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Novel Electro-Thermal Coupling Simulation Technique for Dynamic Analysis of HV (Hybrid Vehicle) Inverter

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Abstract—This paper describes a novel electro-thermal coupling simulation technique mainly focused on the dynamic analysis of the HV inverter during WOT (Wide Open Throttle) operation. This technique can predict the junction temperature of power devices installed within the power module accurately. This simulation technique is composed of an inverter circuit model including power semiconductor device models, a novel compact thermal model suitable for automotive power modules and motor model. Various information and conditions such as motor current, motor rotation speed, switching frequency and variable DC-link voltage are applied to the simulation for carrying out the WOT operation. The comparison between the simulated and measured results indicates that this method offers reasonable accuracy for the IGBT temperature estimation where the worst case error in the IGBT temperature is less than 10 deg-C. It takes 210 min to complete the WOT simulation with duration of 4 seconds.

I. INTRODUCTION

HV (Hybrid Vehicle) system is mainly composed of inverter unit, motor unit and controller. The controller determines the inverter operation based on the status information of torque and rotation speed from the motor. The inverter is a key unit which converts the direct current of the battery into the alternating current to rotate the motor among these units. The power semiconductor devices (IGBTs and Diodes) placed in the power module of the inverter circuit are the main components of the power module and play the role of the switching devices. Because these power semiconductor devices generate a considerable amount of heat due to conduction loss and switching loss, thermal problem about the devices must be taken into account in the design of the power module. And the factor we care most about is the junction temperature of the device determined by the power loss of the device in the design of the power module.

On the other hand, the achievement of good acceleration performance in the dynamic operation state such as WOT (Wide Open Throttle) is paid attention to for the HV system. The inverters with high capacity (high output current and voltage) are required to achieve good acceleration performance of the HV system, which results in the major issue of the increases of the power loss and junction temperature of the semiconductor devices. The power loss of the device depends on the junction temperature. Therefore, electro-thermal coupling simulation techniques, where the estimation of power loss and the calculation of the junction temperature should be combined, become important for predicting the dynamic power loss and junction temperature. Conventional simulation techniques have no capability of estimating various performances of HV inverter in the dynamic operation such as WOT acceleration[1].

This paper describes the novel electro-thermal coupling simulation technique mainly focused on the dynamic analysis of the HV inverter during WOT operation. This technique can predict the junction temperature of the device installed within the power module in the dynamic operation of the inverter accurately.

The remarkable features of this technique are following three items; electro-thermal coupling using temperature dependent power semiconductor device model in power module in HV inverter and compact thermal model suitable for the power module, electrical simulation circuit including motor model to represent load current of the inverter circuit and look-up table of the semiconductor device power loss for reduction of calculation time.

This simulation technique makes it possible to predict the dynamic performances in the HV inverter. Also, this simulation enables us to estimate the contribution of various inverter components to the total inverter performances quantitatively.

II. ELECTRO-THERMAL COUPLING SIMULATION

Fig. 1 shows transient temperature rise of surface of power semiconductor device for step power response. A fixed value can be set for the device temperature in the calculation of about 10 ms because the temperature change is not large in this time range. On the contrary steady thermal analysis should be done by 3D FEM after power loss simulation using circuit simulator in the calculation of over 10 sec because the temperature is saturated in this time range. Electro-thermal coupling simulation is especially required for a few seconds simulation because the temperature change of device is particularly large, therefore temperature-dependent semiconductor device characteristics is required to calculate power loss within the device. The WOT operation is included in this time range.

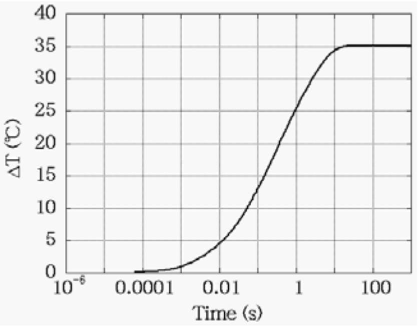

Fig. 1: Example of Transient temperature rise of surface of power device for step power response.

