Letters

An Online Frequency-Domain Junction Temperature Estimation Method for IGBT Modules

Ze Wang and Wei Qiao

***Abstract*—This letter proposes a new frequency-domain thermal model for online junction temperature estimation of insulated-gate bipolar transistor (IGBT) modules. The proposed model characterizes the thermal behavior of an IGBT module by a linear time-invariant (LTI) system, whose frequency response is obtained by applying the fast Fourier transform (FFT) to the time derivative of the transient thermal impedance from junction to a reference position of the IGBT module. The junction temperature of the IGBT is then estimated using the frequency responses of the LTI system and the heat sources of the IGBT module. Simulation results show that the proposed method is computationally efficient for an accurate online junction temperature estimation of IGBT modules in both steady-state and transient loading conditions.**

***Index Terms*—Fast Fourier transform (FFT), frequency domain, insulated-gate bipolar transistor (IGBT), junction temperature, linear time-invariant (LTI) system, online estimation.**

I. INTRODUCTION

ONLINE junction temperature is the crucial information for effective thermal management of insulated-gate bipolar transistor (IGBT) modules to ensure their safe operation. The junction temperature of an IGBT module is usually estimated online by using a thermal model, which characterizes the dynamical thermal behavior of the IGBT module. The most commonly used online thermal models are thermal equivalent circuits [1]–[4], such as the Foster- or Cauer-type thermal equivalent circuits. The thermal equivalent circuits, however, cannot provide accurate junction temperature estimation in fast-varying loading conditions due to their unsatisfactory transient responses. A Fourier technique-based junction temperature estimation method was reported in [5], where the time-domain power loss of the IGBT module was represented by Fourier series and the thermal impedance of the IGBT module was characterized in the frequency domain from the frequency response of a classical transient thermal equivalent circuit. Then, the junction temperature of the IGBT was estimated in the frequency domain. However, that method still relied on the accuracy of the classical thermal equivalent circuit. Three-dimensional thermal models generated by numerical methods [6] could have good transient performance. However, they are computational intensive and, therefore, are impractical for online implementation. Analytical methods [7], [8] can balance between accuracy and efficiency but often use series approximations, which are subject to problems such as series truncation and convergence [9]. Thus, a computationally efficient method that has high accuracy in both steady-state and transient conditions is still desired for online junction temperature estimation of IGBT modules.

This letter proposes a new frequency-domain method for online junction temperature estimation of IGBT modules. The method characterizes the dynamical thermal behavior of an IGBT module by a linear time-invariant (LTI) system, whose frequency response is obtained by applying the FFT to the data of the time derivative of the transient thermal impedance of the IGBT module obtained from numerical simulations or experiments in the time domain. Then, the junction temperature of the IGBT module is estimated online in the frequency domain based on the frequency responses of the LTI system and the heat sources of the IGBT module. Simulation studies are performed to compare the proposed method with the finite-element analysis (FEA) method and the equivalent thermal circuit model provided by the manufacturer for junction temperature estimation of a commercial IGBT module.

II. PROPOSED ONLINE JUNCTION TEMPERATURE ESTIMATION METHOD

The IGBTs with the "standard" power module packaging [10] are considered herein. During the operation of an IGBT module, the heat is generated at the chips and spreads through multiple layers to the bottom of the baseplate, which is cooled by a heat sink or cold plate. The heat conduction in the heat diffusion layers is governed by the Fourier's law. By assuming that the materials are isotropic and neglecting the temperature effects of the materials' thermal properties, a differential form of the Fourier's law governing the heat diffusion in a certain layer in the rectangular coordinate system is given by

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \tag{1}$$

where T is the temperature and α is the thermal diffusivity of the material of the layer. The thermal dynamics of the overall IGBT module can be modeled by the equations similar to (1) for all the layers constrained by the boundary conditions between different layers.

