Thermal Stress Analysis for IGBT Inverter Systems

ABSTRACT

The application of the insulated gate bipolar transistor (IGBT) in medium to high voltage, high current power systems at high switching frequency has increased the need to study the energy loss and the thermal stress of the device. Thermal and thermal stress analyses are essential to optimize the structure and material of the semiconductor module, and to prevent destruction of the devices. In this paper, an electro-thermal IGBT model which can calculate the switching losses over a wide range of working conditions was introduced, and a technique to further increase the simulation speed was explained in detail. To account for the physical geometry of the IGBT modules, a model-order-reduction (MOR) method was used to extract lump-parameter models from finite element (FE) analysis results. The reduced-order thermal model was used together with the IGBT model to simulate accurately both the electrical and the thermal behavior of the semi-conductor device. The current profiles were then imported into the FE simulator to calculate the resulting thermal and thermal stress distribution. To demonstrate the process from system-level simulation to FE thermal stress analysis, a three-phase IGBT inverter system was used as an application example, and some preliminary results were included.

1. INTRODUCTION

The insulated gate bipolar transistor (IGBT) is widely used in medium to high power applications, such as switched-mode power supplies, traction motor control and hybrid vehicles. Simulations to accurately verify circuit behavior and optimize performance rely on accurate IGBT models incorporating all relevant physical effects. The electrical characteristics of power semiconductor devices strongly depend on their junction temperature. Designing a cost competitive power electronics system requires careful consideration of the thermal domain as well as the electrical domain.

An electro-thermal simulation technique provides the most accurate means to estimate the combined electrical and thermal behavior of IGBTs. However, conventional approaches using simple thermal models have encountered difficulties in predicting thermal transient behavior of complex power electronic system. To accurately predict the loss dissipated from an IGBT, a model of the IGBT needs to vary the device characteristics dynamically in response to the instantaneous device temperature.

The IGBT model introduced here calculates the conduction and switching losses of the device over a wide range of operating points and generates an accurate temperature prediction. The electrical and thermal model parameters are extracted from the readily available information in the manufacturers' datasheet.

To simulate accurately the thermal behavior of the power semiconductor devices, finite element analysis on the physical module geometry is usually required. However, this approach can be very computationally expensive, and cannot take into account the dynamic interaction between the thermal and the electrical characteristics. To perform fast multi-physics analysis of the IGBTs, a model-order-reduction method were developed to generate compact thermal models using temperature data captured from measurements or Finite Element (FE) simulation. This thermal model can take into account lateral heat spreading within the module and thermal interference among power devices.

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The temperature distribution in the IGBT modules can cause thermal stress effect. These effects can be studied by coupling heat transfer analysis with structural analysis. The current profile from the lump-parameter electrothermal simulation can be imported into the FE simulator to determine the temperature distribution. The temperature results are then used as inputs in a structural analysis to determine the stress caused by the temperature loads.

In section 2, the eletrothermal IGBT modeling approach was introduced, with a focus on the switching behavior and thermal aspect. The thermal model-order-reduction method was explained in section 3. In section 4, the IGBT model and the reduced-order model were used together to perform the thermal analysis of a three-phase inverter system. A brief conclusion and the future work are summarized in Section 5.

2. THE ELECTROTHERMAL IGBT MODEL

The electrothermal IGBT model presented here is composed of three main parts – the static core, the thermal network and the energy calculation section. The equivalent circuit of the IGBT model is shown in Figure 1, and it comprises mainly three characteristics: the transfer characteristic, the output characteristic, and if applicable, the forward characteristic of the freewheeling diode. The static parameters of the model can be extracted through the characteristic curves in manufacturers' datasheets.

