Research Report

A Novel Electro-thermal Simulation Approach to Power IGBT Modules for Automotive Traction Applications

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自動車走行用パワーIGBTモジュールの電気・熱連成シミュレーション手法の開発

小島崇，山田靖，Mauro Ciappa，Marco Chiavarini，Wolfgang Fichtner

Abstract

This paper describes a novel electro-thermal coupling simulation technique for analyzing automotive IGBT modules. This technique uses a electric circuit simulator and is based on a power semiconductor device model with temperature-dependent characteristics and a novel compact thermal model suitable for automotive IGBT modules. For the device model, a model parameter definition method was proposed, and simulation results of on-voltage characteristics using this model showed good agreement with measurement results. The compact thermal model can take into account lateral heat spreading within the modules and thermal interference among power devices. The thermal model was validated in a comparison of temperature transient responses calculated using the proposed model those calculated by FEM, and those which were measured. The usefulness of the electro-thermal coupling simulation technique was shown in example simulations which included two parallel IGBTs with resistive load.

Keywords

Circuit simulator, IGBT module, Compact thermal model, Model parameter, Hybrid electric vehicle, Power semiconductor device, FEM, Thermal interference

要　旨

ハイブリッド車のインバータシステムの主要構成要素であるパワーIGBTモジュールの動作予測に電気・熱連成解析が必要とされている。本研究では車載IGBTモジュールのインバータ回路動作解析用の新しい電気・熱連成シミュレーション技術を開発した。この技術は温度依存性を持ったパワー半導体素子モデルと車載IGBTモジュールに適した新しいコンパクト熱モデルから構成され，電気回路シミュレータを基盤として実行される。パワー半導体素子モデルについて，素子特性を過渡シミュレーション中に温度変化に応じて動的に変化できるパラメータ定義方法を検討し，オン電圧特性について実測との良好な一致を示した。提案するコンパクト熱モデルは，モジュール内の熱の横方向への広がりと半導体チップ間の熱干渉を表現可能である。熱のステップ応答について実測およびFEM解析との比較を実施し，高精度に温度変化を予測できることを示した。シミュレーション実施例として並列接続されたIGBTの温度上昇を計算し，電気・熱連成解析が有効に機能していることを示した。

キーワード

回路シミュレータ，IGBTモジュール，コンパクト熱モデル，モデルパラメータ，ハイブリッド車，パワー半導体素子，FEM，熱干渉

特集

1. Introduction

In hybrid electric vehicles (HEVs), power IGBT (Insulated Gate Bipolar Transistor) modules, which convert the direct current of the battery into alternating current to rotate the motor, generate a considerable amount of heat because of huge dissipation of electric power. In addition, the electrical characteristics of the power semiconductor devices that are the main components of power IGBT modules (IGBTs and Diodes), depend strongly on their junction temperature. An electro-thermal simulation technique is therefore required to estimate the electrical and thermal behavior of the power IGBT modules. However, conventional approaches using simple thermal models based on circuit simulators have encountered significant difficulties in accurately predicting the transient behavior of complex automotive power modules.[1)]

This paper describes a novel electro-thermal coupling simulation technique for analyzing automotive IGBT modules. This technique is based on a power semiconductor device model for determining temperature-dependent device parameters and a novel compact thermal model suitable for automotive IGBT modules. Since this technique uses a circuit simulator, it has the ability to estimate the detailed electrical characteristics of the devices such as surge voltage and power loss. This technique is capable of solving problems that cannot be solved by the conventional method; for example, imbalanced temperature rise in parallel-connected power devices with different characteristics can be examined

In this paper, first the outline of the electro-thermal simulation methodology is described. Secondly, our proposed parameter definition method for the electrical IGBT model is presented. On-voltage characteristics simulation results using an optimized IGBT model and measurement results are compared. Thirdly, our proposed compact thermal model is validated. Comparison of thermal pulse responses calculated using this thermal model with those which were measured, and also with FEM (Finite Element Method) analysis results is made. Finally, examples of electro-thermal simulation are presented.