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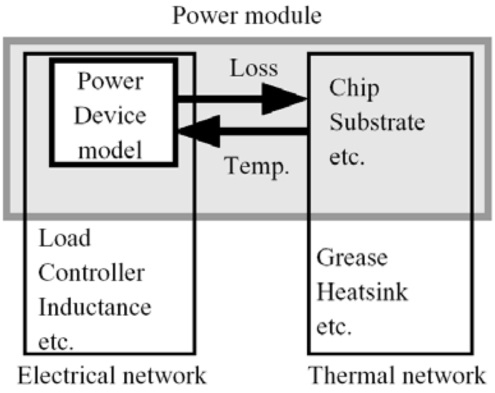


Fig. 2: Diagram of electro-thermal simulation for power IGBT modeles in HVs.

Fig. 2 shows a diagram of the 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.

The device model and the thermal model are described in detail in the following subsections.

A. 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, dominated by the on-voltage conduction loss (shown in Fig.3), and the switching loss, dominated by the switching loss of the tail current in the transient current waveform.

We achieved the IGBT characteristics in the simulator using optimized parameter extraction method and expansion of temperature dependency for several DC parameters. The comparison between inductive load switching characteristics simulated from the IGBT model and measured characteristics is shown in Fig. 4. From this figure it is clearly seen that the simulated results of the Vce waveform is in good agreement with the measured result. The optimized IGBT model is therefore useful for calculating the power loss generated by the IGBT.

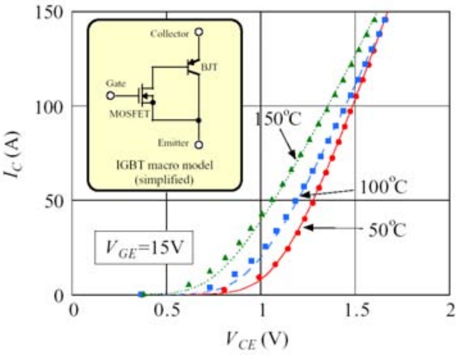


Fig. 3: V_{CE}-I_C characteristics of IGBT measured(dots), simulated (lines).

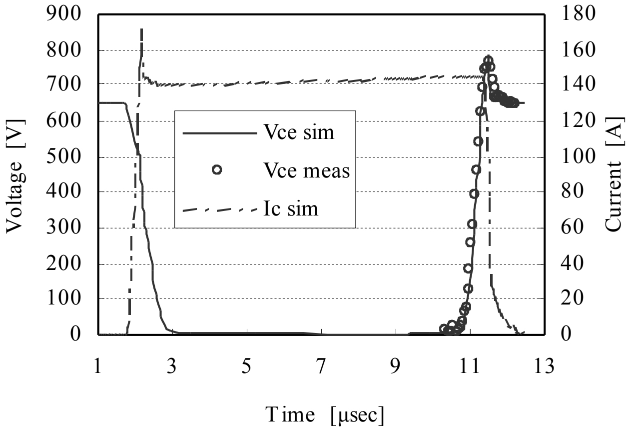


Fig. 4: Measured and simulated dynamic characteristics of IGBT in inverter circuit during turn-off period.

B. Thermal model for Power Module

It is necessary to model two significant phenomena for thermal model of HV power module. It's lateral heat spreading in the power module and thermal interference among power semiconductor devices.

A cross sectional view of the IGBT module is shown in Fig. 5. Silicon IGBTs are mounted on the top of an insulative layer, and that is fixed on a baseplate, by solders respectively.

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 Cauer model shown in Fig. 6 cannot exactly represent a three-dimensional structure having temperature transient[3].

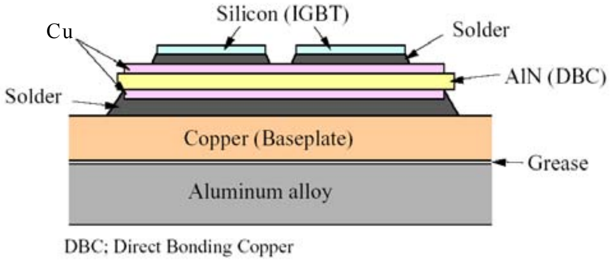


Fig. 5: Cross sectional view of IGBT module.

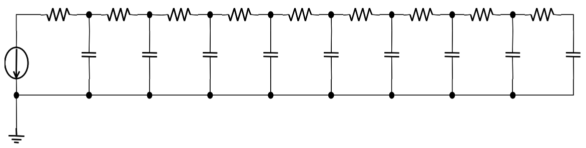


Fig. 6: Cauer model.

