Multi-scale and Multi-domain Simulation of Electrical Power System

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Abstract

An integrated simulation solution in ANSYS Simplorer is presented for multi-scale and multi-domain simulation of electrical power systems. An accurate device-level power semiconductor modeling tool is introduced and verified. Reduced order model (ROM) techniques are then demonstrated to import detailed models from multiple ANSYS finite element analysis (FEA) tools, so they can be interconnected and integrated to system level simulation.
(Keywords: Simulation, Compact model, ROM)

Introduction

With rising scale and complexity, electrical power systems are becoming more challenging to design and analyze [1][2]. This paper presents an integrated simulation solution in Simplorer, which can interconnect various types of physical and behavioral models to simulate complex systems. Two modeling techniques are introduced: 1) compact model and characterization of power semiconductors; 2) ROM extraction of cable, and device packaging with parasitic and cooling effects from ANSYS FEA tools. To showcase combined simulation of these models, two demonstrative examples of electromagnetic interference (EMI) and electro-thermal simulation are described.

Compact Model of Power Semiconductors

To simulate switching characteristics of power electronics, a library of device level power semiconductors and a model characterization tool are provided in Simplorer [3][4]. It enables accurate simulation of off-the-shelf devices, including IGBT, power MOSFET and diode. All information needed to parameterize these models can be found in datasheet.

Fig.1 shows the equivalent circuit inside the IGBT model. It consists of a static core of a MOSFET driven bipolar transistor, around which a set of lumped passive elements and current sources are built to model the dynamic behavior. All capacitances between the terminals are modeled with a capacitor that includes both a depletion capacitance behavior and an enhancement capacitance behavior. It is a function of voltage across the junction V_J:

$$C(V_J) = C_0\left[1 + (\beta - 1)\left(1 - e^{\frac{-V_J\cdot\alpha\cdot(1-\delta)}{(\beta-1)\cdot V_D}}\right)\right]$$

when $V_J > 0$

$$C(V_J) = C_0\left[\delta + \frac{1-\delta}{\left(1-\frac{V_J}{V_D}\right)^{\alpha}}\right] \text{ when } V_J \le 0$$

where α, β, V_D are constant 0.1, 0.5, and 0.6 respectively. And C_0 and δ are parameters to be fitted according to dynamic characteristics of the device. The curves remain differentiable at the transition. In addition, the model also includes operating condition dependency, built-in power loss calculation, and junction to case thermal model for junction temperature simulation.

For demonstration, a model is extracted for Infineon FS400R12A2T4 IGBT. Using the automatic device characterization tool, static and thermal parameters are fitted to datasheet curves, and dynamic parameters are automatically tuned to match switching time and energy data. Fig.2 and Fig.3 plot the simulated output and thermal characteristics of this model against points sampled from datasheet. And Fig.4 verifies the model's switching loss at multiple levels of nominal current.

EMI Simulation with HF Parasitic ROM

Fig.7 is an example of PMSM speed control system, in which the FS400R12A2T4 IGBT model characterized in last section is used to build the inverter.

For this system, the parasitic effects (RLCG) are important for noise spectrum analysis, and are mainly determined by 3D geometry of the printed circuit board (PCB), device packaging, etc. These 3D structures can be modeled in ANSYS Q3D, which extracts frequency dependent RLCG parameters using FEA. To study the influence of the parasitics to the power electronic system, Q3D can generate highly accurate ROM in form of scattering parameter, which can be used in circuit simulation. Fig.5 shows the Q3D model of the example IGBT's package. Its RLCG matrices are calculated up to 100 MHz, and the resulting parasitic ROM is integrated to the IGBTs in Simplorer, as shown in upper right of Fig.7. The same ROM extraction technique is also applied to model a 1m long 3-phase power cable between inverter and electric machine in Fig.7.

The close-loop PMSM speed control is simulated with a reference change at 0.75s. Fig.8 shows the simulated current, and Fig.6 is the junction temperature rise on one of the IGBTs under ideal cooling condition. LISN (CISPR25) is used to measure the conductive EMC between the DC source and the inverter (EUT). The spectrum plot of the voltage output from LISN EMI receiver port is shown in Fig.9, with red represents the result without packaging and cable ROMs and blue represents the result with the ROMs.

Electro-thermal Simulation with Thermal ROM

To simulate realistic thermal performance, 3D geometry of package/heat sink, as well as air flow condition need to be considered. In this example, the 3D package model in Fig.5 is used again in ANSYS Icepak to perform FEA analysis for cooling. Based on the step response file from Icepak, a state space ROM can be generated to use in Simplorer. Fig.10 shows the ROM simulated in Simplorer with matching step response as in Icepak. And Fig.11 demonstrate how the thermal ROM can be connected to the characterized IGBT by exposing its thermal pins.

Conclusion

This paper demonstrates the capability of Simplorer to interconnect accurate power device model with ROMs extracted from various FEA tools. Combination of these modeling techniques within an integrated simulation environment enables investigation on different level details for a complete electrical power system/sub-system. A demonstrative example with integrated components is discussed with reasonable simulation results.

References

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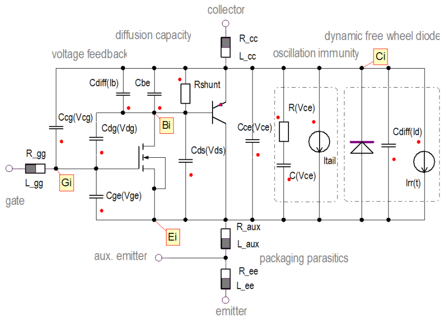

Fig. 1: Equivalent circuit of dynamic IGBT model.