2. Electro-thermal coupling simulation

Figure 1 shows a diagram of our electro-thermal simulation technique for power IGBT modules. In this figure, the module model consists of an electrical model and a thermal model. The device model, where electrical characteristics of IGBTs or diodes are defined, is connected to the thermal model. The instantaneous value of the device power loss is applied to the thermal model, in which the thermal characteristics of the module are defined. Then, the instantaneous device temperature is generated by the thermal model, and the temperature dependent device model parameters are determined using this instantaneous device temperature. These calculations are performed simultaneously using a circuit simulator. As described above, the device model and the thermal model are essential components of an electro-thermal simulation.

3. Simulation models

3. 1 Electrical IGBT model

To accurately predict the loss dissipated from an IGBT, a model for the IGBT needs to vary the device characteristics dynamically with variations of instantaneous device temperature. Since, the widely used circuit simulator known as "SPICE" cannot model temperature-dependent device characteristics, we chose the SIMPLORER circuit simulator (designed by Ansoft Corporation) as the solver for the electro-thermal coupling simulation.[2)] In the IGBT model, the dependence of the characteristics on the temperature can be expressed in the following form.

Generally, the amount of power loss dissipated from an IGBT is determined by the conduction loss,

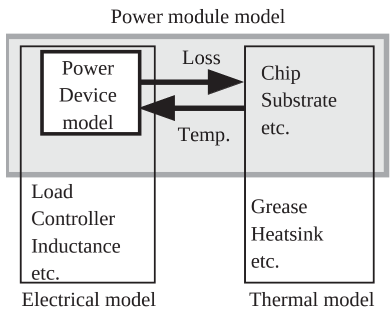


Fig. 1 Diagram of electro-thermal simulation for power IGBT modules in HEVs.

dominated by the on-voltage conduction loss, and the switching loss, dominated by the switching loss of the tail current in the transient current waveform. The IGBT model in SIMPLORER can represent the dependence of the loss of temperature on only three parameters, which are determined by the simple parameter definition method described in this paper. Those parameters are "saturation current of BJT (Bipolar Junction Transistor)" and "base resistance of BJT" for characterizing the on-voltage, and "time constant of tail current" for the tail current. Each of these parameters can be expressed as a function of temperature. Those functions can be optimally determined by minimizing the error between the data calculated from a trial function and the data measured at different temperatures. **Figure 2** shows the comparison between V_{CE} -I_C characteristics simulated from the optimum IGBT model and measured characteristics. From this figure it is clearly seen that the simulated results of the V_{CE} -I_C characteristics are in good agreement with the measured results. The optimized IGBT model is therefore useful for evaluating the power loss generated by the IGBT.

3. 2 Design of compact thermal model

A compact thermal model, which is composed of thermal resistance and thermal capacitance, is strongly required as a thermal model for carrying out the electro-thermal coupling simulation, because the compact thermal model can be implemented using a circuit simulator easily. The conventional compact thermal model such as the Elmore model cannot exactly represent a three-dimensional structure having temperature transient.[3] Specifically, the Elmore model cannot represent lateral thermal spreading and thermal interference on the real IGBT module mounted on the water cooler.

We propose a new compact thermal model to overcome these problems. **Figure 3** shows the "cell" for each physical domain, which consists of the thermal resistance and capacitance. In the cell, two parallel thermal resistance and capacitance sub-circuits are connected in series. The thermal impedance ($Z_{th}(t)$) of the cell can be expressed by the following equation,

$$Z_{th}(t) = R_1\{1\text{-}\exp(t/R_1C_1)\} + R_2\{1\text{-}\exp(t/R_2C_2)\} \quad \cdots\cdots (1)$$

where the parameters R_1, R_2, C_1 and C_2 are determined to minimize errors in comparison with results calculated by FEM. The cells corresponding to physical layers in the IGBT module are connected in series to represent the total thermal model of the IGBT module.

Figure 4 shows the time dependence of thermal impedances calculated using the optimum compact thermal model and the transient heat FEM (the transient response to the heat unit step). Because the thermal impedance generated by the compact thermal model agrees with that by FEM, the proposed compact thermal model is suited to represent the IGBT module.

In addition, the proposed thermal model has the capability to represent the interference of the heat flux from different heat sources that are adjacent to each other. Specifically, the interference of the heat flux can be represented by merging the individual thermal models at individual points where the different heat fluxes interfere with each other.

Figure 5 shows the thermal model for a module with two IGBTs connected in parallel. In this model, the IGBTs which are the heat sources are represented as current sources. In Fig. 5, the interference area is indicated by the circle.

