside and outside the IGBT modules. Second, the loading of power electronics devices is closely related to the mission profiles of the converter system [8], and the thermal dynamics of multichip IGBT modules is getting complex.

The thermal behaviors of a multichip IGBT module can be seen as the thermal diffusion across different solid regions with isotropic materials from multiple heat sources [9], [10], which can be described by a three-dimensional (3-D) heat diffusion equation. Serval models have been developed to solve this equation.

Numerical methods are most frequently employed to analyze the multichip thermal problem, including finite difference method, finite-element method (FEM), and finite volume method [11]. Take FEM as an example, there are two limitations for thermal coupling analysis of power device: 1) The cooling system outside IGBT module in FEM is usually represented by the heat transfer coefficient, which is hard to be accurately determined under different cooling conditions. Also, FEM is difficult to simulate the degradation of cooling conditions, especially the process of thermal grease degradation. 2) Time-consuming when analyzing transient thermal-coupling behaviors because FEM is inefficient to calculate the temperatures in long-term mission profile [12], [13].

Another method for solving multichip thermal problem is to describe the thermal coupling behaviors based on lumped *RC* networks. Although these models can be easily implemented on electro-thermal coupling simulation, they cannot provide 3-D spatial temperature distribution throughout the IGBT module [14]. Consequently, a matrix-based thermal model has been developed [10]. The simplest matrix-based thermal coupling model composed of pure thermal resistances as stated in [15] was first proposed and then matrix-based thermal impedance model emerged [13]. However, most of the existing models use ambient/heatsink temperature as the reference node for simplicity of modeling and characterization, and the interface between power module and heat sink surface is typically not well defined [16]. Moreover, these existing models cannot be easily applied if the cooling conditions are changed [17]. For example, when the fan speed of a forced air-cooling system is changed, each element of the existing models should be modified, which brings difficulty to application.

To deal with this challenge, this letter establishes a lumped thermal coupling model for a multichip IGBT module, which enabling the case temperature as reference node. The case node and heatsink node in this proposed model correspond to actual

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measuring points, so these nodes have physical meanings. As a result, the case temperature can be directly obtained from the proposed model while the case temperature should be derived from the junction temperature in the conventional model. Furthermore, this proposed thermal coupling model can be applied for electro-thermal simulations under complex mission profiles ensuring accurate temperature predictions at full bandwidth while the dynamic performance of case temperature obtained from conventional model has huge deviation. Last but not the least, the proposed thermal impedance for external cooling condition, and the thermal coupling impedance matrix inside IGBT module, are separated at the point of case temperature. Thereby, the changes of cooling condition outside IGBT module can be individually considered.

II. Proposed Thermal Coupling Model With Case Temperature as Reference Node

For a multichip IGBT module, every chip will heat up its neighboring chips and this effect can be represented by thermal impedance matrix, where the thermal coupling impedance is measured by heating up one chip and measuring the thermal responses occurring for all other chips. Then, the junction temperature for each chip can be obtained by

$$\boldsymbol{T_j}(t) = \boldsymbol{Z_{jref}}(t) \cdot \boldsymbol{P} + \boldsymbol{T_{ref}} \tag{1}$$

It is assumed that the number of chips is N, $\boldsymbol{P}$ is constant vector dimensioned N×1, and $\boldsymbol{Z_{jref}}$ satisfies

$$\boldsymbol{Z_{jref}} = \begin{bmatrix} Z_{j1ref@1} & Z_{j1ref@2} & \cdots & Z_{j1ref@N} \\ Z_{j2ref@1} & Z_{j2ref@2} & \cdots & Z_{j2ref@N} \\ \vdots & \vdots & \vdots & \vdots \\ Z_{jNref@1} & Z_{jNref@2} & \cdots & Z_{jNref@N} \end{bmatrix} \tag{2}$$

where the diagonal element in the thermal impedance matrix means self-heating of each chip. The other elements represent the coupling between two different chips, for example $Z_{j1ref@N}$, means coupling heating for the first chip from the *N*th chip.

In the existing models, the ambient temperature or the heat sink temperature is assumed to be isothermal with reference temperature $\boldsymbol{T_{ref}}$, thereby the elements of $\boldsymbol{T_{ref}}$ are constants [18] for simplicity of modeling and characterization.

