Letters

A Thermal Modeling Method Considering Ambient Temperature Dynamics

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***Abstract*—This letter proposes a thermal modeling method for power electronic components. It represents the thermal dynamics introduced by the ambient temperature variation, which cannot be achieved by existing analytical methods. By using the superposition theorem and time-domain analysis, the limitations of the existing analytical method based on stable ambient temperature are investigated. Then, the proposed thermal modeling method, which considers the thermal dynamics from both power loss and ambient temperature disturbances, is presented. In order to obtain the thermal coefficients in the proposed model, two solutions are provided based on frequency-domain modeling. Experimental verification is given to proof the accuracy of the proposed thermal modeling method considering the ambient temperature dynamics.**

***Index Terms*—Ambient temperature, mission profile, power electronic components, thermal dynamics, thermal model.**

I. INTRODUCTION

IT HAS been revealed that the thermal stress is one of the most critical stressors in a power electronic system . For power semiconductor devices, the temperature variation may cause fatigues like bond-wire lift-off and cracks on the soldering layer and the thermal grease. For power capacitors, thermal stress and its variation result in the reduction of capacitance and the increase of equivalent series resistance (ESR) [1]. Therefore, thermal modeling is essential, and its accuracy has a significant impact on the thermal management, reliability prediction, and system protection. This letter proposes a novel thermal modeling method with improved accuracy for power electronic components, which considers the thermal dynamics from both the self-heating and ambient temperature. It has the following features: first, it represents the thermal dynamics from the ambient temperature, which cannot be neglected for the components with the same level of time constant with the ambient temperature profile (e.g., capacitor, inductor, and heat sink). Second, it is an analytical model with accessible thermal coefficients, which is suitable for long-term thermal analysis with an ambient temperature and power loss profile.

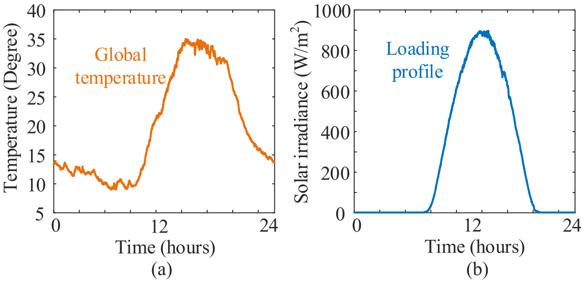

Fig. 1. Long-term mission profile in a photovoltaic application of Denmark [4]. (a) Daily global ambient temperature. (b) Daily loading profile.

Existing thermal modeling methods for long-term thermal analysis are based on the thermal impedance of power components, power loss profile, and a stable ambient temperature. A Cauer model based on the physical structure of the component is considered to be a relatively correct model to describe the thermal behaviors. However, it is hard to use because of the thermal impedance based on internal geometry, and materials have all to be determined with the help of finite-element method simulation, and its analytical model is complex and time-consuming for long-term thermal analysis [2]. Therefore, in the literature, the Foster model with its analytical model is an often used method [3]. It is based on the measurement of temperature dynamics of power components and then mathematical fitting of the measured/simulated temperature curves. By using this model, the dynamic thermal behaviors can be guaranteed, provided with a power loss profile. But it cannot represent the thermal dynamics from the local ambient temperature, which is affected by both the global ambient (i.e., ambient temperature outside an enclosure) and internal power losses and thermal dissipations within the enclosure of a power electronic system. For example, Fig. 1 shows a daily profile in Denmark [4], which introduces 30°–60° variation of local ambient temperature. Due to the large time constant of passive components, the temperature of the hotspot or junction with the ambient temperature variation should be flat. However, by using the existing model, the temperature of the components would experience a variation immediately, which results in overestimation.

This letter investigates the limitation of the existing thermal modeling methods from the ambient temperature variation aspect. Then, a thermal modeling method considering both the self-heating and the ambient temperature profile is proposed

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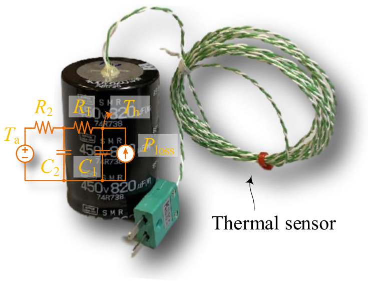

Items	Value
Cauer	
R_1	4.4 K/W
C_1	365 J/K
R_2	4.1 K/W
C_2	188 J/K
Foster	
R_1	3.4 K/W
C_1	342 J/K
R_2	5.2 K/W
C_2	228 J/K

Fig. 2. Capacitor under testing as reference for study and its thermal parameters.

