Simulation Technology for Power Electronics Equipment

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ABSTRACT

As there is increasing demand for higher efficiency and power density of the power electronics equipment, it has become more important to develop the equipment by connecting the design of wiring structure, cooling structure and electromagnetic interference (EMI), which were previously designed individually. Fuji Electric is working on the realization of such a connection by using a device simulation model. This simulation model makes it possible to understand the switching characteristics after the implementation into circuits. In addition, the simulation result can effectively be applied to the design of the other components. Since it is now possible to estimate the temperature of a component and an EMI noise level precisely at the beginning of the design stage, the cooling structure and EMI filters can be developed effectively shorter period than before.

1. Introduction

Fuji Electric's power electronics technology is one of its core technologies for achieving energy creation in photovoltaic power generation and wind power generation, as well as energy savings in the efficient utilization of the created energy. Power electronics equipment has already become prevalent in a wide range of applications, but in recent years, it has been required to achieve higher efficiency and power density in order to fulfill the increasing demands of efficient use of energy resources. In addition, the range of application for power electronics equipment needs to be expanded to meet the diverse requirements of customers, while a shorter development time is also demanded to ensure the timely release of products that meet market needs.

Fuji Electric has made use of a variety of simulation technologies to develop products that meet these demands. However, there is also a need to further enhance our simulation technology in order to satisfy even more stringent demands in the future. The main purpose of this paper is to describe our high-precision device simulation model, which is capable of linking with separately performed simulations related to wiring structure design, cooling structure design and electromagnetic interference (EMI) design. By using this simulation technology, we are able to determine the efficiency and size of equipment during the initial development stage, as well as shorten the development period by reducing the number of prototypes.

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2. Device Design Simulation Technology

2.1 Design elements in the main circuit of power electronics equipment

Figure 1 shows the main design elements in the main circuit of power electronics equipment. Power electronics equipment utilizes high-speed switching by means of power devices such as insulated gate bipolar transistor (IGBT) and metal-oxide-semiconductor field-effect transistor (MOSFET) to convert electricity (voltage, current) to a desired form (AC/DC, amplitude). When developing the main circuit for power electronics equipment, it is necessary that the completed product satisfy the required specifications, and this requires combining the wiring structure design (required for proper switching), cooling structure design (required for dissipating heat generated due to the conduction losses and switching losses of devices) and EMI design

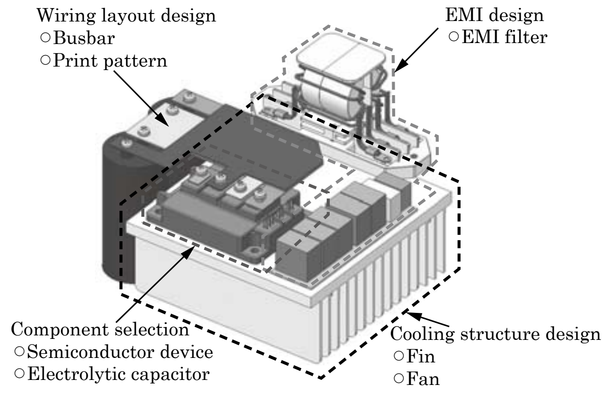

Fig.1 Design elements in the main circuit of power electronics equipment

(required for preventing electromagnetic noise trouble associated with voltage and current fluctuation during high-speed switching).

2.2 Simulation configuration

Fuji Electric utilizes simulations for the 3 types of design elements. The configuration of the device design simulation is shown in Fig. 2. In the conventional simulation shown in Fig. 2 (a), device design is carried out while optimizing each of the elements separately by means of simulations. When doing this, the required switching characteristics (surge voltages, losses) of the power device are obtained through trial manufacturing and experimenting. However, since the elements interact with each other, this affects the characteristics of the elements. As a result, a locally optimized element may not result in an optimized design of the entire equipment. Therefore, the optimization of power electronics equipment required repeated trial manufacturing and evaluation. Repeated trial manufacturing and evaluation not only leads to extended development periods, but also makes it more difficult to satisfy more advanced requirements, especially for elements that greatly depend on the expertise of the developer.

As a result, an equipment design that does not depend on trial manufacturing is needed to be able to analyze the behavior of the entire device during the design stage. This is achieved by means of the configuration shown in Fig. 2 (b), in which development is linked together with the device simulation model. The device simulation model is the focal point of development and it makes it possible to utilize the 3 types of simulations by linking them together. The configuration of this simulation makes it possible to carry out device design without trial manufacturing since actual measurements are not required.

