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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 can not 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 is 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.**

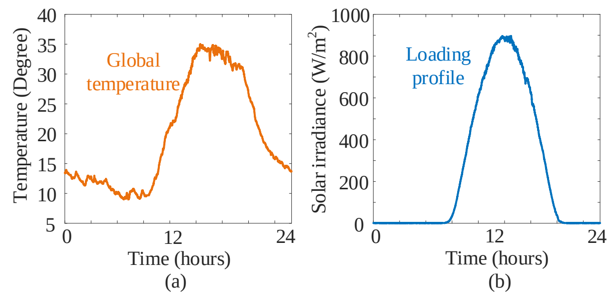

Fig. 1. Long-term mission profile in a PV application of Denmark [4]: (a) Daily global ambient temperature and (b) Daily loading profile.

I. Introduction

It has been revealed that the thermal stress is one of the most critical stressors in power electronics 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 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: firstly, it represents the thermal dynamics from the ambient temperature, which can not be neglected for the components with the same level of time constant with the ambient temperature profile (e.g., capacitor, inductor and heat sink). Secondly, it is an analytical model with accessible thermal coefficients, which is suitable for long-term thermal analysis with ambient temperature and power loss profile.

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Existing thermal modeling methods for long-term thermal analysis are based on the thermal impedance of the 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 (FEM) simulation, and its analytical model is complex and time-consuming for long-term thermal analysis [2]. Therefore, in all 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 can not 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 degrees variation of local ambient temperature. Due to the large time constant of passive components, the temperature of the hot-spot 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 over-estimation.

This letter investigates the limitation of the existing thermal modeling methods from the ambient temperature variation

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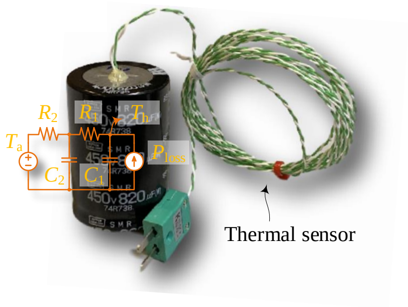
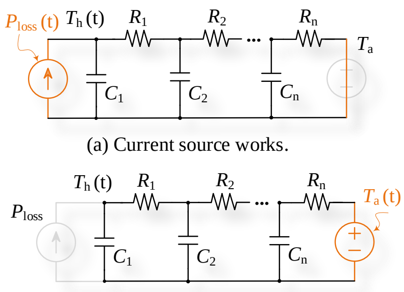


Cauer	
Items	Value
R_1	4.4 K/W
C_1	365 J/K
R_2	4.1 K/W
C_2	188 J/K
Foster	
Items	Value
R_1	3.4 K/W
C_1	342 J/K
R_2	5.2 K/W
C_2	228 J/K

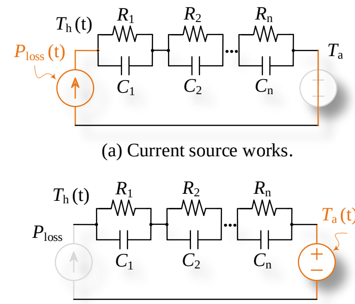
Fig. 2. Capacitor under testing as reference for study and its thermal parameters.



(a) Current source works.

(b) Voltage source works.

Fig. 3. Equivalent circuit diagram of Cauer model with superposition theorem.



(a) Current source works.

(b) Voltage source works.

Fig. 4. Circuit diagram of Foster model with superposition theorem.

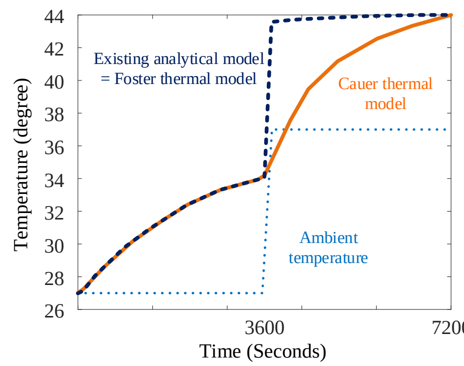


Fig. 5. Thermal dynamic comparison between simulation results of Cauer model, Foster model and existing analytical thermal model, where the ambient temperature raises from 27 to 37 degree at 3,600 seconds.

aspect. Then a thermal modeling method considering both the self heating and ambient temperature profile is proposed with the help of frequency-domain modeling [5]. The proposed method can improve the accuracy of the temperature estimation significantly. The structure of this letter is as follows: Section II presents the limitation of the existing thermal modeling methods; Section III discusses the proposed model with its coefficients extraction method; Section IV verifies the accuracy of the proposed model, followed by the conclusions.

II. Limitation of Existing Thermal Modeling Method

A Cauer model is considered as the correct model, which is analyzed firstly 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 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 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 hot spot. 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. 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 hot spot 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 B.