A. Proposed Thermal Coupling Model With T_c as Reference and Calculation of Z_{ch} and Z_{ha}

In the proposed model, case temperature is selected as $\boldsymbol{T_{ref}}$ in (1), so the junction temperatures are calculated by

$$\boldsymbol{T_j}(t) = \boldsymbol{Z_{jc}}(t) \cdot \boldsymbol{P} + \boldsymbol{Z_{ch}}(t) \cdot \boldsymbol{P} + \boldsymbol{Z_{ha}}(t) \cdot \boldsymbol{P} + T_a. \tag{3}$$

In most datasheet for IGBT modules, only the case-to-heatsink thermal resistance per chip/module is provided, which is ambiguous and difficult to be applied considering the thermal coupling effects. In the proposed model, new terms of thermal impedance including thermal coupling effect is applied for both the thermal interface Z_{ch} and heatsink Z_{ha}.

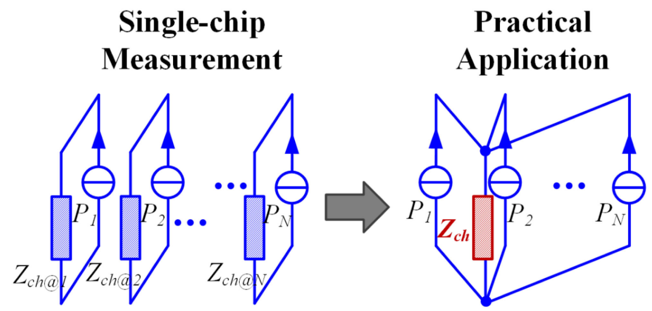

Fig. 1. Proposed modeling method for thermal interface Z_{ch} considering thermal coupling effects.

Take thermal coupling effect of two chips as an example, the superposition theorem [19] can be applied to calculate Z_{ch} and it satisfies the equation of

$$P_1 \cdot Z_{ch@1}(t) + P_2 \cdot Z_{ch@2}(t) = (P_1 + P_2) \cdot Z_{ch}(t). \tag{4}$$

Therefore, the thermal impedance of thermal interface Z_{ch} including thermal coupling effects can be calculated as

$$Z_{ch}(t) = \frac{P_1 \cdot Z_{ch@1}(t) + P_2 \cdot Z_{ch@2}(t)}{P_1 + P_2}. \tag{5}$$

It can be extended into the case of N chips, among which m chips are heated

$$Z_{ch}(m,t) = \frac{\sum_{i=1}^{m} P_i \cdot Z_{ch@i}(t)}{\sum_{i=1}^{m} P_i}. \tag{6}$$

The principle of the proposed calculation process for Z_{ch} is shown in Fig. 1, which demonstrates the superposition theorem applied for the calculation of Z_{ch} in this proposed model.

Similarly, Z_{ha} when considering thermal coupling effects can be calculated by

$$Z_{ha}(m,t) = \frac{\sum_{i=1}^{m} P_i \cdot Z_{ha@i}(t)}{\sum_{i=1}^{m} P_i}. \tag{7}$$

As a result, Z_{ch} and Z_{ha} in (6) and (7) can reflect the thermal coupling effects happened between case and ambient, which are different from the one used in the conventional thermal impedance models without consideration of thermal coupling. Furthermore, the thermal impedance matrix for IGBT module, and the thermal coupling matrix for external cooling condition, are completely separated, as can be seen in (3). Therefore, the changes of cooling conditions outside IGBT module can be considered individually.

B. Experimental Characterization and Demonstration

In order to verify the proposed model, several experiments are conducted. First, the measuring points for the case and heatsink should be determined. Then, the elements of proposed model in (3) are characterized by heating up one chip and measuring the thermal responses occurring for all the chips and nodes. Finally, the proposed model with calculated Z_{ch} and Z_{ha} in Fig. 1 should be verified in multichip working conditions.