3. Device Simulation Technology

3.1 Analysis of device operating waveform in conventional simulations

In order to achieve the simulation configuration shown in Fig. 2 (b), the development of a high-precision device simulation model is absolutely essential. The technology for analyzing the device operating waveform has been under study for a long time, but in general, it can be broadly divided into 2 different types. However, based on the reason indicated below, it is difficult to apply the technology to the design of power electronics equipment.

One of the types is a technology for performing analysis through the use of a behavior model obtained by fitting the electrical characteristics of the device. This technology is normally implemented in a circuit simulator that is generally used in the waveform analysis. Since there are comparatively few configuration parameters, it can be operated quickly and easily by device design engineers. However, this model is effective only in the limited operating conditions, and, therefore, it is still difficult to obtain an accurate operating waveform in power electronics equipment which is operated under various conditions of the gate driving and temperature.

The other type is a device simulator technology for analyzing the internal state of the spatial distribution of the carrier density and electric field based on the device structure model and semiconductor physical properties in order to obtain the electrical properties. This technology is capable of accurate analysis and is used in device development, but it takes a long time to analyze a single switching waveform. Therefore, it takes too much time to perform the analysis of linkage with the circuit simulator for simulating the behav-

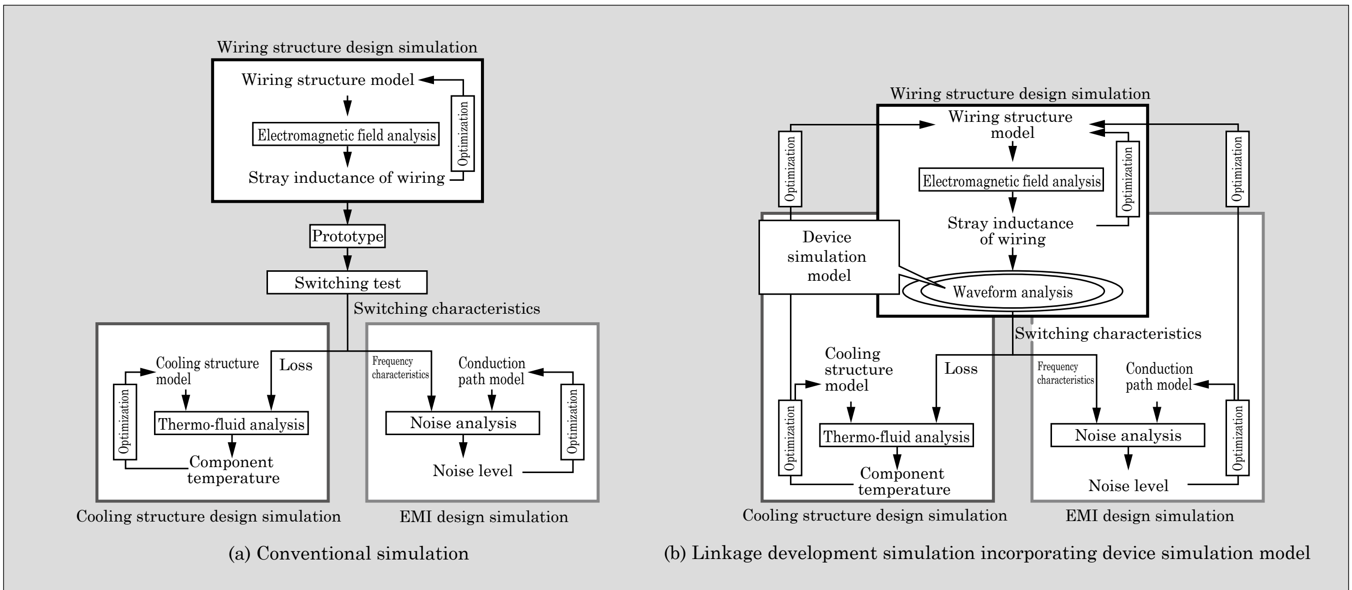

Fig.2 Configuration of device design simulation

ior of power electronics equipment, which carries out switching repeatedly. As a result, it is difficult to apply this technology to the design of power electronics equipment.

3.2 Principles of the device simulation model

Fuji Electric has developed a device simulation model capable of operating in a circuit simulator for performing high-precision analysis under various operating conditions. This model is currently being utilized in the development of power modules.