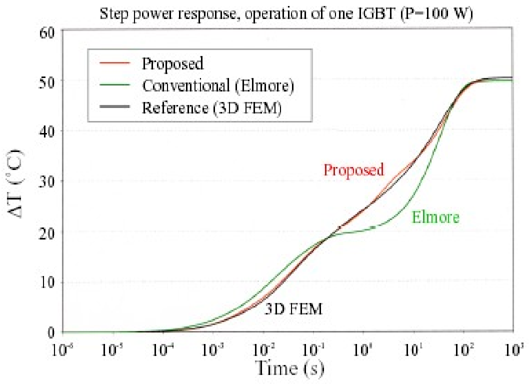


Fig. 7: Comparison of calculated results among proposed model, Cauer model and 3D-FEM for step power response.

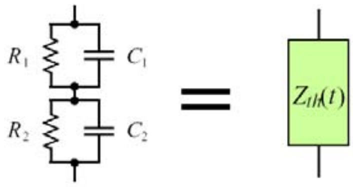


Fig. 8: Cell of proposed compact thermal model.

Therefore certain disagreement occurs on a transient response shown in Fig. 7. Specifically, the Cauer model cannot represent lateral thermal spreading on the real IGBT module mounted on the water cooler because the model is only applicable for a single exponential phenomenon.

To overcome these problems, we propose a new compact thermal model. Fig. 8 shows the "cell" for each physical domain, which consists of the thermal resistance and capacitance. In the cell, two parallel thermal resistance and capacitance subcircuits are connected in series. The thermal impedance ($Z_{th}(t)$) of the cell can be expressed by the following equation,

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

where the parameters R_1, R_2, C_1 and C_2 are determined to minimize errors in comparison with results calculated by 3D-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 (Fig. 9). Fig. 7 and 10 show 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

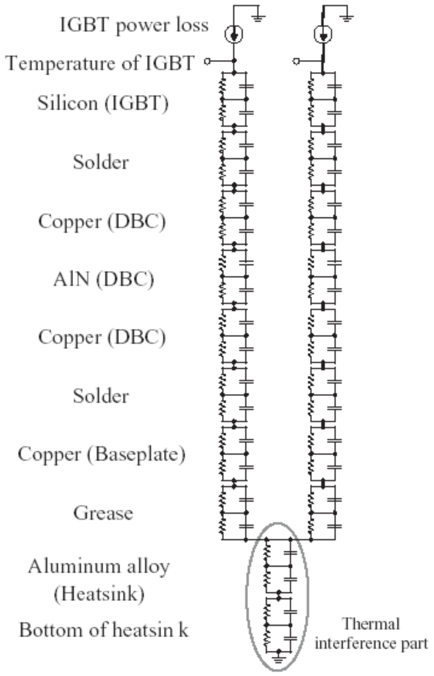
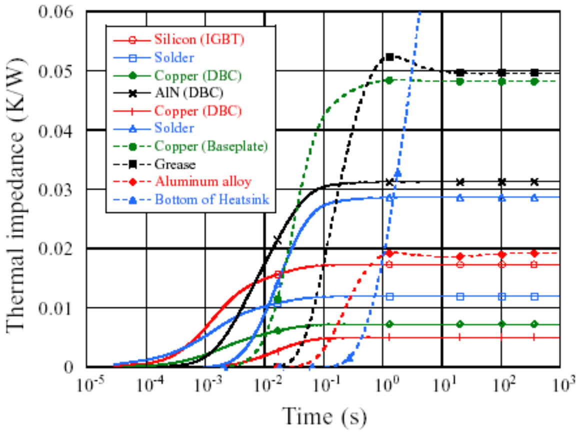
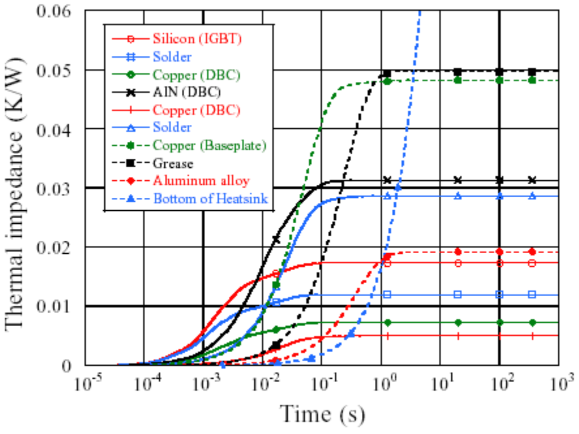


Fig. 9: Compact thermal model of package/heatsink system for single IGBT.