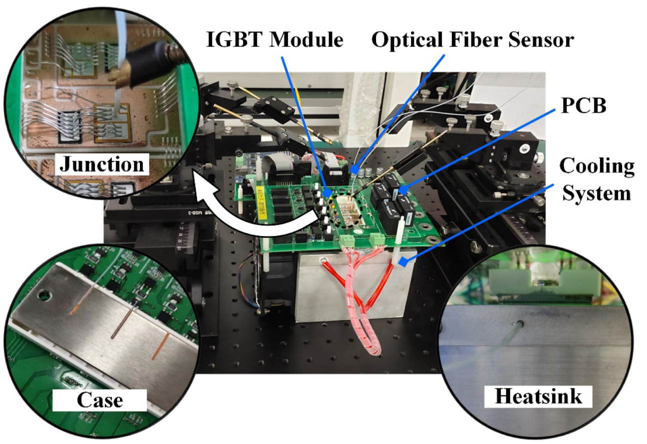

Fig. 2. Experimental setup for thermal characterization of the IGBT module.

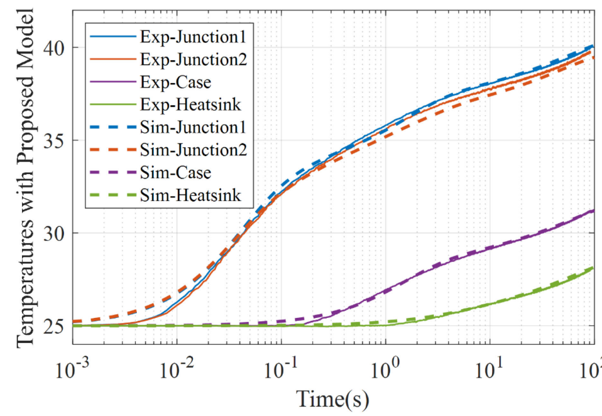

Fig. 4. Comparison of simulated step temperature responses when T1 and T2 are heated with 15 A simultaneously by using the proposed model.

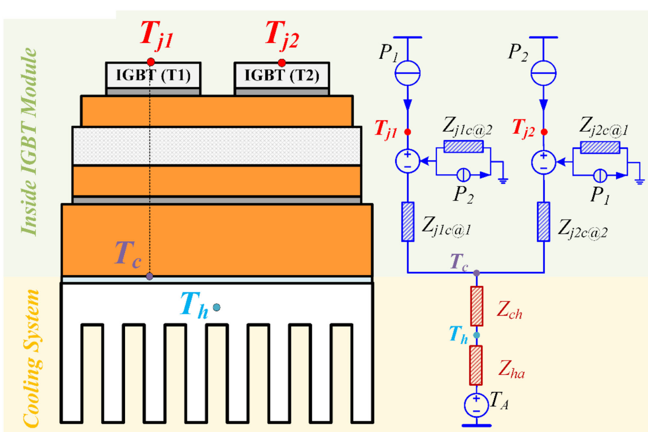

Fig. 3. Locations of measuring points in experiments in cross-sectional view and the proposed model.

A 650 V/75 A IGBT power module is used in this letter, which is composed of six IGBTs and six diodes in three-phase half-bridge configuration. The experimental setup shown in Fig. 2 satisfies standard JESD51-14 [20] and optical fiber sensors are applied here for temperature measurements. The sensors applied in the setup have a measurement range of −40 °C to +250 °C with an accuracy of ±0.3 to 0.8 °C, the response time is limited to 5 ms. The locations of the measuring points are illustrated in Fig. 3: the central junction temperature of chip T1 (T_{j1}), the central temperature of chip T2 (T_{j2}), the case temperature (T_c), and the heatsink temperature (T_h). It shows that the measuring point for case temperature is allied right underneath T1, and the measuring point for heatsink temperature is allied between T1 and T2. The proposed model with calculated Z_{ch} and Z_{ha} in Fig. 1 is also illustrated in Fig. 3, which shows that the nodes in this model strictly correspond to these measuring points.

The thermal coupling effects between two neighbor chips T1 and T2 in Fig. 3 are studied by heating with constant current of 25 A separately, and the transient temperature responses of four measuring points are recorded, respectively. The conduction voltage of T1 is 1.18 V when T1 is heated, so a step power loss of 29.5 W is applied to the chip. The conduction voltage of T2 is 1.20 V when T2 is heated, so a step power loss of 30.0 W is applied to the chip. It should be noted that if the responses of junction and case temperature under step power loss (which contains broad range of frequency components in FFT spectrum) are characterized accurately, the thermal description under most working conditions will work well. Actually, the method of using step conduction loss can reduce uncertainties and errors in loss estimation, and this approach is widely adopted by standards and device manufacturers. When the curves of thermal impedances are extracted, they can be fitted into Foster-type expressions [10], thereby the elements of the proposed model can be characterized from single-chip measurements.