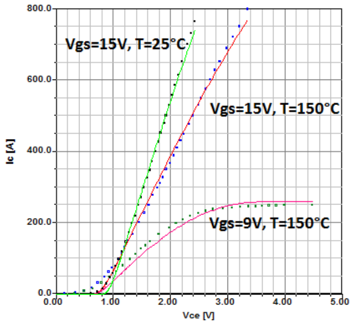

Fig. 2: Output characteristics of extracted IGBT model

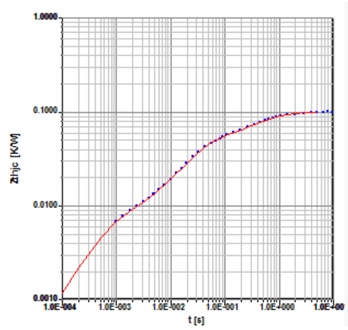

Fig. 3: Transient thermal resistance junction to case

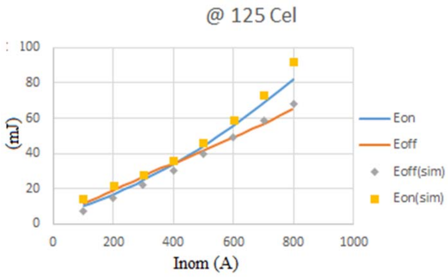

Fig. 4: Switching energy of extracted IGBT model.

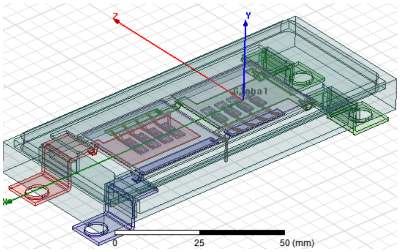

Fig. 5: Package structure of the IGBT device

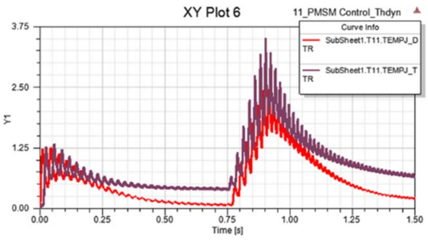

Fig. 6: Simulation of junction temperature rise

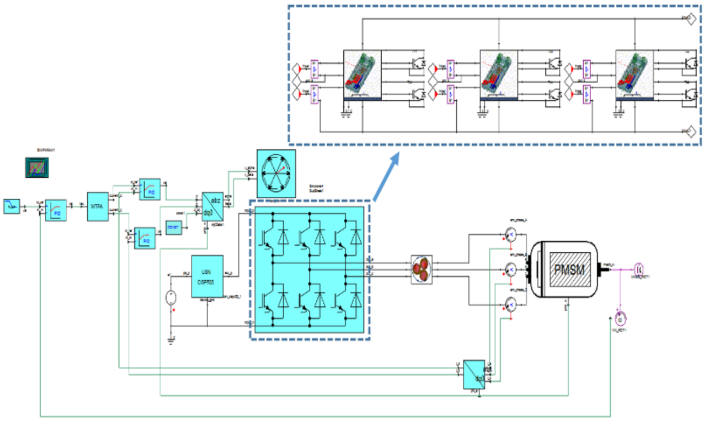

Fig. 7: System level PMSM speed control schematic with packaging and cable.

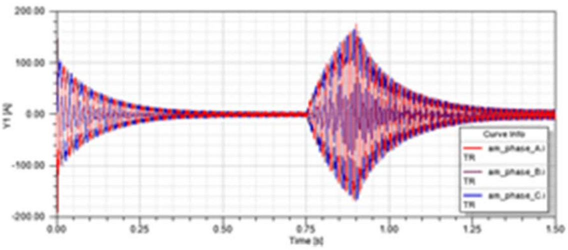

Fig. 8: PMSM speed control three phase currents

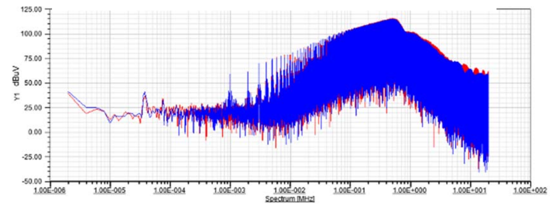

Fig. 9: Noise spectrum plot from LISN

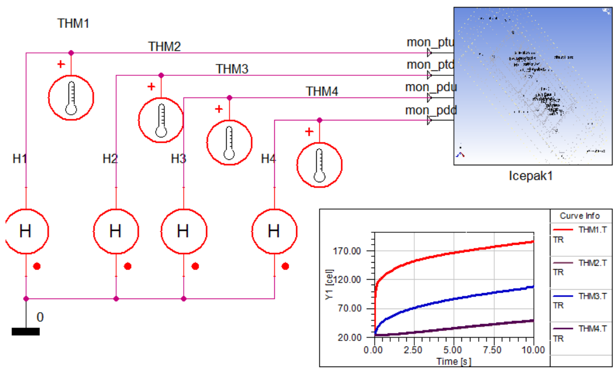

Fig. 10: Step response of thermal ROM for IGBT package

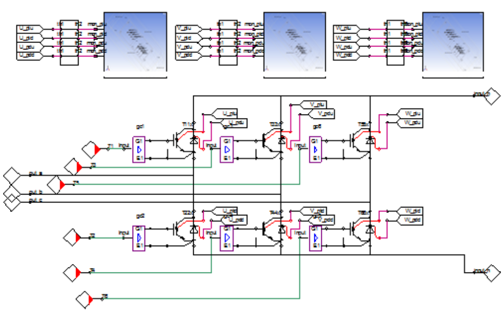

Fig. 11: Electro-thermal simulation of a 3-phase IGBT inverter