The developed simulation model is configured with an equivalent circuit model based on semiconductor's internal physical phenomena. Figure 3 shows the equivalent circuit model of the IGBT. The IGBT is indicated by the electrical component symbols as shown in Fig. 3 (a). The equivalent circuit model for the internal structure of the IGBT is configured as shown in Fig. 3 (b) by connecting in series the PiN diode and MOSFET. The capacitors are also connected to each terminal. The current of the PiN diode flows according to the carrier (holes and electrons) concentration distribution gradient and carrier recombination, and the current is calculated by obtaining the diffusion current and the recombination current. Furthermore, since carrier accumulation and delivery occur in the drift layer. The current due to this phenomenon is obtained to calculate the tail current during turn-off period. The current through the MOSFET is calculated based on the conductivity of the channel depend on the gate voltages. In addition, the terminal-to-terminal capacitance is calculated from the device's internal structure and the width of the depletion layer.

By determining the parameters to be used in the equivalent circuit model from the analysis results of the device simulator, it is possible to reproduce the electrical characteristics based on the device characteristics. As a result, it is possible to build a model that matches the actual requirements even when there are

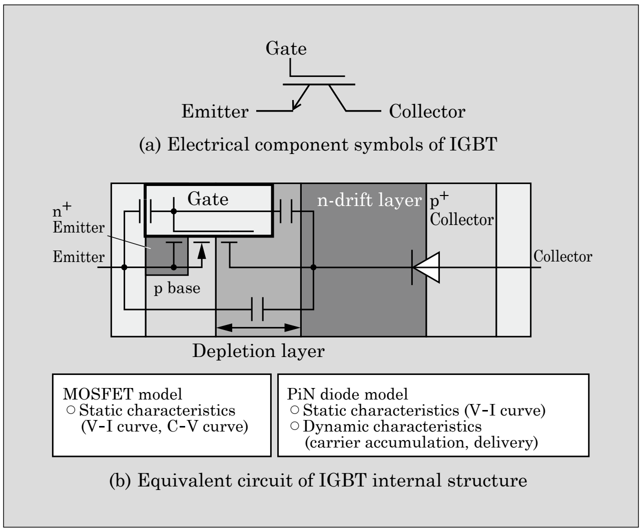

Fig.3 IGBT device equivalent circuit model

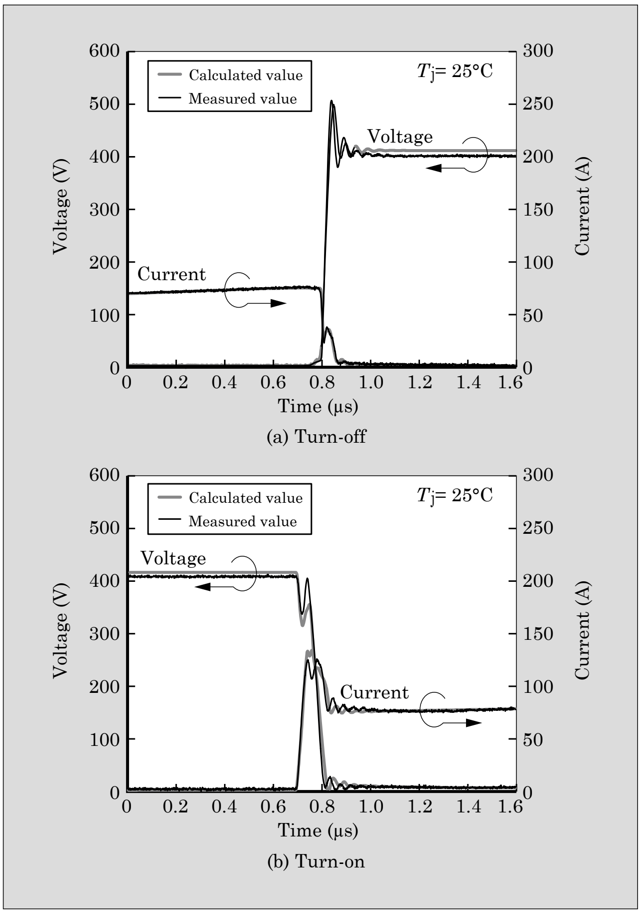

Fig.4 Switching waveform of IGBT

changes in the switching conditions (voltage, current), driving conditions (gate voltage, resistance) and temperature.

Figure 4 shows a comparison of the measured switching waveform and the calculated switching waveform of the device equivalent circuit model for the IGBT (T_j = 25 °C). Error in switching losses (i.e., the error in the calculated values compared with the measured values) is 5.4% at turn-off and 3.3% at turn-on. This indicates that it is possible to implement high-precision analysis. Furthermore, the slope of voltages and currents, as well as their parasitic oscillation match the measured values. The error for peak values is 1.6% for voltage and 6.5% for current. It is indicating that the actual behavior can be simulated with good precision.