According to the proposed calculation method in (6), the multichip Z_{ch} can be obtained as listed in Table I. Compared with the case-to-heatsink thermal resistance per module provided in datasheet, the thermal resistance of calculated Z_{ch} by proposed method is much larger. To prove the accuracy of proposed model, experimental verification is carried out, and the step responses of two IGBT chips heated simultaneously with 15 A are illustrated in Fig. 4. It shows that the temperature estimation by the proposed thermal coupling model has good agreement with experimental measurements.

C. Comparison of Different Models

The main difference between proposed model and existing models is that the "case temperature" in this proposed model corresponds to a physical point on the surface of the baseplate, but the "case temperature" in existing models refers to a virtual temperature based on the assumption of uniform temperature distribution on the baseplate. Thus, the case temperature in conventional model is usually obtained by backwards calculation from junction temperature that the temperature rise caused by the junction-to-case thermal impedance is subtracted and then step response of calculated case temperature is shown in Fig. 5. It demonstrates that the dynamic performance of calculated case temperature by conventional model has huge deviation under the condition of Fig. 4. As a result, the conventional model is unable to predict case temperature under complex mission profile accurately, so that only junction-to-case thermal resistance is

TABLE I
PROPOSED Z_{ch} AND Z_{ch} FROM DATASHEET

Parameter	*Measured Single-chip Z_{ch} of T_1*	*Measured Single-chip Z_{ch} of T_2*	*Calculated Multi-chip Z_{ch}*	*Z_{ch} per IGBT from Datasheet*	*Z_{ch} per Module from Datasheet*
R_{ch}	0.15 K/W	0.04 K/W	0.0945 K/W	0.198 K/W	0.020 K/W
C_{ch}	8.01 J/K	45.06 J/K	13.68 J/K	–	–

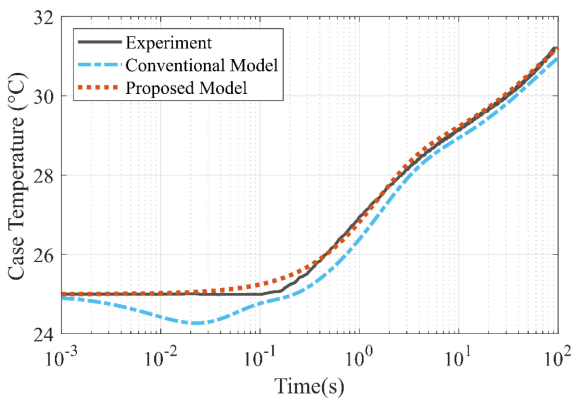

Fig. 5. Case temperature simulated by conventional model and proposed model under the condition of Fig. 4.

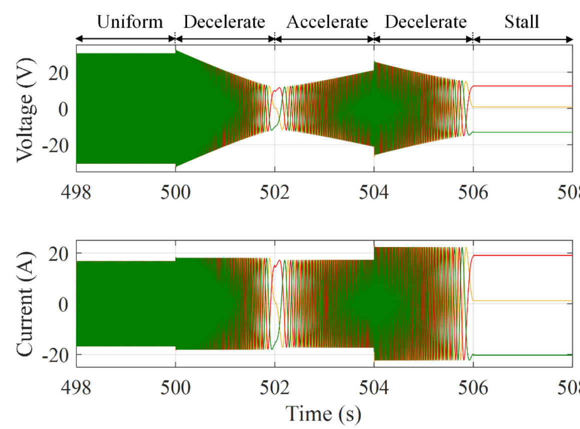

Fig. 6. Three-phase voltage and current waveforms of the system with designed electric machine drive mission profile.