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The exact solution to (1) can be very complex if the module geometry and boundary conditions are taken into account. However, since (1) is linear, the dynamical thermal behavior of an IGBT module can be characterized by an LTI system by neglecting the cooling system performance variations. In this section, the relationship between an IGBT's power loss $p_{\rm loss}(t)$ and the temperature rise from junction to case $\Delta T_{jc}(t)$, is characterized by a high-order LTI system $h_{pj}(t)$, which represents the time-domain impulse response of $\Delta T_{jc}(t)$ excited by the heat source $p_{\rm loss}(t)$. The junction temperature $T_j(t)$ is then given by

$$T_j(t) = \Delta T_{jc}(t) + T_c(t) = p_{\rm loss}(t) * h_{pj}(t) + T_c(t). \qquad (2)$$

In this letter, $T_j(t)$ is estimated in the frequency domain as follows using the Fourier transform technique to avoid determination of the explicit expression for $h_{pj}(t)$ and calculation for the convolution between $p_{\rm loss}(t)$ and $h_{pj}(t)$

$$\begin{aligned} T_j(t) &= p_{\rm loss}(t) * h_{pj}(t) + T_c(t) \\ &= F^{-1}(P_{\rm loss}(e^{j\omega}) \cdot H_{pj}(e^{j\omega})) + T_c(t) \qquad (3) \end{aligned}$$

where $P_{\rm loss}(e^{j\omega})$ is the frequency spectrum of $p_{\rm loss}(t)$ obtained by using the Fourier transform, $H_{pj}(e^{j\omega})$ is the frequency response of $h_{pj}(t)$ obtained by using the Fourier transform, and F^{-1} is the inverse Fourier transform. The $h_{pj}(t)$ can be determined by taking the time derivative of the transient thermal impedance $Z_{jc}(t)$ from junction to case, i.e.

$$h_{pj}(t) = \frac{dZ_{jc}(t)}{dt}. \qquad (4)$$

The values of $Z_{jc}(t)$ can be easily obtained from FEA simulations or experiments.

For a compact IGBT module consisting of multiple heat sources, the superposition principle can be applied to characterize the thermal behavior of the whole IGBT module to obtain the junction temperatures at multiple chips of interest. The matrix form of the proposed method to obtaining the junction temperatures of *n* chips of interest for an IGBT module with *m* heat sources is given by

$$\begin{bmatrix} T_{j1} \\ T_{j2} \\ \vdots \\ T_{jN} \end{bmatrix} = F^{-1}\left(\begin{bmatrix} H_{11} & H_{12} & \cdots & H_{1M} \\ H_{21} & H_{22} & \cdots & H_{2M} \\ \vdots & \vdots & \ddots & \vdots \\ H_{N1} & H_{N2} & \cdots & H_{NM} \end{bmatrix} \begin{bmatrix} P_1 \\ P_2 \\ \\ P_M \end{bmatrix} \right) + T_c \cdot \mathbf{1}_{1\times N} \qquad (5)$$

where $H_{nm}(n = 1, \ldots, N \text{ and } m = 1, \ldots, M)$ is the frequency response of the temperature rise from the *n*th junction to case excited by the *m*th source P_m, and $\mathbf{1}_{1\times N}$ is a *N*-dimensional column vector with all elements being 1. The value of H_{nm} can be determined by the Fourier transform of the time derivative of $Z_{nm}(t)$, which is the equivalent transient thermal impedance from the *n*th junction to case when only the *m*th source is powered. The value of $Z_{nm}(t)$ can be obtained from FEA simulations or experiments.

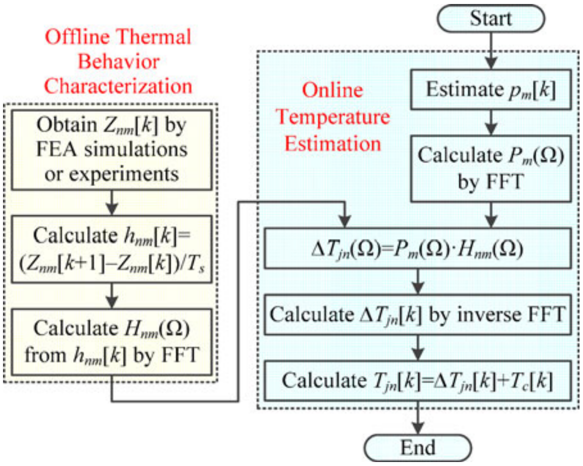


Fig. 1. Flowchart of the proposed method.

In digital system applications, the discrete-time form of (3) is given by

$$\begin{aligned} T_j[k] &= p_{\rm loss}[k] * h_{pj}[k] \cdot T_s + T_c[k] \\ &= F^{-1}(P_{\rm loss}(\Omega) \cdot H_{pj}(\Omega)) \cdot T_s + T_c[k] \qquad (6) \end{aligned}$$

where *k* is the index of the discrete-time sequence, T_s is the sampling period, $P_{\rm loss}(\Omega)$ is the discrete Fourier transform (DFT) of $p_{\rm loss}[k]$, $H_{pj}(\Omega)$ is the frequency response of $h_{pj}[k]$, and $h_{pj}[k]$ can be calculated by

$$h_{pj}[k] = \frac{Z_{jc}[k+1] - Z_{jc}[k]}{T_s}. \qquad (7)$$

The DFT can be efficiently computed using the FFT. The flowchart of the proposed method is illustrated in Fig. 1.