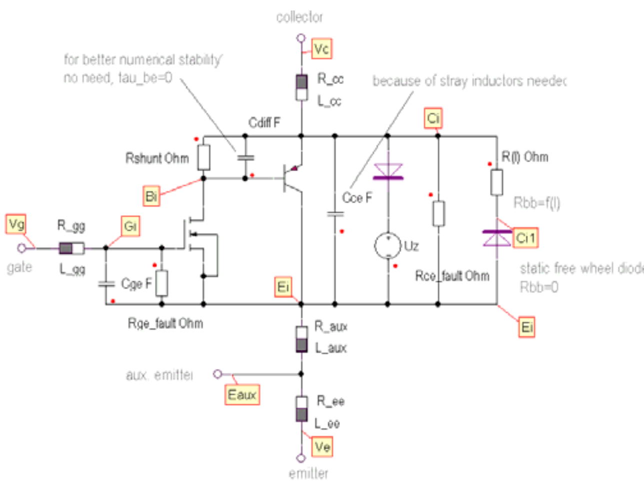


Figure 1. The equivalent circuit of the IGBT models

The electrothermal IGBT model an internal network and the parameters can be obtained directly from manufacturers' datasheets, or extracted through the transient thermal impedance curves. In the application example in section 5, the internal thermal network of the IGBT was replaced by the reduced-order thermal model from FE analysis, which will be explained in the following section.

The switching losses are calculated at each switching period, and detailed information on the calculation of the energy losses can be found in [3]. During the turn-on and turn-off transitions, power pulses are injected into the thermal network to estimate the corresponding junction temperature, as shown in Figure 2. The amplitude of the rectangular power pulses (note that the shape of the power pulses doesn't affect the junction temperature simulation) can be calculated according to Equation 1.

$$P_{ON} = \frac{E_{ON}}{T_{ON}}, \quad P_{OFF} = \frac{E_{OFF}}{T_{OFF}}, \quad P_{DC} = V_{CE,sat}\Big|_{V_{GE},I_C} \cdot I_C \qquad (1)$$

where P_{ON}, P_{OFF}, E_{ON}, E_{OFF} are on- and off-switching power dissipation and energy losses, respectively; P_{DC} is the conduction power dissipation; T_{ON} and T_{OFF} are the power injection pulse durations; and $V_{ce,sat}$ is the saturation collector-emitter voltage.

The duration of the power pulses should be assigned under consideration of the switching period of the gate drive signal. If the IGBT is working under high switching frequency, very small simulation time step is required to obtain correct junction temperature calculation. As a consequence, the simulation speed of the IGBT model can be limited by the switching speed of the gate drive signals. To reach a compromise between the junction temperature accuracy and the simulation speed, the IGBT model includes an energy "averaging" mode. Under this mode, the average switching power losses are calculated over several switching cycles and injected into the thermal network. This approach results in reasonable steady state junction temperature estimation and a lower sensitivity to the simulation time step. Figure 3 shows the junction temperature profile of an IGBT device and its freewheeling diode using different approaches.

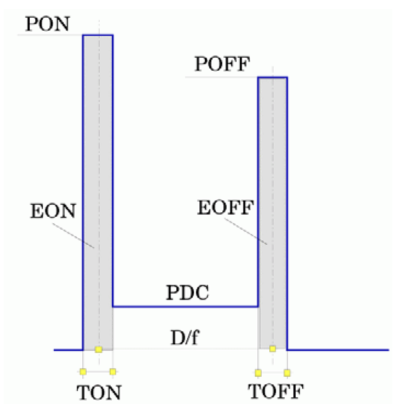


Figure 2. Power injection into the thermal network

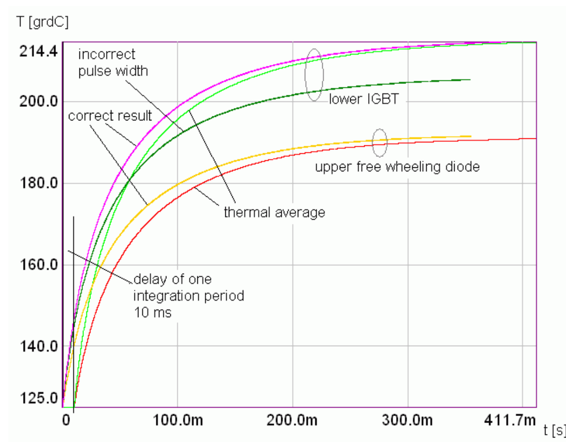


Figure 3. Temperature profile of an IGBT model with free-wheeling diode

The "thermal average" curves come from the "averaging" mode. When power pulses are injected at each switching period, a large simulation step in relation to the switching period can result in large errors in the temperature calculation (results marked as "Incorrect pulse width"); while using the thermal "averaging" approach, after a short transient period relatively accurate temperature estimation is achieved without excessive limitation on the time step.