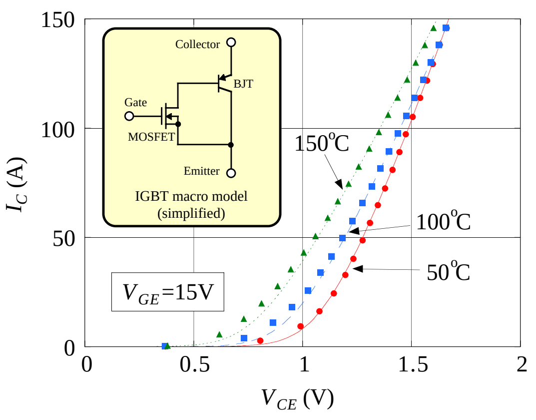


Fig. 2 V_{CE} -I_C characteristics of IGBT measured (dots), simulated (lines).

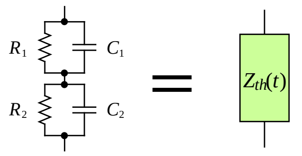


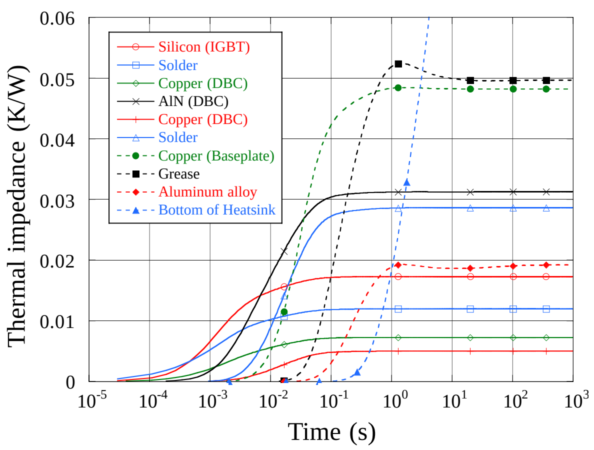
Fig. 3 Cell of proposed compact thermal model.

Figure 6 shows the temperature transient responses to the heat unit step calculated using the proposed compact thermal model. In the case that thermal interference does not occur (operation of one IGBT), the lateral thermal spreading is accurately modeled, because the result calculated using the proposed model is in agreement both with the FEM and the measured results. Also in the case that thermal interference occurs, (operation of two IGBTs), the result calculated using the proposed model is in agreement with that calculated by the FEM, showing that the thermal interference is accurately modeled.

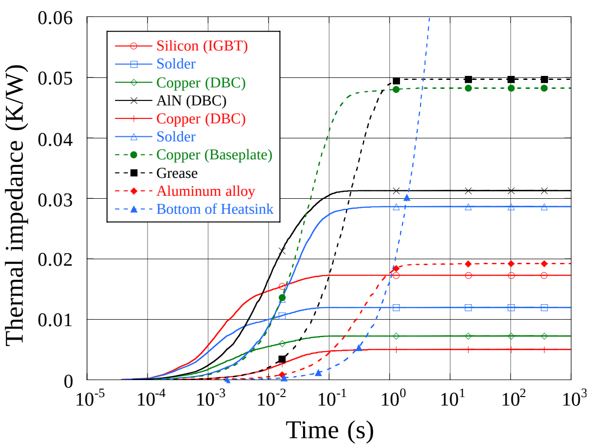
4. Examples of electro-thermal coupling simulation

In this chapter, a representative example of the electro-thermal coupling simulation is presented. The commercial power module product "2 in 1 module" was chosen as a test sample, which is composed of two IGBTs connected in parallel. The simulation circuit is shown in **Fig. 7**.

Figure 8 shows the detailed junction temperature (T_j) transition in an electro-thermal coupling simulation in the case of two successive switching cycles. The T_j of the IGBT increases rapidly with both turn-on and turn-off of current, and it rises slowly during the "on" state and decreases slowly during the "off" state.



(a) Calculated by FEM



(b) Calculated using the proposed model

Fig. 4 Thermal impedance for each layer.