3.3 Example of device design via coupled simulation

As mentioned earlier, utilizing a device simulation model makes it possible to analyze the behavior of devices with high precision, enabling device design without having the actual measurements. In this section, we describe an example of using this device simulation model with regard to device selection, wiring structure design, cooling structure design and EMI design.

(1) Device selection and wiring structure design

In order to reduce the generated loss of the device and increase the efficiency of equipment, it is necessary to utilize the high-speed switching of the device and implement proper device selection and wiring structure design. However, the switching characteristics (e.g. surge voltage and switching losses) for the device type and wiring structure fluctuate in a complex manner, and as a result, the optimal characteristics need to be obtained by changing the conditions and performing evaluation based on detailed experiments.

When the device simulation model is used, these complex fluctuations can be accurately simulated, and device selection and wiring structure design can be implemented without requiring actual-equipment evaluation. The switching waveform when connecting IGBTs in parallel is shown in Fig. 5. The utilized IGBT is the exact same one used in the switching waveform measurements shown in Fig. 4. The impact of the stray inductance of the wiring and current flowing in the device causes the switching waveform to fluctuate in a complex manner, and although switching losses increased by 30% during turn-off, it decreased by 50% during turn-on. By utilizing the device simulation model, switching loss error becomes 0.6% and 2.9% respectively. Furthermore, conventional methods would see an increase in loss of about 40% when conditions change, but the device simulation model improves on this significantly.

(2) Cooling structure design

The cooling structure (fin, fan) is one component that occupies a large area in power electronics equipment. In order to reduce the size of equipment, components need to be arranged in consideration of the heat quantity and air flow of the components; thus one requirement is the development of a more compact cooling structure design capable of high-efficiency cool.

Fuji Electric has utilized thermo-fluid analysis to develop an analysis technique for examining the optimal placement of components. When the arrangement of components is changed, the wiring structure also changes, and as a result, generated loss for the device also fluctuates as explained previously. Traditionally, these changes were incorporated into the design as margin. However, when using the device simulation model and thermo-fluid analysis, accurate analysis can be made of loss and temperature based on component arrangement, thereby enabling a design with very little margin.

In addition, since device loss depends on temperature, the temperature of the device also varies with changes in generated loss based on cooling capacity. In conventional cooling structure design, it was common for analysis to be performed for the generated loss of the device by using the loss of a certain temperature (for example, T_j = 150 °C). However, this approach led