3. REDUCED-ORDER THERMAL MODEL [1]

In this study, the model order reduction method used the linear superposition theory to extract the lump-parameter reduced thermal network from the transient responses of finite element analysis. The linear superposition theory states that the temperature rise at any given point in the system is the sum of the independently derived temperature increase attributable to each heat source in the system.

This thermal model reduction method is applicable to linear thermal systems, or to non-linear thermal systems around a desired working point. Also, except for those heat sources, all the other boundary conditions need to stay fixed over the time and space of interest. For a system with n heat sources, the linear superposition theory can be illustrated as following:

$$\begin{bmatrix} \Delta T_1(t) \\ \Delta T_2(t) \\ \vdots \\ \Delta T_n(t) \end{bmatrix} = \begin{bmatrix} \theta_{11}(t) & \varphi_{12}(t) & \cdots & \varphi_{1n}(t) \\ \varphi_{21}(t) & \theta_{22}(t) & \cdots & \varphi_{2n}(t) \\ \vdots & \vdots & \ddots & \vdots \\ \varphi_{n1}(t) & \varphi_{n2}(t) & \cdots & \theta_{nn}(t) \end{bmatrix} [h_1(t) \quad h_2(t) \quad \cdots \quad h_n(t)]^T \tag{1}$$

where ΔT_i is the temperature rise at node i, $\theta_{ii}(t)$ is the self-heating thermal impedance of node i, $\varphi_{ij}(t)$ is the "interaction" thermal impedance of node i due to heat source j, and $h_i(t)$ is the heat source applied at node i. Members of the theta matrix can be represented in the system simulator by the equivalent Forster thermal network, as shown in Figure 4.

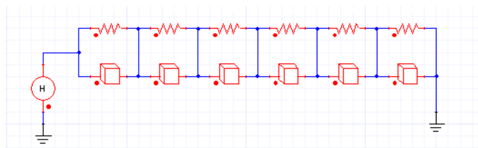


Figure 4. Foster thermal network

The time-domain expression of the Forster network can be written as following:

$$Zth(t) = \sum_{i=1}^{m} R_{thi} \cdot (1 - e^{-t/\tau_i}) \tag{2}$$

where m is the number of RC pairs, and parameters R_{thi} and τ_i can be extracted through fitting the transient thermal impedance curves.

4. SIMULATION and TEST

Figure 5 shows the system under study – a three-phase IGBT inverter driving an induction machine. The power losses from the IGBTs were injected into the reduced-order thermal model from the FA analysis using Ansys Icepak. The geometry of the IGBT package with heat sink and cool fans is shown in Figure 6. Figure 7 shows the junction temperatures the IGBTs. The current profiles shown in Figure 8 were imported into Ansys Maxwell®, and the thermal results were then used in Ansys Workbench® to generate the thermal stress distribution. Figure 9(a) shows the bus bar of the IGBT package without thermal load, and the deformation of the structure is demonstrated in Figure 9(b).