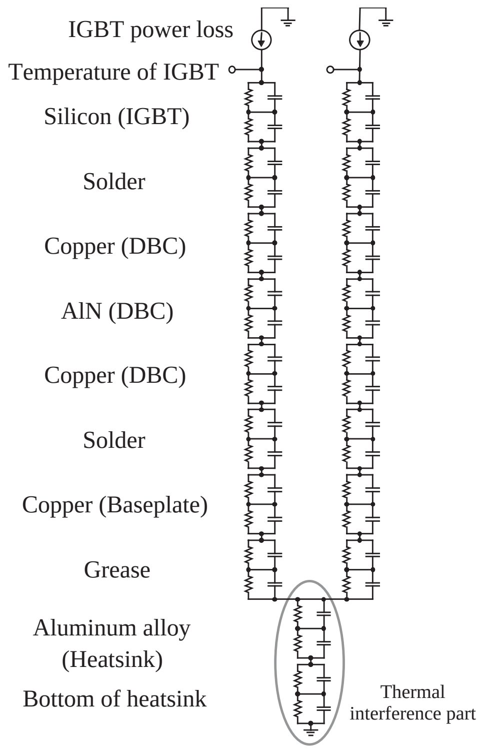


Fig. 5 Compact thermal model of package/heatsink system including two IGBTs.

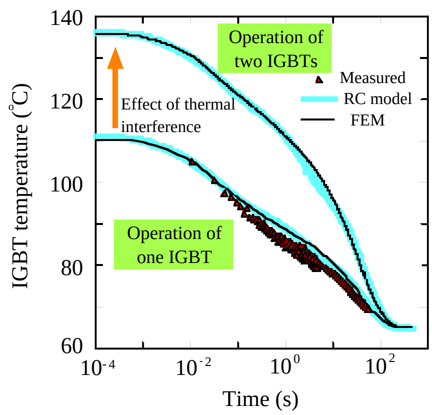


Fig. 6 Calculated (lines) and measured (symbols) pulse response system without (lower curve) and with thermal interference (upper curve). Power loss at the steady-state (before turn-off) is 93.7 W.

Two examples of simulation using the proposed technique are shown below.

A. In the case of different threshold voltages

Figure 9(a) shows the transient behavior of T_j and the collector current for the two paralleled IGBTs that have slightly different threshold voltages ($IGBT_1$: 6.83 V, $IGBT_2$: 6.33 V). Both the inrush current and the steady-state current are larger in $IGBT_2$ because of its smaller threshold voltage. Because the inrush and steady-state current of $IGBT_2$ is larger than that of $IGBT_1$, the local power loss of $IGBT_2$ becomes higher than that of $IGBT_1$. The higher local power loss led to a faster T_j increase in $IGBT_2$.

B. In the case of different thermal resistances

In this example, the solder layers under the two IGBTs are assumed to have different heat resistances because of the presence of voids or cracks. In spite of the fact that the collector currents of the IGBTs were almost the same, the T_j of $IGBT_2$ increased faster than that of $IGBT_1$ because of the higher thermal resistance of $IGBT_2$ (Fig. 9(b)).

In the above cases, computational time of the electro-thermal coupling simulation was only 10% longer than that of the conventional electric circuit simulation.

Because the above results explain expected phenomena qualitatively, the electro-thermal simulation technique using the proposed model is useful.

Here we must address undesirable results caused by the small time increments in the circuit simulation. For example, a simulation using detailed power device models requires short time increments on the order of nano-seconds. However, an unexpected loss of a few kW is often generated in the simulation using such short time increments. If this large loss is applied to the compact thermal model, an unrealistic increase of T_j over 1,000 ^oC will occur momentarily. This unrealistic simulation result can be eliminated by applying average power loss to the current source implemented into the compact thermal model. **Figure 10** shows the transient behavior of T_j in the simulation where power loss averaged over a time span of 0.1 ms or 1 ms

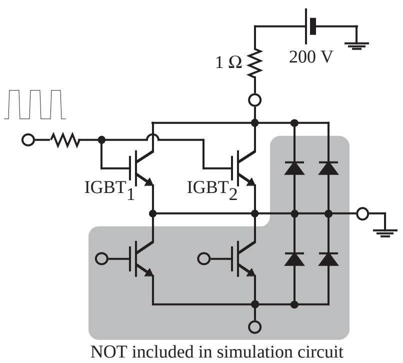


Fig. 7 Simulation circuit.