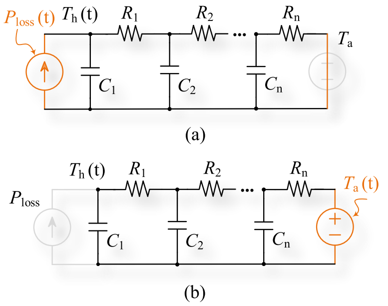

Fig. 3. Equivalent circuit diagram of the Cauer model with the superposition theorem. (a) Current source works. (b) Voltage source works.

with the help of frequency-domain modeling [5]. The proposed method can improve the accuracy of the temperature estimation significantly. The rest of this letter is structured as follows. Section II presents the limitation of the existing thermal modeling methods. Section III discusses the proposed model with its coefficient extraction method. Section IV verifies the accuracy of the proposed model, followed by the conclusions.

II. LIMITATION OF EXISTING THERMAL MODELING METHODS

A Cauer model is considered as the correct model, which is analyzed first as a reference. Then, the limitation of the Foster model and its analytical model is discussed. The quantitative results in following analysis are based on the coefficients of a given capacitor in Fig. 2, which are extracted from testing.

A. Thermal Network Modeling With the Superposition Theorem

The thermal model can be analyzed as an electrical circuit. Therefore, the superposition theorem can be applied to evaluate the impact from heat source (current source) and ambient temperature (voltage source) disturbances, separately. The circuit diagrams of the Cauer model based on the superposition theorem are shown in Fig. 3. When the heat source is applied, the voltage source is short circuit. When the ambient temperature disturbance is applied, the heat source is open circuit. It can be seen that the self-heating and ambient temperature disturbances introduce different thermal dynamics on the hotspot. The Cauer model is assumed to correctly present the thermal behavior of the power components, but it is complex to derive the high-order analytical model and time-consuming for long-term thermal analysis [6].

The circuit diagrams of the Foster model with self-heating and ambient temperature disturbances are shown in Fig. 4.

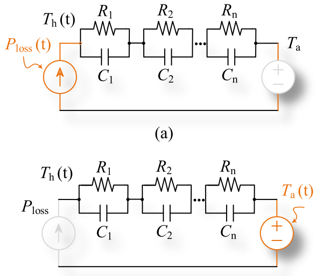

Fig. 4. Circuit diagram of the Foster model with the superposition theorem. (a) Current source works. (b) Voltage source works.

The thermal dynamics can be represented correctly, when the self-heating disturbance is applied. However, when the ambient temperature disturbance is considered, the ambient temperature variation would appear at the hotspot immediately without any dynamic process due to the open circuit of the heat source. This phenomenon can also be found in the analytical model, which is discussed in Section II-B.

B. Limitation of the Existing Methods

The general analytical model commonly used to estimate the hotspot temperature is

$$T_{\mathrm{h}} = P_{\mathrm{loss}} Z_{T_{\mathrm{h}}} + T_{\mathrm{a}} \tag{1}$$

where T_{a} and T_{h} are the ambient and hotspot temperatures, respectively. $Z_{T_{\mathrm{h}}}$ represents the thermal impedance from hotspot to the ambient, which can be derived from the Cauer model or the Foster model. This commonly used analytical model has the same thermal behavior with the Foster model, which represents the thermal dynamic of the self-heating, while cannot represent the thermal dynamic from the ambient temperature. The thermal dynamics of the referred Cauer model and the existing analytical model in (1) with self-heating and ambient temperature disturbances in the time domain are shown in Fig. 5. At the beginning, only the power loss disturbance P_{loss} is introduced; the two models present the same thermal dynamics. At the time of 3600 s, the ambient temperature begins to increase. The estimated temperature based on the existing analytical model increases immediately, while the temperature from the referred Cauer model increases slowly due to large thermal capacitance.

From the above analysis, the limitation of the existing thermal model can be seen as follows: when the ambient temperature profile is applied to the existing analytical thermal model, the thermal dynamic of the temperature variation cannot be seen in the hotspot, while instead of a temperature jump.