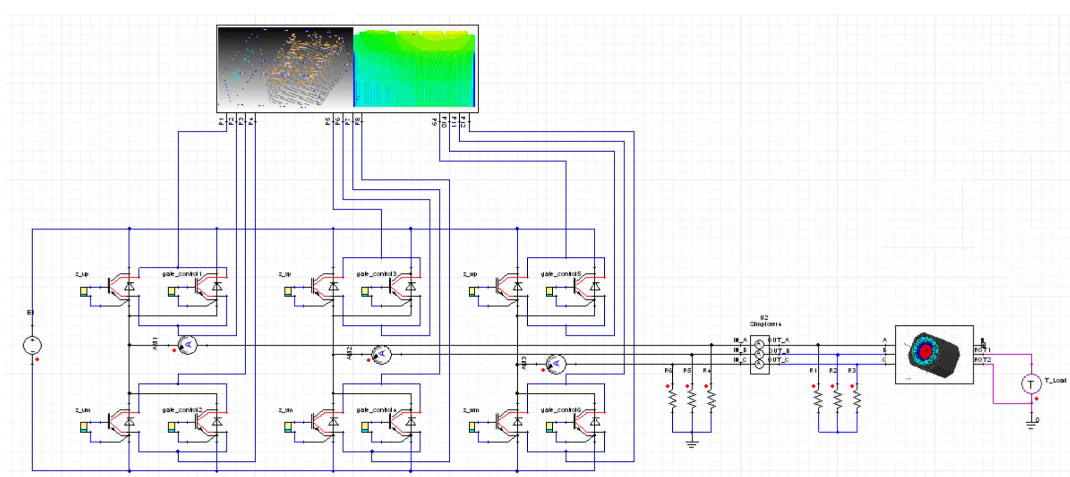


Figure 5. A three-phase IGBT inverter system with reduced-order thermal model

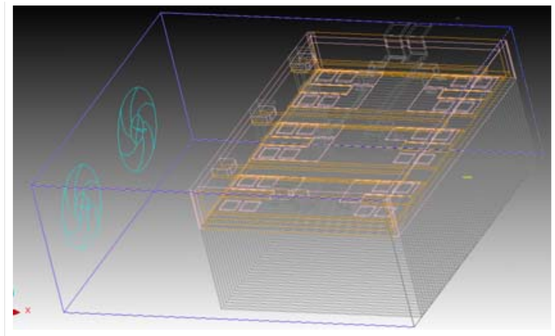


Figure 6. Geometry of a 12-pack IGBT package with heat sink and cooling fans

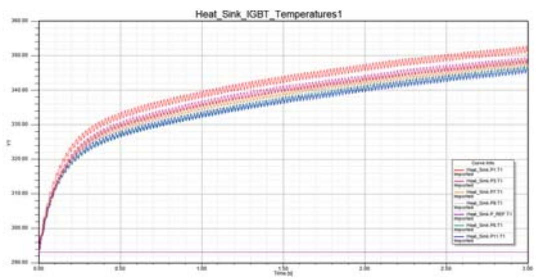


Figure 7. Junction temperature of the IGBTs

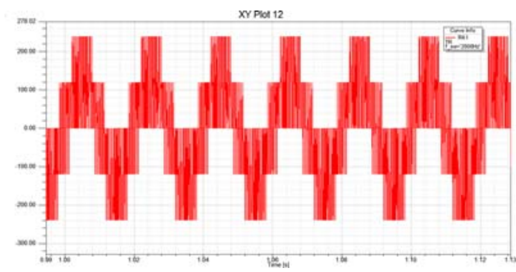
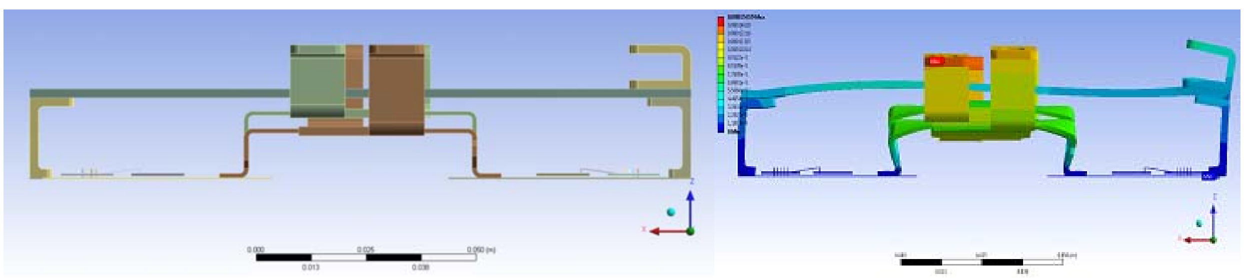


Figure 8. Current profile of the load current (one phase)



(a) Before applying thermal load **(b) Deformation with thermal load**

Figure 9. Thermal stress distribution

5. CONCLUSIONS AND FUTURE WORK

This paper presented an integrated process to perform thermal and thermal stress analysis on IGBT devices. The electrothermal IGBT model together with the reduced-order thermal model provided fast and accurate prediction of the device junction temperature, and current profiles can be further used in the FE simulation tool to derive thermal stress distribution. In the final paper, more simulation results will be included and analyzed in detail.

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