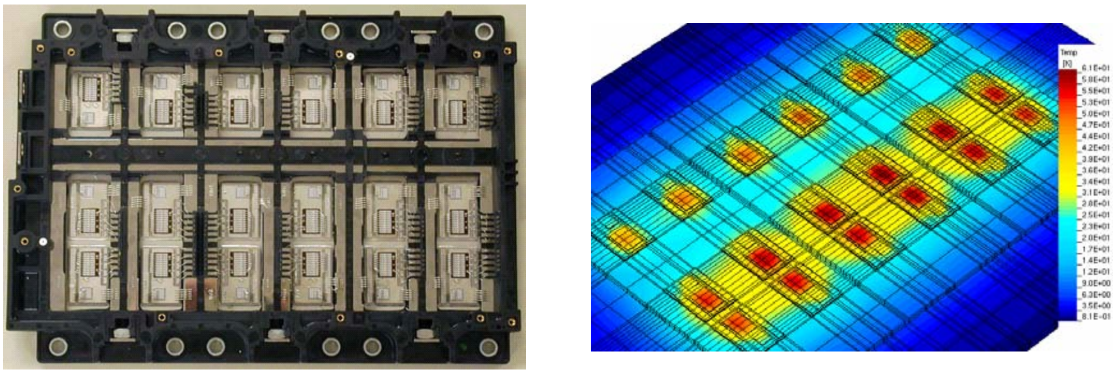


(a) Calculated by FEM



(b) Calculated using the proposed model

Fig. 10: Thermal impedance for each layer.



$$\begin{pmatrix}T_1\\T_2\\T_3\\T_4\end{pmatrix}=\begin{pmatrix}R_{11}&R_{12}&R_{13}&R_{14}\\R_{21}&R_{22}&R_{23}&R_{24}\\R_{31}&R_{32}&R_{33}&R_{34}\\R_{41}&R_{42}&R_{43}&R_{44}\end{pmatrix}\cdot\begin{pmatrix}P_1\\P_2\\P_3\\P_4\end{pmatrix}$$

$$\begin{pmatrix}dT_1\\dT_2\\dT_3\\dT_4\end{pmatrix}=\frac{d}{dt}\begin{pmatrix}Z_{11}^{th}(t-\tau)Z_{12}^{th}(t-\tau)Z_{13}^{th}(t-\tau)Z_{14}^{th}(t-\tau)\\Z_{21}^{th}(t-\tau)Z_{22}^{th}(t-\tau)Z_{23}^{th}(t-\tau)Z_{24}^{th}(t-\tau)\\Z_{31}^{th}(t-\tau)Z_{32}^{th}(t-\tau)Z_{33}^{th}(t-\tau)Z_{34}^{th}(t-\tau)\\Z_{41}^{th}(t-\tau)Z_{42}^{th}(t-\tau)Z_{43}^{th}(t-\tau)Z_{44}^{th}(t-\tau)\end{pmatrix}\cdot\begin{pmatrix}P_1(\tau)\\P_2(\tau)\\P_3(\tau)\\P_4(\tau)\end{pmatrix}$$

$$T_1=\underbrace{R_{11}P_1}_{\text{Self heating part}}+\underbrace{R_{12}P_2+R_{13}P_3+R_{14}P_4}_{\text{Thermal interference part}}$$

Fig. 11: Schematic view and example of thermal matrix for large current multi-chip power module.

module.

Also, thermal interference can be represented using the proposed model. Thermal interference in a power module is very complicated because the module are generally comprised by three phase electrical circuit with upper and lower arm. In addition, paralleled connections of IGBT are commonly used for the large current operation. The thermal matrix can be used for the thermal network including the interference in the modules. Schematic view of the actual module is shown in Fig. 11 and an example of the thermal matrix is also shown in the figure. In this case, strong thermal interference occurs among neighboring 4 devices. The temperature transient responses to the heat unit step calculated using the proposed compact thermal model is shown in Fig. 12. The result calculated using the proposed model is in agreement with that calculated by the FEM for every device, showing that the thermal interference is accurately modeled.

