Electromagnetic Noise Simulation Technology for Power Electronics Equipment

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ABSTRACT

Power electronics have been becoming more widely used as core products for achieving energy savings and energy creation. However, power electronics equipment may cause electromagnetic noise interference, such as communication failure and malfunction and damage of electronic equipment. For preventing electromagnetic noise interference caused by conduction noise and radiation noise, Fuji Electric has been developing various simulation-based technologies, including the improvement of the analysis accuracy of electromagnetic noise generated by power electronics equipment to comply with relevant regulations, analysis models from which we can select a simplified or detailed one depending on applications, and applications for power electronics systems in addition to that for single equipment.

1. Introduction

In conserving energy to make efficient use of electric energy and in creating energy such as via photovoltaic power generation and wind power generation, power electronics are widely in use as core products. Power electronics equipment can freely convert electricity into easy-to-use forms by performing high-speed switching of power semiconductors such as insulated-gate bipolar transistors (IGBTs) and metal-oxide-semiconductor field-effect transistors (MOSFETs) and are effectively applied in various situations. Mass production of next-generation power semiconductors that use silicon carbide (SiC) and gallium nitride (GaN) started recently. With further loss reduction achieved, technologies for improving the efficiency and miniaturizing devices are being vigorously developed.

While power electronics equipment is very convenient, it emits to the surrounding environment currents and electromagnetic waves that make a noise during operation. This may cause electromagnetic noise interference and lead to the malfunction of and damage to electronic equipment. To prevent these electromagnetic noise failures, sufficient reduction of electromagnetic noise emitted to the surrounding environment is required of power electronics equipment. Increasing the switching speed in order to reduce the losses of power electronics equipment causes an increase in the energy of the electromagnetic noise emitted to the surrounding environment. This in turn requires the development of technology for protecting the surrounding environment by containing the electromagnetic noise within devices.

Fuji Electric utilizes simulation technology for preventing electromagnetic noise interference resulting from power electronics equipment.

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2. Electromagnetic Noise Simulation

In recent years, many manufacturers have been working on electromagnetic noise simulation of power electronics equipment and various results are reported. Fuji Electric was among the first to undertake technological development for electromagnetic noise simulation of power electronics equipment in order to apply it to products.

2.1 Noise reduction required of power electronics equipment

Figure 1 shows a schematic diagram of electromagnetic noise generated by power electronics equipment. Because of high-speed switching (a few to a few hundred kHz) of power semiconductors, power electronics equipment generates large electromagnetic noise as

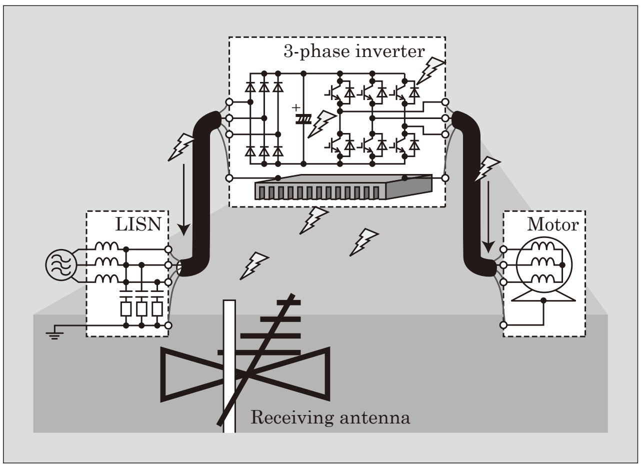

Fig.1 Schematic diagram of electromagnetic noise generated by power electronics equipment

conduction noise if it is radiated outside through input/output power cables, and as radiation noise if emitted as radio waves from various parts.

To prevent failures caused by these types of electromagnetic noise, electrical equipment including power electronics equipment is required to reduce the electromagnetic noise under various regulations. In particular, following the obligation to place CE marking on products, stipulated by the EMC Directive*1 in Europe (within the EU member states) in 1996, various methods of electromagnetic noise reduction have been proposed. With power electronics equipment, however, reducing the electromagnetic noise generated and improving the performance (loss reduction) are in a trade-off relationship. This requires repetition of trial and error every time a product is developed to take electromagnetic noise countermeasures, which consumes large amounts of time and labor.

To conform to the EMC Directive without going through trial and error, Fuji Electric started developing technology to simulate the electromagnetic noise of power electronics equipment.