B. Limitation of the Existing Methods

The general analytical model commonly used to estimate the hot-spot temperature is

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

T_{a} and T_{h} are the ambient and hot-spot temperature, respectively. $Z_{\mathrm{T_h}}$ represents the thermal impedance from hot spot to the ambient, which can be derived from Cauer model or Foster model. This commonly used analytical model has the same thermal behavior with Foster model, which represents the thermal dynamic of the self heating, while can not 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

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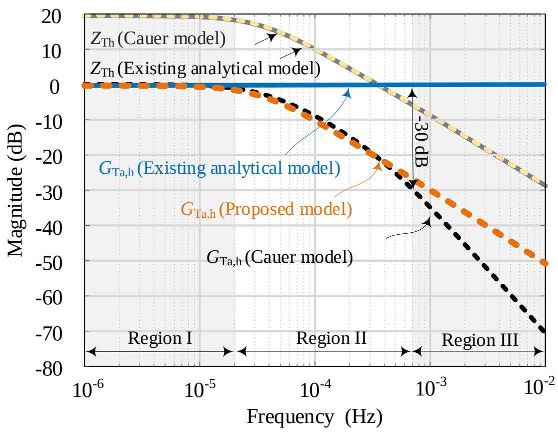

Fig. 6. Bode plot of critical gains in $Z_{\mathrm{T_h}}(s)$ and $G_{\mathrm{T_{a,h}}}(s)$ using referred Cauer model, existing thermal model and proposed thermal model in the frequency domain.

time of 3,600 seconds, the ambient temperature begins to raise. The estimated temperature based on existing analytical model raises immediately, while the temperature from the referred Cauer model raises slowly due to large thermal capacitance.

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

III. Proposed Thermal Modeling Method Considering Ambient Temperature Dynamics

A. Proposed Thermal Model

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

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

A transfer function $G_{\mathrm{T_{a,h}}}(s)$ from the ambient temperature to the hot-spot temperature is added in the thermal model. Therefore, the thermal dynamics from both self heating and ambient temperature disturbances can be considered for thermal analysis. The issue is to determine $G_{\mathrm{T_{a,h}}}(s)$.

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

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

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

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

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

$$G_{\mathrm{T_{a,x}}}(s) = \prod_{k=n}^{x} G_{\mathrm{k}}(s) \tag{4}$$

$$\begin{cases} G_{\mathrm{k}}(s) = \frac{1/C_1 s}{1/C_1 s + R_1} & (k = 1) \\ G_{\mathrm{k}}(s) = \dfrac{\frac{R_{\mathrm{k-1}}}{1 - G_{\mathrm{k-1}}(s)} // \frac{1}{C_{\mathrm{k}} s}}{\frac{R_{\mathrm{k-1}}}{1 - G_{\mathrm{k-1}}(s)} // \frac{1}{C_{\mathrm{k}} s} + R_{\mathrm{k}}} & (k = 2, 3, ..., n) \end{cases}$$

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). Taking the coefficients in Fig. 2 into (4), $G_{\mathrm{T_{a,h}}}(s)$ 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 $G_{\mathrm{T_{a,h}}}(s)$ 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

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

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

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

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

IV. Application in Long-term Thermal Analysis with 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 820 uF/450 V electrolytic capacitor from Nippon Chemi Con as shown

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

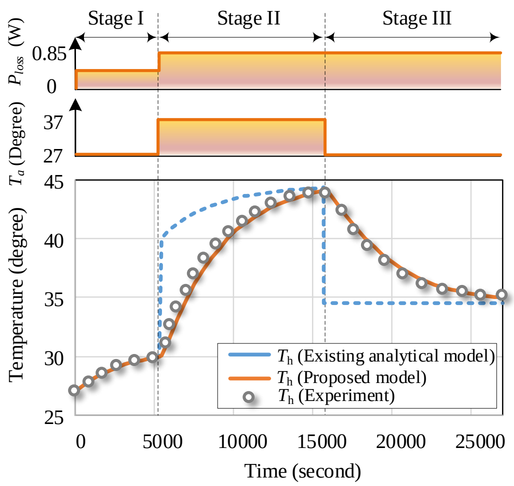

Fig. 7. Comparison of hot-spot temperature for experiments and simulation using the proposed model and existing thermal model.

in Fig. 2. ESR is 196 mΩ at 100 Hz and 27 degree. 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 environment and loading profile, 10 degree temperature variation is assumed to verify the accuracy of the proposed model. The 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 proposed model agree with the experimental results. In the second stage, due to a step change of T_a and P_loss occur at 5,400 seconds, T_h from existing thermal model is immediately changed, and then raises slowly. In the last stage with T_a drop and continue 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 are highly agree 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 hot-spot 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 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

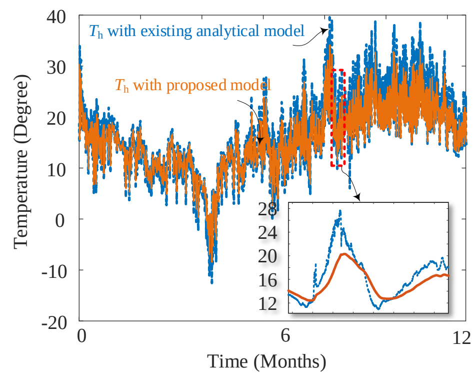

Fig. 8. Estimated hot-spot temperature comparison between the existing thermal model and proposed model with one-year ambient temperature profile.

ambient temperature dynamics are considered. It will introduce nonnegligible impact on the temperature prediction, thermal management, reliability evaluation and system protection.

V. Conclusions

This letter proposes a thermal modeling method considering the ambient temperature dynamics. The ambient temperature variation will appear on the hot-spot temperature immediately in existing analytical model, due to the thermal dynamics from ambient temperature is ignored. By using the 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 loose the thermal dynamic accuracy. The proposed thermal model can also be extended to other components in power electronic applications.

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