The proposed method has the following advantages.

1) *High Accuracy:* The accuracy of the proposed method relies on the accuracy of $h_{pj}(t)$ of the IGBT module, which can be estimated offline accurately. Therefore, the proposed method is capable of approximating the accurate numerical thermal model obtained from FEA simulations or the experiment measurements online with a good precision.
2) *Computational Efficient:* The computational cost of the proposed method depends on the sampling frequency of the quantities in (5). According to the Nyquist–Shannon sampling theorem, the sampling frequency f_{sw} of the power losses in (5) should be more than twice the highest harmonics of the power losses. According to the power loss calculation equations in [11], the highest harmonics of the power losses in an inverter are just several times higher than the line frequency, if the power losses are averaged over each switching period. Thus, the proposed method does not require a high sampling frequency. The proposed method has a computational complexity of O($K \times \log_2 N_l$), where *K* is the number of the time-domain data samples of the power losses and N_l is the order of the LTI system. The value of N_l is the product of the sampling frequency (e.g., 1 kHz) and the settling time to the steady state (typically, 5–10 s) of the transient response of

TABLE I
MATERIAL PROPERTIES OF THE IGBT MODULE

Material	Mass Density (kg/m^3)	Thermal Conductivity (W/(m · °C))	Specific Heat (J/(kg · °C))
Silicon	2329	119	755
Solder	7400	63.2	230
Copper	8890	383	385
ALN	3260	180	740

the time-domain thermal impedance. The computational complexity of the proposed method is in the same order as that of a thermal equivalent circuit model O($K \times N_{rc}$), where N_{rc} is the order of the thermal equivalent circuit. Therefore, the proposed method is computationally efficient for online junction temperature estimation.

3) *Easy to Build:* The derivation of a high-fidelity analytical thermal model from physical principles or the extraction of a high-fidelity low-order numerical thermal model from a high-order numerical thermal model of an IGBT module usually involves significant mathematical complexity and difficulty, especially when the target IGBT module has high geometry complexity and multichip thermal crossing coupling. The proposed method does not have any problem with mathematical complexity or difficulty.

III. SIMULATION VALIDATION

A. *Offline Thermal Behavior Characterization for an IGBT Module*

Simulation studies are performed to validate the proposed method against a FEA thermal model built in Autodesk Simulation Multiphysics (i.e., the reference model) and the fourth-order thermal equivalent circuit model provided by the manufacturer [12] for junction temperature estimation of a commercial IGBT module CM400DY-12NF. The IGBT module has a half-bridge configuration. Each IGBT switch on a direct bond copper (DBC) stack consists of two IGBT chips in parallel, and each IGBT chip has a free-wheeling diode (FWD) connected in antiparallel. The IGBT module has a typical high-power module architecture [10], which is a multilayer structure with an aluminum nitride (ALN) ceramic layer and a copper baseplate. The layer thickness information of the IGBT module is provided by Powerex Inc. The material properties are provided in Table I.

In the FEA thermal model, a fine mesh is used for the chips, solder interfaces, and DBC stack; while a relatively coarse mesh with 7551 three-dimensional (3-D) elements is used for the baseplate. The total mesh of the FEA thermal model of the IGBT module has 25 955 3-D elements and 39 090 nodes. Assume that the power losses are generated inside the chips close to their top surfaces [8]. Therefore, the calculated power losses can be converted to heat fluxes applied at the top surfaces of the chips [3]. The cooling for the IGBT module is simplified to heat convection at the bottom surface of the baseplate with a constant heat convection rate of 10 000 W/(m^2 · °C). The ambient temperature is 65 °C. The IGBT module is operated as a leg in a two-level three-phase inverter. The case temperature is measured at the point specified on the Outline Drawing and Circuit Diagram on the datasheet [13] of the IGBT module.