2.2 Simulation of conduction noise

In order to conform to the EMC Directive, the intensity (level) of conduction noise radiated outside through cables must be measured and evaluated over a range from 150 kHz to 300 MHz as noise voltage (noise terminal voltage) at a line impedance stabilization network (LISN) that simulates a power system. The noise voltages for all of the phases must be reduced the regulation value or less.

The conduction noise simulation for deriving the noise terminal voltage of the power electronics equipment subject to the regulation is illustrated in Fig. 2. As shown in Fig. 2(a), conduction noise simulation can be roughly divided into 3 phases: (1) detailed modeling of a device to reproduce the impedance of the device, (2) circuit analysis that simulates circuit operation and (3) data processing of the results of circuit analysis. For modeling a device, an equivalent circuit model is built: For circuit components that allow measurement of impedance, LCR circuit elements are combined based on the results of measurement and, for printed boards and structural components that do not readily allow measurement, electromagnetic field analysis is used. For input/output power cables, the effects of the length and layout at the time of measurement are also factored into the circuit analysis. In addition, to ensure an agreement between the results obtained by circuit analysis and those measured as noise terminal voltages, data processing is done to reproduce the bandwidth of the spectrum analyzer, etc. when temporal waveforms are converted into frequency spectra.

*1: EMC Directive: Refers to one of the technical requirements to be met for acquisition of a CE Mark that relates to electromagnetic compatibility (EMC).

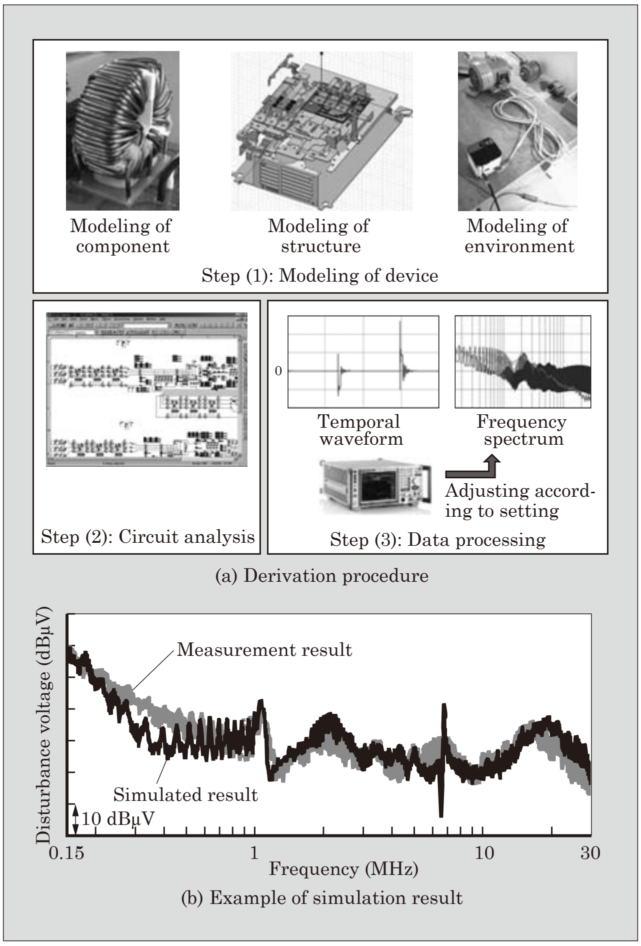

Fig.2 Conduction noise simulation

The accuracy of estimating the noise terminal voltage improves as the device is modeled in more detail. With the conditions used for building the most complicated model, simulation results are almost agree with measurement results over the entire range from 150 kHz to 30 MHz subject to the regulation for noise terminal voltage as shown in Fig. 2(b).

2.3 Simulation of radiation noise

The intensity (level) of radiation noise is measured as the radiation field intensity by using a receiving antenna located 10 m away from the power electronics equipment. In this case, the power electronics equipment must be rotated by 360 degrees. Then, the maximum value obtained as the height and angle (horizontal and vertical) of the receiving antenna is varied must be reduced to no higher than the regulation value.