III. PROPOSED THERMAL MODELING METHOD CONSIDERING AMBIENT TEMPERATURE DYNAMICS

A. Proposed Thermal Model

Based on the limitation of the existing analytical model, a new thermal modeling method considering the ambient temperature disturbance is proposed, which can be written as

$$T_{\mathrm{h}} = P_{\mathrm{loss}} Z_{T_{\mathrm{h}}}(s) + T_{\mathrm{a}} G_{T_{\mathrm{a,h}}}(s). \tag{2}$$

A transfer function $G_{T_{\mathrm{a,h}}}(s)$ from the ambient temperature to the hotspot temperature is added in the thermal model. Therefore, the thermal dynamics from both self-heating and ambient

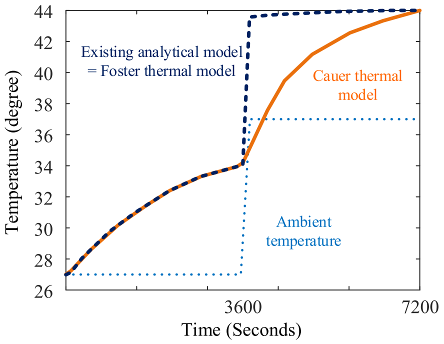

Fig. 5. Thermal dynamic comparison between simulation results of the Cauer model, the Foster model, and the existing analytical thermal model, where the ambient temperature raises from 27° to 37° at 3600 s.

temperature disturbances can be considered for thermal analysis. The issue is to determine $G_{T_{\mathrm{a,h}}}(s)$.

B. Suggested Solutions to Obtain $G_{T_{\mathrm{a,h}}}(s)$

Two solutions to obtain the transfer function $G_{T_{\mathrm{a,h}}}(s)$ are provided in this section based on the Cauer model and the Foster model, respectively.

1) Cauer-Model-Based Method: If the detailed Cauer model can be acquired, the following analytical model with high accuracy can be used to derive $G_{T_{\mathrm{a,h}}}(s)$. Based on the circuit analysis, the frequency-domain transfer function from heat disturbance to the temperature of layer x can be modeled as

$$\begin{cases} Z_{T_{\mathrm{x,a}}}(s) = \dfrac{1}{\frac{1}{R_{\mathrm{x}}+Z_{T_{\mathrm{x+1,a}}}(s)}+C_{\mathrm{x}}s}, & (x=1,2..,n-1)\\[2ex] Z_{T_{\mathrm{x,a}}}(s) = \dfrac{1}{\frac{1}{R_{\mathrm{x}}}+C_{\mathrm{x}}s}, & (x=n) \end{cases} \tag{3}$$

where n is the number of layers and $Z_{T_{\mathrm{x,a}}}(s)$ is the impedance from layer x to the ambient temperature. R_{x} and C_{x} represent the thermal resistance and the capacitance of each layer of the power components, respectively. The frequency-domain transfer function from the ambient temperature disturbance to the temperature difference between layer x and the ambient temperature is

$$G_{T_{\mathrm{a,x}}}(s) = \prod_{k=n}^{x} G_{\mathrm{k}}(s)$$
$$\begin{cases} G_{\mathrm{k}}(s) = \dfrac{1/C_1 s}{1/C_1 s + R_1}, & (k=1)\\[2ex] G_{\mathrm{k}}(s) = \dfrac{\frac{R_{\mathrm{k-1}}}{1-G_{\mathrm{k-1}}(s)}//\frac{1}{C_{\mathrm{k}}s}}{\frac{R_{\mathrm{k-1}}}{1-G_{\mathrm{k-1}}(s)}//\frac{1}{C_{\mathrm{k}}s}+R_{\mathrm{k}}}, & (k=2,3,\ldots,n) \end{cases} \tag{4}$$

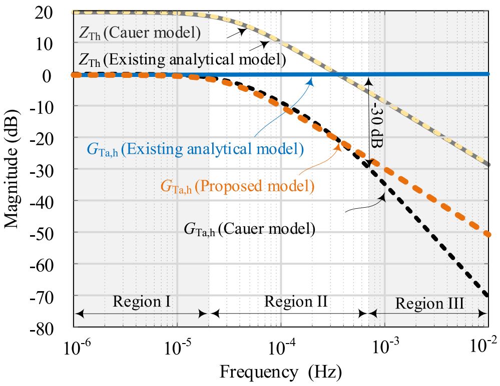

Fig. 6. Bode plot of critical gains in $Z_{T_{\mathrm{h}}}(s)$ and $G_{T_{\mathrm{a,h}}}(s)$ using the referred Cauer model, the existing thermal model, and the proposed thermal model in the frequency domain.

where $G_{\mathrm{k}}(s)$ is the transfer function of temperature from layer $k+1$ to k. The derived analytical model is a general one, which can be applied to other power components. As an example, the two-order capacitor thermal model is shown in (5) shown at the bottom of this page. Taking the coefficients in Fig. 2 into (4), $G_{T_{\mathrm{a,h}}}(s)$ can be obtained.