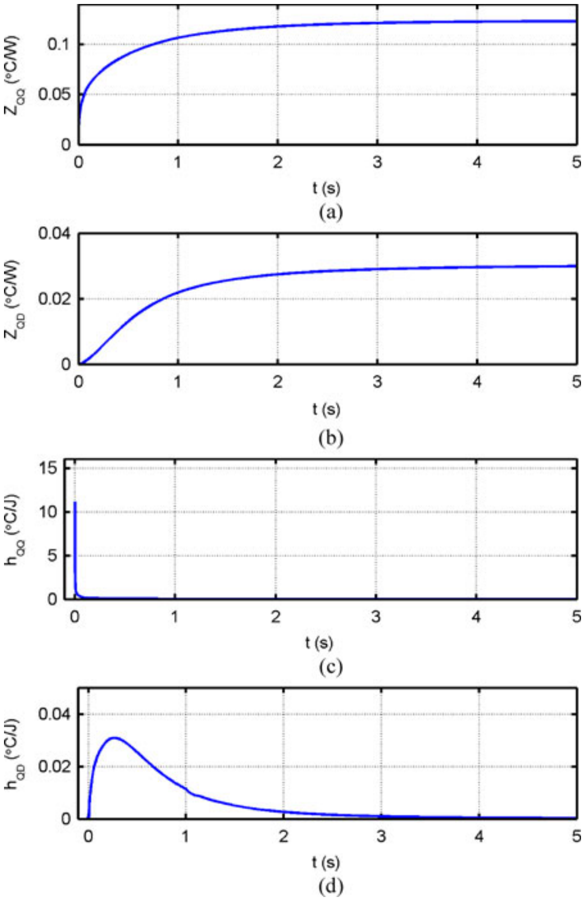


Fig. 2. Transient thermal impedance responses from the junction of the IGBT chip to case and the corresponding LTI system responses: (a) $Z_{QQ}(t)$; (b) $Z_{QD}(t)$; (c) $H_{QQ}(t)$; and (d) $H_{QD}(t)$.

The transient thermal impedances from the junction of the IGBT chip to case, $Z_{QQ}(t)$ and $Z_{QD}(t)$, which are obtained when the IGBT chip is powered alone and its parallel FWD is powered alone, respectively, are shown in Fig. 2. The settling times to the steady state of $Z_{QQ}(t)$ and $Z_{QD}(t)$ are 5 s. The $h_{QQ}(t)$ and $h_{QD}(t)$ in Fig. 2, which are determined by taking the time derivatives of $Z_{QQ}(t)$ and $Z_{QD}(t)$, respectively, are the impulse responses of the LTI systems characterizing the relationships between the IGBT junction temperature and the power losses generated by the IGBT and the FWD, respectively. The sampling frequency is 1 kHz for the proposed method. Therefore, the order of the LTI systems used in the proposed method is 5000.

B. *Online Junction Temperature Estimation for the IGBT Module*

A transient load, which mimics the starting process of an electric motor in a hybrid electric vehicle (HEV), is applied to the

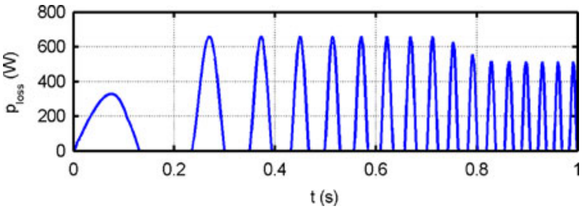
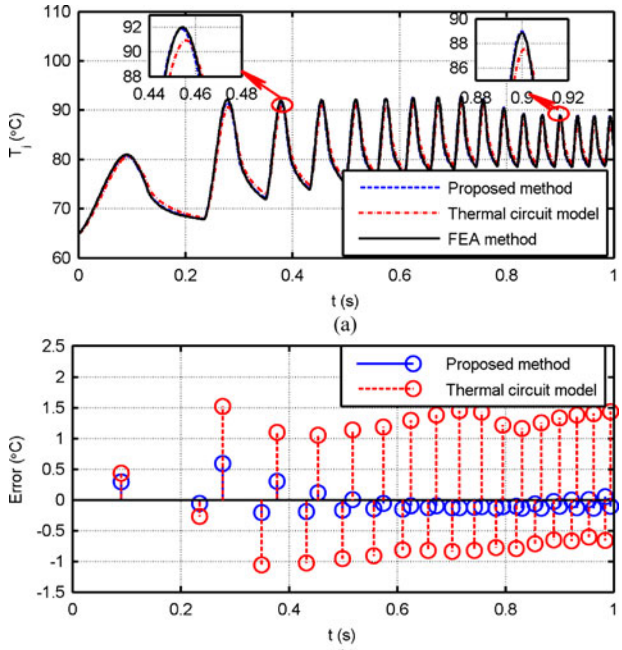


Fig. 3. Total power loss profile of the IGBT chips in one switch of the IGBT module in a transient load condition.