Simulating radiation noise is much more difficult than conduction noise. This is because that, as shown in Fig. 1, while conduction noise is evaluated only by the voltage that has reached the LISN, radiation noise is emitted into space from numerous sources of radiation unintentionally formed in the device. Figure 3 shows an example of measuring and simulating radiation noise, which is an area that Fuji Electric is work-

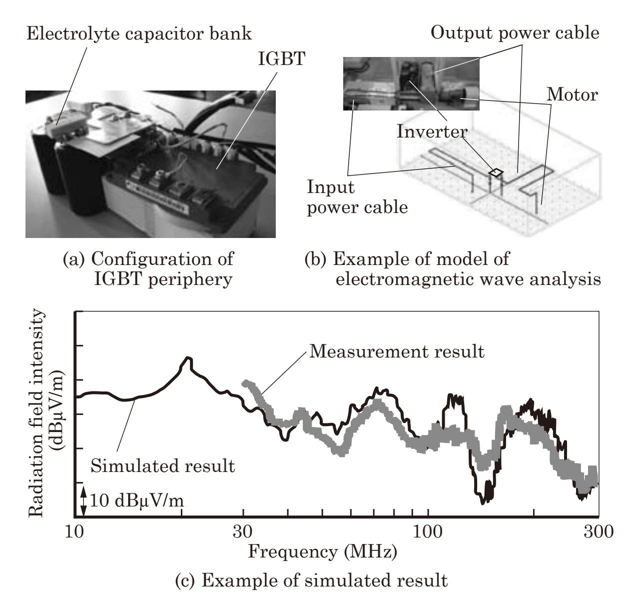

Fig.3 Radiation noise simulation

ing on. The description here is mainly about the difference from conduction noise simulation.

As compared with the switching frequency of power electronics equipment, the evaluation frequency for radiation noise is high at 30 to 300 MHz. This makes it difficult to obtain switching waveforms that include this frequency component accurately by circuit analysis. Accordingly, for electromagnetic noise simulation at 10 MHz or higher, switching waveforms measured by simulating IGBT peripheral circuitry as shown in Fig. 3(a) are factored into circuit analysis.

What is required next is electromagnetic wave analysis. For simple circuit operation, circuit analysis and electromagnetic wave analysis can be obtained at the same time. But it is difficult to link analyses on the complicated circuit operation of power electronics equipment with electromagnetic wave analysis. Radiation noise simulation can be roughly divided into modeling, circuit analysis and electromagnetic wave analysis and a different analysis software application is used for each of them. For this reason, handing over data to link these processes with each other is the key. First, for impedance modeling, a distributed constant circuit, rather than a lumped constant circuit combining LCR circuit elements, must be simulated. In particular, print pattern and component arrangement have a major effect, and electromagnetic field analysis is used to model them into a distributed constant circuit, which is factored into circuit analysis. In circuit analysis, the current that flows to the antenna formed in each location is determined. Antennas are formed unexpectedly here and there in the device but the dominant antenna is identified, and this is then factored into the electromagnetic wave analysis. For electromagnetic wave analysis, only the shapes of major antennas are modeled to derive the radiation field 10 m away based on the current that flows.

Figure 3(b) shows an example of a model for analyzing radiation noise from an inverter. The inverter is simulated by using a loop antenna for the IGBT peripheral structure and dipole antennas for the input/output power cables. The effective area of the loop antenna and the effective length of the dipole antennas greatly contribute to the analysis accuracy, so the antenna shapes must accurately simulate these. The interference between the antennas caused by phase difference is determined by data processing based on the results of the electromagnetic wave analysis for the respective antennas.

Figure 3(c) shows an example of the result of radiation field intensity simulation obtained by these processes. It can be confirmed that the general trends agree in the range from 30 to 300 MHz, in which significant electromagnetic noise is generated in power electronics equipment. Note, however, that it still has various issues such as finding a method to identify in advance the antenna that provides the dominant source of radiation, in addition to improving the accuracy.

3. Examples of Application of Electromagnetic Noise Simulation Technology

3.1 Application to product development

As shown in Section 2, electromagnetic noise simulation of power electronics equipment achieves high accuracy by reproducing the devices and measurement environment with high accuracy. However, it is difficult to apply such simulation to product development due to its long analysis time in addition to the cumbersome procedure. To deal with the issue, we use simple and detailed analysis models appropriately according to the product development process.

To obtain results, radiation noise simulation requires more labor and time than conduction noise simulation, so we consider applying it only to those targets for which it is more effective. This subsection presents a case in which it is applied to the design of housing of power electronics equipment.