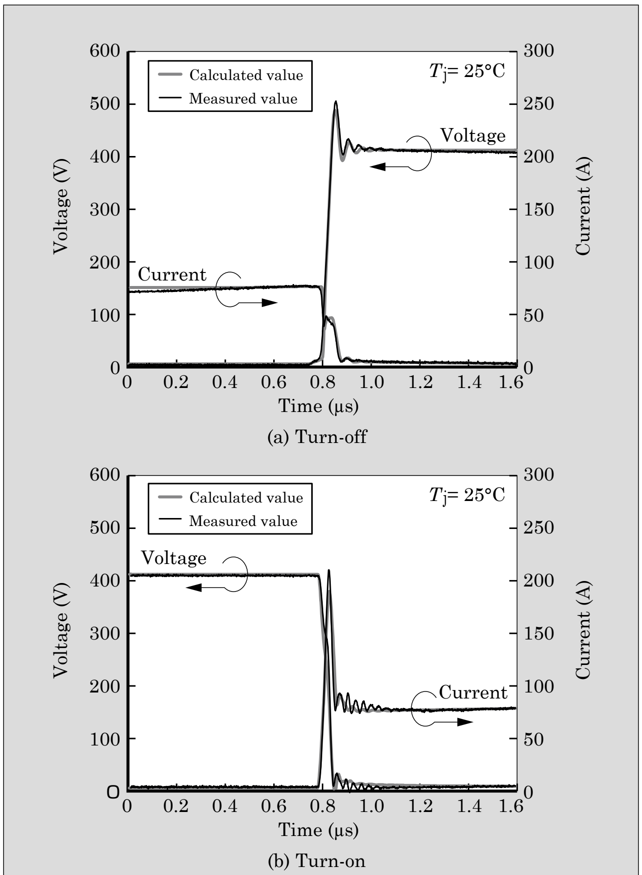

Fig.5 Switching waveform when connecting IGBTs in parallel

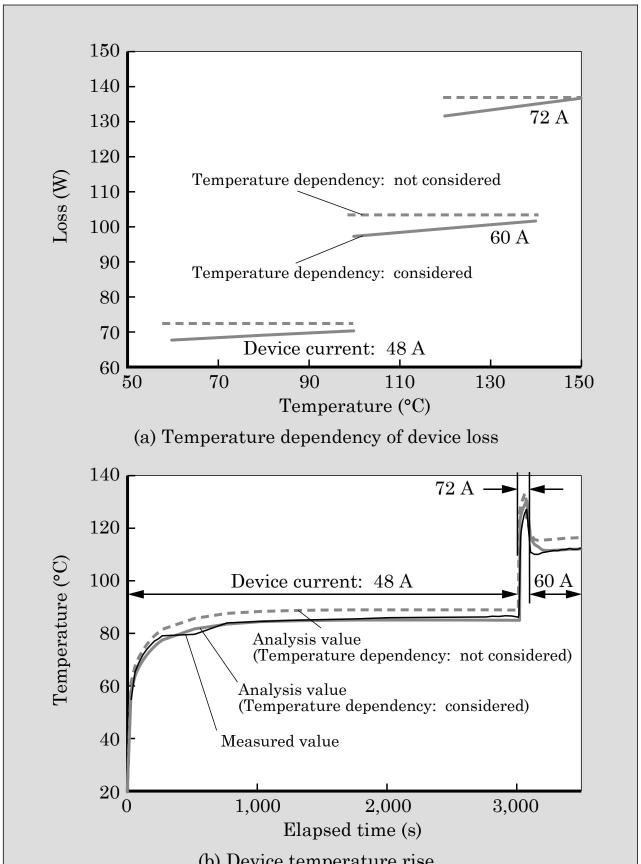

Fig.6 Thermo-fluid analysis considering temperature dependency of device loss

to degradation in precision. Figure 6 shows a thermo-fluid analysis taking into account the temperature dependency of the device loss. Loss tends to increase in proportion to increases in temperature for the temperature dependency of the device loss shown in Fig. 6 (a). The temperature increase of the device when changing the current flowing in the device stepwise from 48 A to 72 A, and then to 60 A is shown in Fig. 6 (b). When consideration is not made for temperature dependency, an error up to 7 °C may exist, but this is improved to 3 °C when temperature dependency was considered. Using the device simulation model in this way makes it possible to perform more precise thermal analysis, and it contributes to reducing the size of the cooling structure, as well as shortening the development period.

(3) EMI design

Sharp changes in the voltage and current in the switching operations of semiconductor devices are a source of noise in power electronics equipment, and electromagnetic noise is emitted through the propagation of parasitic capacitance and space inside the equipment. Suppressing these types of noises through proper EMI design is very important for not only reducing the size of equipment, but also for increasing the reliability.

Fuji Electric has constructed an EMI analysis platform capable of optimizing EMI design before starting trial manufacture for the equipment. By utilizing electromagnetic field analysis, it is possible to implement noise conduction path modeling and estimate the noise components emitted from the equipment. Traditional EMI analysis utilizes the maximum value of each frequency component derived from the observed waveform, and then estimates the noise components to be emitted.

By incorporating a physical model for the device into the platform, it becomes possible to carry out high-precision estimations before starting trial manufacture for the equipment. The amount of noise emission is regulated for each frequency component. EMI design can be performed with even greater precision if accurate estimation can be made of the frequency components of the noise producing switching waveform.

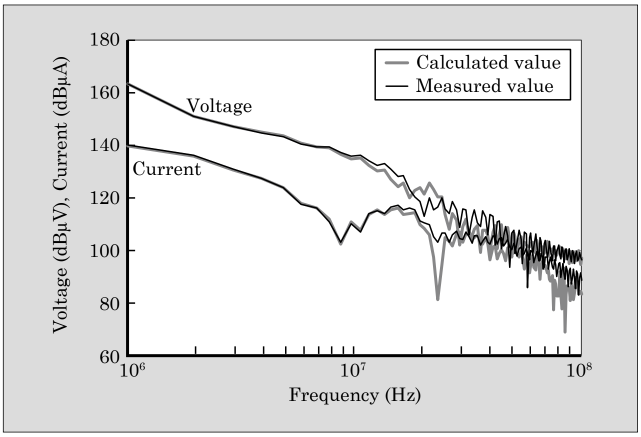

Fig.7 Frequency characteristics of switching waveform during turn-off

Figure 7 shows the frequency characteristics of the switching waveform during turn-off shown in Fig. 4(a). The frequency components for the measured values and calculated results show good agreement, and it is anticipated that high-precision EMI design will be implemented without manufacturing equipment and taking measurements.

4. Postscript

By utilizing a high-precision device simulation model for power electronics equipment design, we have shown that it is possible to perform high-precision design without the need of creating prototypes.

In the future, we plan to simplify the linkage work required for each simulation tool and establish an equipment design technology for optimizing the design of equipment while shortening the development time.

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