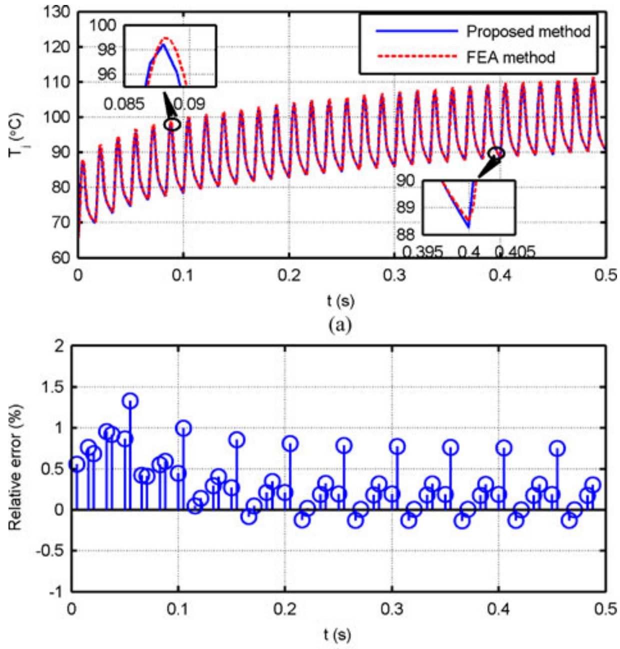
(a)

(b)

Fig. 4. Comparison $T_j(t)$ estimated by the three methods when the inverter is operated with a transient load: (a) junction temperature; and (b) error at peaks and valleys with respect to the FEA method.

inverter to evaluate the accuracy of the proposed method for online junction temperature estimation. The rotor speed of the motor is accelerated from 0 r/min at 0 s to 500 r/min at 1 s. The currents through the IGBT module during this period are generated by simulating an HEV powertrain using battery model provided by the MATLAB/Simulink example library. In a thermal equivalent circuit model, since the thermal equivalent circuits from junction to case of the IGBTs and the FWDs are only interconnect at the heatsink, the thermal cross-coupling effects between chips in an IGBT module can only be partially addressed [14]. Thus, for fair comparison between different methods, the thermal couplings between IGBTs and FWDs are neglected in all of the three models. The power losses generated by the chips are calculated based on the simulated currents as well as the conduction voltage–current curve and switching loss–current curve provided by the datasheet of the IGBT module [13]. The total power loss profile of the IGBT chips in one switch of the module is shown in Fig. 3, where the power loss is averaged over each switching period.

Fig. 4(a) compares the values of the junction temperature $T_j(t)$ estimated by the proposed model, the thermal equivalent circuit, and the FEA method. The values of $T_j(t)$ fluctuates in the range of 10–15 °C. The value of $T_j(t)$ obtained from the proposed method matches that of the FEA method better than the thermal equivalent circuit. As shown in Fig. 4(b), the errors of the junction temperature estimated by the proposed method at its peaks and valleys are almost less than 0.2 °C with the maximum of 0.6 °C at 0.28 s during the transient load. On the other hand, the errors of the equivalent thermal circuit model are between 1 and 1.6 °C at the peaks and between 0.6 and 1.1 °C at the valleys. The results show that in general the junction temperature estimation error of the proposed method is less than 20% of that of the equivalent thermal circuit model. Moreover, when the line frequency of the inverter increases, the relative error of $T_j(t)$ obtained from the equivalent thermal circuit model with respect to its amplitude of variations in one cycle increases because of more dynamic changes in the power loss. However, the increase of the inverter line frequency does not affect the proposed method, as long as the highest harmonic of the power loss is lower than half of the sampling frequency of the power loss.



(a)

(b)

Fig. 5. Comparison of $T_j(t)$ estimated by the proposed method and the FEA method when the inverter is operated at a constant operating condition: (a) junction temperature; (b) relative error at peaks and valleys with respect to the FEA method.

The proposed method is further examined by comparing with the FEA method at a constant operating point of the converter: 400 V dc-link voltage, 400 A output current, power factor of 0.8, unity modulation index, 5 kHz switching frequency, and 60 Hz line frequency. In this study, the thermal couplings between the chips of IGBTs and FWDs are considered in both models to further examine the capability of the proposed method for handling the thermal coupling effects. The results in Fig. 5 show a negligible difference between the proposed method and the FEA method because the relative error of the junction temperature estimated by the proposed method is almost always less than 1% with respect to that obtained from the FEA method.