Figure 4 shows an example of housing analysis. As shown in Fig. 4(a), the housing of an inverter may be configured by combining cooling fins and sheet metal or made by aluminum die casting, and the former tends to generate larger radiation noise. The housing is grounded and the potential at any point is ideally equal to 0 V. However, with the large area, minute potential variations may occur. It has been found that this minute potential variation may cause large radiation noise. Hence we use a simulation to design housing that mitigates the minute potential variations. Figure 4(b) shows an analysis model that extracts the cooling fins, sheet metal and electrolyte capacitors at the ground potential. Based on the results of simulation that uses a partial model like this, the housing is designed to achieve a configuration that reduces the

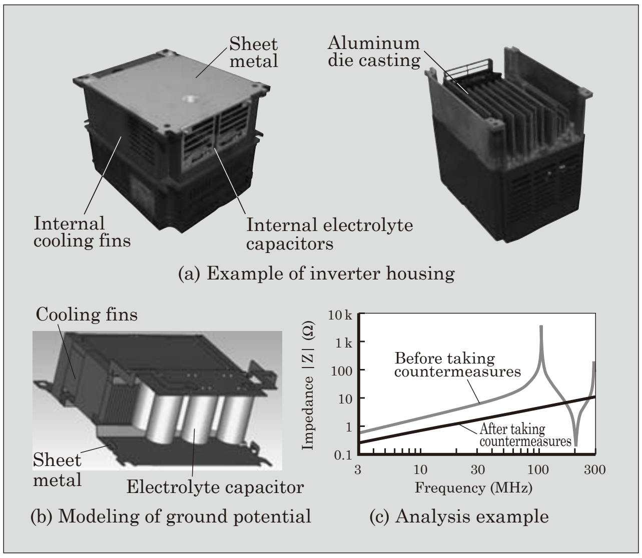

Fig.4 Housing analysis example

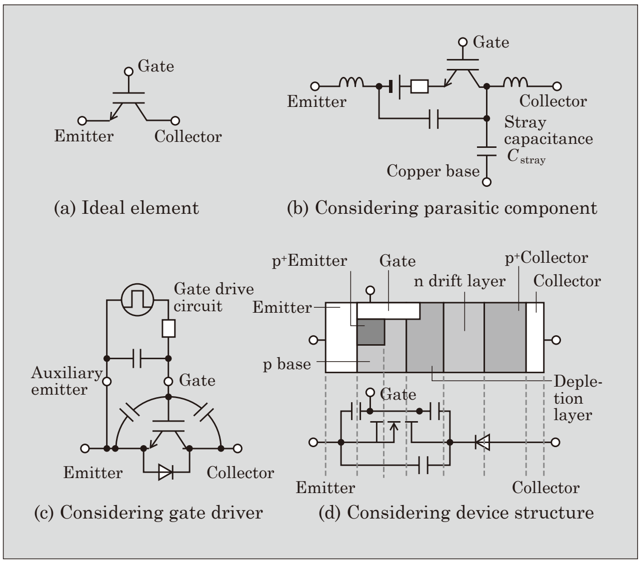

Fig.5 Transition of IGBT device model

impedance between the connection points, for which the minute potential variation should be mitigated, and prevents the formation of an unwanted resonant peak as shown in Fig. 4(c). This is effective in reducing radiation noise.

Such simulation with part of the device extracted, which features simple modeling and short analysis time, allows exploration of a better configuration by repeated analysis.

3.2 Study of accuracy improvement

Sometimes, electromagnetic noise arises from a product-specific circuit and/or structure, where the generation mechanism is unclear and is difficult to deal with. In those cases, we build a more detailed model to further improve the analysis accuracy, thereby gaining an understanding of the generation mechanism to formulate countermeasures to take.

(1) Mode conversion

Conduction noise is subject to a phenomenon called mode conversion. The common mode component conducted through the ground wire and the differential mode component conducted through the power supply line may have their paths changed during conduction through various locations, and this is referred to as mode conversion. The noise caused by this mode conversion is generally difficult to reduce. With actual measurement, grasping the generation of mode conversion itself is difficult. However, use of simulation allows the paths and mechanism of mode conversion to be grasped relatively easily. In addition, to reduce the noise caused by mode conversion, countermeasures can be formulated such as those that eliminate the paths of mode conversion and shift the resonance frequency, which are difficult to identify by measurement alone.

(2) Modeling of switching characteristics

To improve the accuracy of electromagnetic noise simulation, we are developing technology to accurately model the switching characteristics of power semiconductors, which is the source of the noise. In the development of power semiconductors, device simulators capable of accurately reproducing a single switching characteristic have been utilized. But they are difficult to combine with circuit operation of power electronics equipment, which is characterized by repeated switching. For this reason, applying device models of power semiconductors to circuit analysis of electromagnetic noise simulation had many problems.