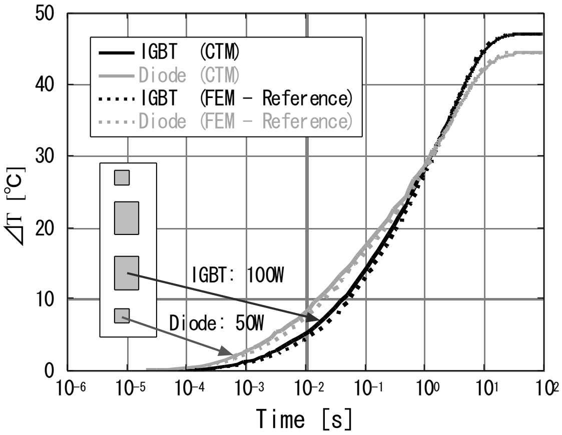


Fig. 12: Comparison of calculated results among proposed model and 3D-FEM for step power response with thermal interference.

III. MOTOR MODEL

In the dynamic inverter simulation for HV, a motor model has to be connected to the inverter circuit model as a load for accurate power loss simulation in power devices. Because duty ratio of current passing through the power devices is carried out only by motor and its control. We used conventional analytical PMSM (Permanent Magnet Synchronous Motor) model in the simulation and drove it using PWM (Pulse Width Modulation) control method[2].

IV. FAST CALCULATION

Circuit simulation using the power device model described above requires short time increments on the order of nanoseconds. However, this device model is not adequate for transient temperature simulation such as WOT operation, because unrealistic calculation time is required. We developed a method to look-up prepared device power loss tables to reduce the calculation time. Parameters of the power loss look-up tables are device current, device temperature and DC-link voltage of inverter. To make accurate look-up tables of power loss, accurate simulation models are required for IGBT driving circuit, smoothing capacitor on the inverter power supply and stray inductance of power module. The WOT operation simulation was able to be finished within realistic calculation time using developed look-up table method.

V. SIMULATION RESULT

The proposed electro-thermal simulation technique was evaluated for WOT operation with a "6 in 1 module" where three IGBTs and three diodes are connected in parallel on each arm. Initially ,motor frequency is zero in this simulation, and it is monotonically increased. The simulation is finished when the motor torque is changed to

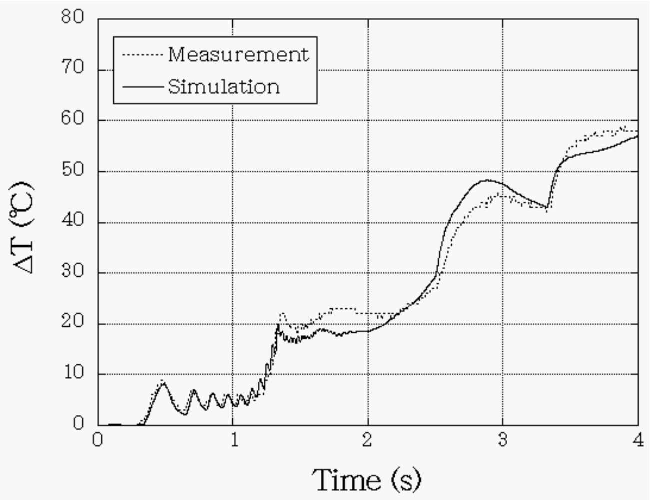


Fig. 13: Prediction of IGBT temperature for WOT operation.

decrease. Following time-series data are applied as simulation conditions;

- Motor torque
- Motor frequency
- DC-link voltage of inverter
- Carrier frequency of inverter.

Power losses generated in power semiconductor devices are obtained from look-up tables. The simulated and measured results are compared to determine the accuracy of the simulation technique in Fig. 13. The comparison between the simulated and measured results indicates that this method offers reasonable accuracy for the IGBT temperature estimation as shown in the figure where the worst case error in the IGBT temperature is less than 5 %. The fundamental advantage of this simulation technique is the CPU time efficiency compared to conventional electric-thermal coupling simulation. In the inverter simulation above, the time step is chosen to be 1 μs and it takes 210 minutes to complete the WOT simulation with duration of 4 seconds.

VI. CONCLUSION

We have described a novel electro-thermal coupling simulation technique mainly focused on the dynamic analysis of the HV inverter during WOT operation. Key components of this technique are electro-thermal coupling using semiconductor device model and compact thermal model, motor model and look-up table of the semiconductor device power loss. Junction temperature of power devices was able to be predicted over a short amount of time such as 210 minutes with duration of 4 seconds using this technique, and the worst case error in the device temperature was less than 5 %.

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