2) Foster-Model-Based Method: In most cases, the coefficients in the Cauer-network-based thermal model are not accessible, so a Foster-model-based method to derive $G_{T_{\mathrm{a,h}}}(s)$ is provided. Based on the circuit analysis, as shown in Fig. 4, the frequency-domain transfer function from P_{loss} to T_{h} can be derived as

$$Z_{T_{\mathrm{h}}}(s) = \sum_{x=1}^{n}\left(\frac{1}{\frac{1}{R_{\mathrm{x}}}+C_{\mathrm{x}}s}\right). \tag{6}$$

The thermal coefficients of the Foster model can be measured and mathematical fitted from testing results. The bode plots of $Z_{T_{\mathrm{h}}}(s)$ and $G_{T_{\mathrm{a,h}}}(s)$ using the referred Cauer model and the Foster model as well as the existing analytical model are shown in Fig. 6, where $Z_{T_{\mathrm{h}}}(s)$ of the two models are the same, but $G_{T_{\mathrm{a,h}}}(s)$ are different. The gain of $G_{T_{\mathrm{a,h}}}(s)$ from the Foster model is 0 dB in the whole frequency band, while $G_{T_{\mathrm{a,h}}}(s)$ from the referred Cauer model behaves like a low-pass filter. From (5), it can be seen that the gain of $G_{T_{\mathrm{a,h}}}(s)$ in the low-frequency range (e.g., lower than $1e^{-3}$ Hz) is $1/\sum_{x=1}^{n} R_{\mathrm{x}}$ times of $Z_{T_{\mathrm{h}},2}(s)$, while in the high-frequency range, it is determined by $Z_{T_{\mathrm{h}},1}(s)$. Because the bandwidth of the ambient temperature profile is normally within $1e^{-3}$ Hz, $G_{T_{\mathrm{a,h}}}(s)$ can be simplified to

$$G_{T_{\mathrm{a,h}}}(s) = \frac{Z_{T_{\mathrm{h}},2}(s)}{\sum_{x=1}^{n} R_{\mathrm{x}}} \approx \frac{Z_{T_{\mathrm{h}}}(s)}{\sum_{x=1}^{n} R_{\mathrm{x}}}. \tag{7}$$

$$T_{\mathrm{h}} = P_{\mathrm{loss}}\left(\overbrace{\frac{R_1R_2C_2s}{C_1C_2R_1R_2s^2+(C_1R_1+C_1R_2+C_2R_2)s+1}}^{Z_{T_{\mathrm{h}},1}(s)}+\overbrace{\frac{R_1+R_2}{C_1C_2R_1R_2s^2+(C_1R_1+C_1R_2+C_2R_2)s+1}}^{Z_{T_{\mathrm{h}},2}(s)}\right)$$
$$+\,T_{\mathrm{a}}\frac{1}{C_1C_2R_1R_2s^2+(C_1R_1+C_1R_2+C_2R_2)s+1} \tag{5}$$

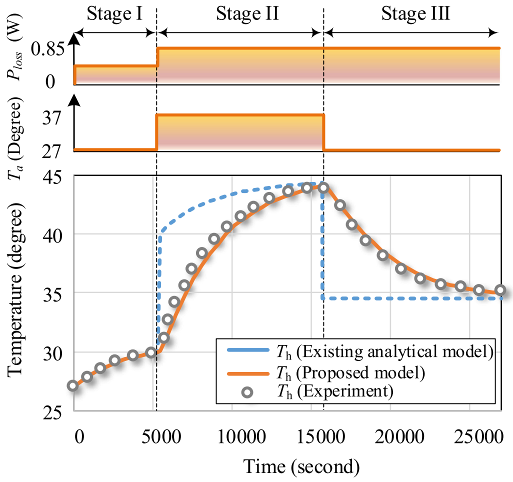

Fig. 7. Comparison of hotspot temperature for experiments and simulation using the proposed model and the existing thermal model.

The bode plot is shown in Fig. 6. In Region I, there is no difference among the referred Cauer model, the existing analytical model, and the proposed model. In Regions II and III, the maximum estimated error by using the existing model and the proposed model is 0 and -30 dB of the ambient temperature variation, respectively, where the accuracy is significant improved.