Figure 5 shows transition of an IGBT device model. With the ideal element in Fig. 5(a) as the basis, the initial noise analysis had surrounding parasitic components (inductance and capacitance) added to the model as shown in Fig. 5(b). Adding the stray capacitance C_{stray} has made it possible to simulate paths of noise without omission. In Fig. 5(c), the gate driver characteristics are also added to model the switching characteristics in more detail. However, switching characteristics are reproduced by fitting to measurement data. This lead to the problem of larger errors caused by significant changes in the peripheral circuitry and/or device temperature. Recently, as shown in Fig. 5(d), a model based on the device internal structure has been built to allow for more accurate simulation of switching characteristics[1]. By applying this model, high estimation accuracy has been realized in electromagnetic noise simulations without the need for measurement data.

3.3 Application to power electronics systems

To prevent electromagnetic noise interference on site while conforming to standards, we are moving ahead with a study on simulations intended for power electronics systems composed of power electronics equipment, control devices, detectors, etc.

Figure 6 shows an example of the configuration of a motor drive system. A motor drive system has a large

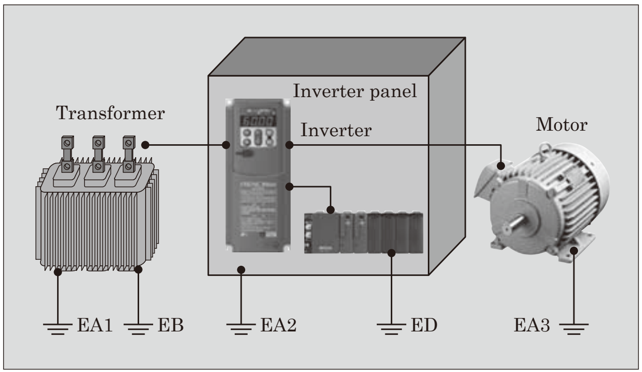

Fig.6 Example of motor drive system configuration

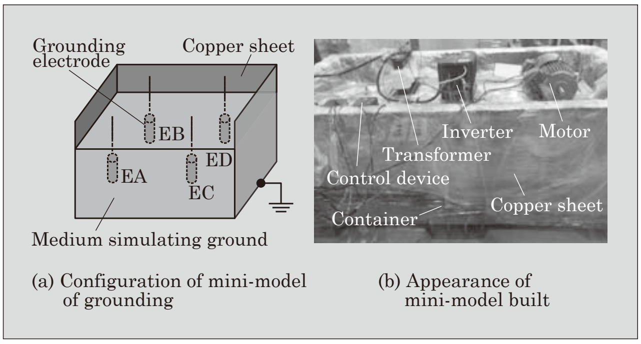

Fig.7 Configuration of mini-model for evaluating effect of grounding portion

transformer, inverter panel, motor, etc. laid out in a vast area that can be as large as a few tens of meters square. In a power electronics system like this, electromagnetic noise emitted to the surrounding environment and the conduction noise flowing into control devices and detectors located in the inverter panel may greatly vary depending on how devices are grounded.

Traditionally, the respective devices in a motor drive system are connected to grounding electrodes of Classes A to D with the grounding resistance values specified according to the voltage and purpose of the respective devices. However, the choices of grounding methods have increased as the use of equipotential bonding for grounding, which is specified in the International Electrotechnical Commission (IEC) standards, has been permitted along with the revision of the "Interpretation of Technical Standards for Electrical Equipment" in FY2011. If the merits and demerits of various grounding conditions can be grasped by verification in advance, it will be effective for mitigating electromagnetic noise.

Accordingly, in order to grasp the effect of the grounding portion on electromagnetic noise, we built a mini-model for evaluating the effect of the grounding portion (see Fig. 7). In this mini-model, a medium simulating the ground is filled in a container and electrodes simulating grounding electrodes are implanted, as shown in Fig. 7(a). Then, as shown in Fig. 7(b), the transformer, inverter, motor and control device connected to the respective grounding electrodes are combined to build a mini-model of the power electronics system in an area of about 2 m × 1 m. We have made use of the results of verification obtained with this model and built an equivalent circuit that simulates the behavior of the grounding portion. By combining with the conduction noise simulation described earlier, it is now possible to grasp the behavior of electromagnetic noise through grounding of the power electronics system. This has made it possible to identify in advance the best combination of the grounding methods of various types of devices that can be performed on site.

4. Postscript

This paper has described Fuji Electric's electromagnetic noise simulation technology for power electronics equipment. The study started with theoretically reproducing electromagnetic noise generated by power electronics equipment. And it is now widely utilized to include applications to product development by streamlining and applications to power electronics systems, not to mention improvement of analysis accuracy.

In the future, we intend to continue expanding the scope of application of electromagnetic noise simulation and work on establishing the technology to prevent electromagnetic noise interference.

References

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