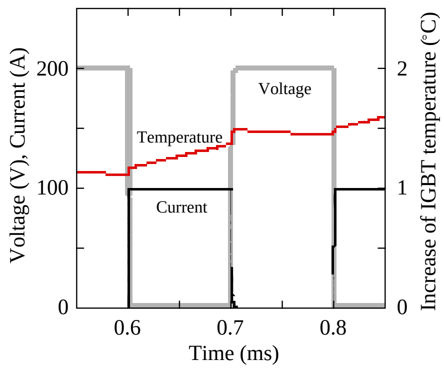
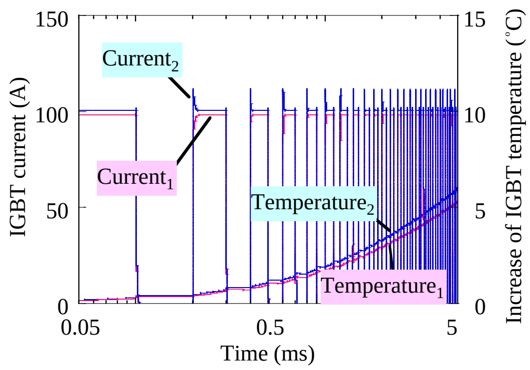
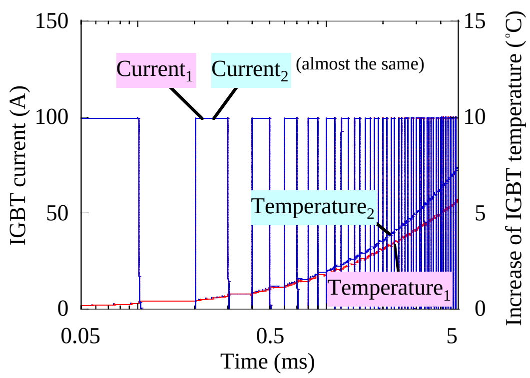


Fig. 8 Simulated temperature of one IGBT in switching operation.



(a) The case of different threshold voltages
($IGBT_1$: 6.83 V, $IGBT_2$: 6.33 V).



(b) The case of different thermal resistances
($IGBT_1$:0.49 K/W, $IGBT_2$:0.54 K/W).

Fig. 9 Simulated transient behavior of T_j and of I_C in paralleled IGBTs.

is implemented into the compact thermal model. It is clear that any unexpected rapid rise and fall of T_j is eliminated by the averaging taken over a time span of 1ms. Implementation of average power loss into the compact thermal model will not have a fatal influence on the estimation of T_j in the power module, because it takes from a few tens of seconds to a few hundreds of seconds for the module to reach thermal equilibrium.

5. Conclusion

We have described a novel simulation technique for performing electro-thermal simulation. Key components of this technique are an electrical IGBT model with temperature dependent characteristics and a novel compact thermal model. The parameters of the IGBT model are defined as analytical functions of temperature, and dynamic variations of the parameters are calculated in a simple manner. The proposed compact thermal model of power IGBT modules can take into account lateral thermal spreading and thermal interference. The usefulness of the electro-thermal coupling simulation technique was shown in example simulations which include two parallel IGBTs with resistive load.

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References

1) Hefner, A. R. and Blackbum, D. L. : "Thermal Component Models for Electrothermal Network Simulation", IEEE Trans. Com., Packag. and Manuf. Tech., **17**(1994), 413-424

2) "SIMPLORER 6.0 User Manual", Ansoft Corp. (2002)

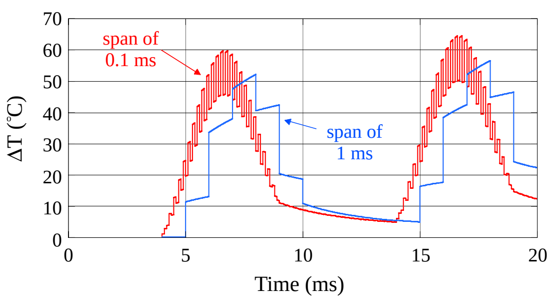

Fig. 10 Effect of power loss averaging on eliminating unrealistic temperature.

3) Yun, C.-S., Ciappa, M., Malberti, P. and Fichtner, W. : "Thermal Component Model for Electrothermal Analysis of IGBT Module Systems", IEEE Trans. on Adv. Packag., **24**(2001), 401-406

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