IV. CONCLUSION

This letter has proposed a computationally efficient, high-fidelity, easily built, online, frequency-domain junction temperature estimation method for IGBT modules.The proposed method characterized the dynamical thermal behavior of an IGBT module by an LTI system, which approximated an FEA thermal model for the IGBT. The junction temperature was then estimated from the FTT-based frequency responses of the LTI system and the heat sources of the IGBT module. The proposed method removed the need of deriving an explicit expression of the system's transfer function and could be easily built using numerical simulations or experiments. The proposed method has been validated by simulation studies for a commercial IGBT module. Results have shown that the accuracy, particularly the accuracy during transient operating conditions, of the proposed method is comparable to the FEA method and is much higher than the commonly used equivalent thermal circuit model. However, the computational cost of the proposed method is much lower than that of the FEA method and is comparable to the equivalent thermal circuit model. In addition to junction temperature, the proposed method can also be used to estimate the temperatures at any other points of interest in an IGBT module.

REFERENCES

[1] K. Ma, A. S. Bahman, S. Beczkowski, and F. Blaabjerg, "Complete loss and thermal model of power semiconductors including device rating information," *IEEE Trans. Power Electron.*, to be published.

[2] A. Castellazzi, "Comprehensive compact models for the circuit simulation of multichip power modules," *IEEE Trans. Power Electron.*, vol. 25, no. 5, pp. 1251–1264, May 2010.

[3] M. Musallam and C. M. Johnson, "Real-time compact thermal models for health management of power electronics," *IEEE Trans. Power Electron.*, vol. 25, no. 6, pp. 1416–1425, Jun. 2010.

[4] P. L. Evans, A. Castellazzi, and C. M. Johnson, "Automated fast extraction of compact thermal models for power electronic modules," *IEEE Trans. Power Electron.*, vol. 28, no. 10, pp. 4791–4802, Oct. 2013.

[5] J. J. Nelson, G. Venkataramanan, and A. M. El-Refaie, "Fast thermal profiling of power semiconductor devices using Fourier techniques," *IEEE Trans. Ind. Electron.*, vol. 53, no. 2, pp. 521–529, Apr. 2006.

[6] N. Rinaldi, "On the modeling of the transient thermal behavior of semiconductor devices," *IEEE Trans. Electron Devices*, vol. 48, no. 12, pp. 2796–2802, Dec. 2001.

[7] M. Janicki, G. De Mey, and A. Napieralski, "Transient thermal analysis of multilayered structures using Green's functions," *Microelectron. Reliab.*, vol. 42, no. 7, pp. 1059–1064, Jul. 2002.

[8] B. Du, J. L. Hudgins, E. Santi, S. Member, A. T. Bryant, P. R. Palmer, and H. A. Mantooth, "Transient electrothermal simulation of power semiconductor devices," *IEEE Trans. Power Electron.*, vol. 25, no. 1, pp. 237–248, Jan. 2010.

[9] K. Cole, A. Haji-Sheikh, J. Beck, and B. Litkouhi, *Heat Conduction Using Green's Functions*, 2nd ed. New York, NY, USA: CRC Press, 2011.

[10] J. Lutz, H. Schlangenotto, U. Scheuermann, and R. D. Doncker, *Semiconductor Power Devices: Physics, Characteristics, Reliability*. Berlin, Germany: Springer-Verlag, 2011.

[11] L. Wei, J. Mcguire, R. A. Lukaszewski, and S. Member, "Analysis of PWM frequency control to improve the lifetime of PWM inverter," *IEEE Trans. Ind. Appl.*, vol. 47, no. 2, pp. 922–929, Mar.–Apr. 2011.

[12] *Normalized Transient Thermal Impedance (Z_{th}) Using T_c Reference Point Under Chip for 600 V and 1200 V A, NF, NFH and S Series IGBT modules*, Powerex, Appl. Note, 2012.

[13] Mitsubishi, "Mitsubishi IGBT module CM400DY-12NF," CM400DY-12NF datasheet, Feb. 2009.

[14] T. Poller and S. D'Arco, "Influence of thermal cross-couplings on power cycling lifetime of IGBT power modules," in *Proc. 7th Int Conf. Integr. Power Electron. Syst.*, Mar. 2012, pp. 1–6.