IV. APPLICATION IN LONG-TERM THERMAL ANALYSIS WITH THE AMBIENT TEMPERATURE PROFILE

A. *Proof the Accuracy of the Proposed Method*

In order to verify the accuracy of the proposed thermal modeling method, a capacitor with integrated sensors is tested temperature disturbances. The testing sample is an 820-μF/450-V electrolytic capacitor from Nippon Chemi Con, as shown in Fig. 2. The ESR is 196 mΩ at 100 Hz and 27°. With 2.1-A/100-Hz current ripple injection, the power loss of the capacitor is 0.85 W. Considering the local ambient temperature affected by both the environment and the loading profile, 10° temperature variation is assumed to verify the accuracy of the proposed model. Experimental results with two disturbances are shown in Fig. 7. In the first stage with power loss injection, T_h from the existing thermal model and the proposed model agree with the experimental results. In the second stage, because a step change of T_a and P_loss occurs at 5400 s, T_h from the existing thermal model is immediately changed and then increases slowly. In the last stage with T_a drop and continuous power loss injection, T_h with the existing thermal model drops with the ambient temperature immediately. In all the process, the proposed analytical thermal model agrees well with the experimental results.

B. *Impact of the Proposed Thermal Model in the Long-Term Thermal Analysis*

The proposed thermal modeling method considers the thermal dynamics of the ambient temperature, which will affect the temperature prediction in the long-term thermal analysis. A comparison of the estimated hotspot temperature between the existing analytical thermal model and the proposed thermal model is presented. The capacitor sample with corresponding coefficients in Fig. 2 is used for the case study. The yearly ambient temperature profile [4] is applied, and the power loss injection is assumed to be 0.85 W all the time. Fig. 8 shows that the thermal stress of the capacitor becomes flat, when the ambient temperature dynamics are considered. It will introduce a nonnegligible impact on the temperature prediction, thermal management, reliability evaluation, and system protection.

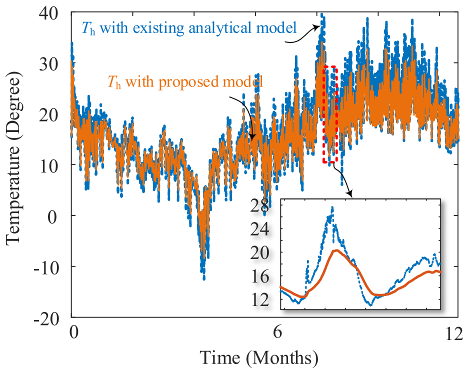

Fig. 8. Estimated hotspot temperature comparison between the existing thermal model and the proposed model with the one-year ambient temperature profile.

V. CONCLUSION

This letter proposes a thermal modeling method considering the ambient temperature dynamics. The ambient temperature variation will appear on the hotspot temperature immediately in the existing analytical model, because the thermal dynamics from the ambient temperature is ignored. By using frequency-domain modeling, a comprehensive thermal model considering the impact from both the self-heating and ambient temperature variation is proposed to represent the overall thermal dynamics. It can provide an authentic temperature estimation when the power loss and ambient temperature profile is considered, while the conventional analytical model loses the thermal dynamic accuracy. The proposed thermal model can also be extended to other components in power electronic applications.

REFERENCES

[1] H. S.-H. Chung, H. Wang, F. Blaabjerg, and M. Pecht, *Reliability of Power Electronic Converter Systems*. Stevenage, U.K.: IET, 2015.

[2] *Application Note—Thermal Equivalent Circuit Models*, Infineon, Neubiberg, Germany, 2008.

[3] H. Wang, P. Davari, H. Wang, D. Kumar, F. Zare, and F. Blaabjerg, "Lifetime estimation of dc-link capacitors in adjustable speed drives under grid voltage unbalances," *IEEE Trans. Power Electron.*, vol. 34, no. 5, pp. 4064–4078, May 2019.

[4] Y. Shen, A. Chub, H. Wang, D. Vinnikov, E. Liivik, and F. Blaabjerg, "Wear-out failure analysis of an impedance-source PV microinverter based on system-level electrothermal modeling," *IEEE Trans. Ind. Electron.*, vol. 66, no. 5, pp. 3914–3927, May 2019.

[5] K. Ma, N. He, M. Liserre, and F. Blaabjerg, "Frequency-domain thermal modeling and characterization of power semiconductor devices," *IEEE Trans. Power Electron.*, vol. 31, no. 10, pp. 7183–7193, Oct. 2016.

[6] R. Bayerer, T. Herrmann, T. Licht, J. Lutz, and M. Feller, "Model for power cycling lifetime of IGBT modules—Various factors influencing lifetime," in *Proc. Conf. Integr. Power Electron. Syst.*, Mar. 2008, pp. 1–6.