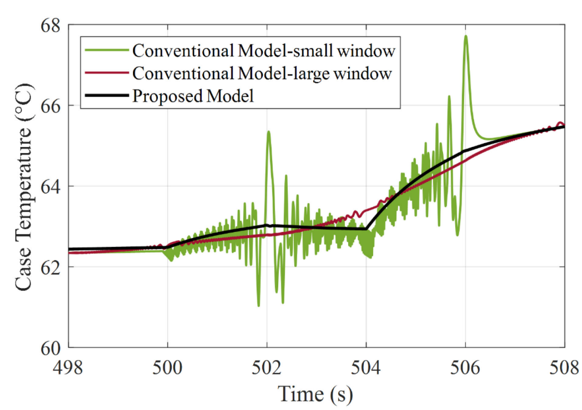

Fig. 7. Simulated case temperature with different models under electric machine drive mission profile of Fig. 6.

considered to calculate the case temperature as stated in [10]. Therefore, the proposed model can provide more information than conventional model since the case temperature simulated by proposed model has good agreement with experimental result in full bandwidth.

III. Application, Advantages, and Discussions

A. Measurement Points for Case Temperature

The case node in this model can be any point on the baseplate of the module, so the thermal impedance of junction to case cannot be simply set as the one provided by the datasheets from manufacturers. But for simplicity, it is recommended to select the center point as case reference. For example, if the center point underneath the module is selected as the case temperature for a module composed of six IGBTs and six diodes, only half thermal impedances between junction and case need to be measured and the remaining thermal impedances can be set as the same as the corresponding ones because of the centrosymmetric layout of the chips. In practice, the internal negative temperature coefficient (NTC) resistor can be applied to measure the baseplate temperature. In this case, the thermal impedance between each junction and the case should be measured because NTC is usually located at the edge of the module.

B. Advantages of Proposed Model and Some Applications

One of the advantages of the proposed model is that it can be applied for electro-thermal simulations, so the thermal behaviors under any complex mission profile can be accurately estimated. An example of electric machine drive mission profile is designed for case study here and the electro-thermal simulation is carried out by using PLECS. Fig. 6 illustrates the three-phase voltage and current waveform of this mission profile and the predicted case temperature by proposed model is plotted in Fig. 7. As for the conventional model, it is complicated to calculate the case temperature from junction temperature under this complex mission profile because the rapid temperature fluctuation will not happen at the baseplate, thereby filtering algorithm is needed. Fig. 7 illustrates the case temperature predicted by conventional model applying moving average filter with two different parameters. It can be seen that the filter parameter has a huge impact on the prediction of case temperature, so it is rather complicated for conventional model to provide accurate case temperature under complex mission profiles.

TABLE II
PROPOSED CALCULATED Z_{ch} UNDER DIFFERENT COOLING SYSTEMS

Parameter	*Natural Cooling*	*Air Cooling with Fan Speed of 1.0 m/s*
R_{chM}	0.0945 K/W	0.0829 K/W
C_{chM}	13.68 J/K	14.57 J/K

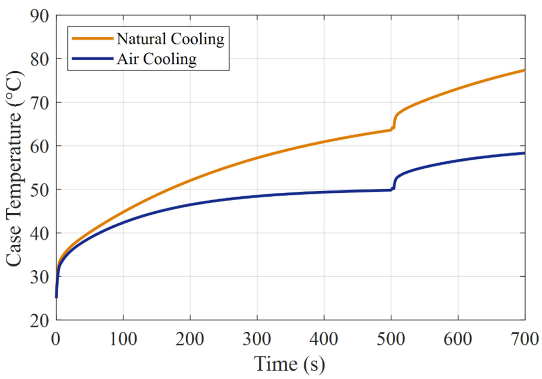

Fig. 8. Case temperature with different cooling conditions under the mission profile of Fig. 6.

Since the thermal coupling impedance inside device and the one outside device is decoupled in this proposed model, the case temperature under different cooling systems can be compared by simply changing the outside thermal impedance Z_{ch} and Z_{ha}. An example of two different cooling conditions is considered in this letter: natural cooling and air cooling with fan speed of 1.0 m/s. Table II shows the proposed Z_{ch} under the two different cooling systems and the corresponding case temperatures with the mission profile of Fig. 6 is shown in Fig. 8.

IV. CONCLUSION

This letter introduces a novel matrix-based thermal coupling model by using case temperature as reference node for transient thermal coupling analysis of the multichip IGBT modules. In this model, the thermal impedance for the thermal grease and heatsink considering thermal coupling effect is proposed and the detailed calculation process is introduced. The main advantage of the proposed model is that it separates the external cooling system and the IGBT module while modeling, thereby the changes happened outside can be considered. The accuracy of proposed model is verified through experiments.

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