Analysis of High Frequency Characteristics of Power Inverter using Accurate IGBT Model based on Datasheet and Measurement

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***Abstract*— The output voltage and current from dc-ac inverter generate switching noises and may cause electromagnetic interference (EMI) problems to other electronic systems. To analyze high frequency switching behavior of an inverter accurately, an accurate IGBT model is essential. In this study, an insulated gate bipolar transistor (IGBT) is modeled using datasheet and measurement data to analyze the high frequency characteristics of a high-power full-bridge inverter. The effectiveness of the proposed IGBT model is verified by comparing the simulated results of the inverter using the proposed IGBT model with measured results in frequency domain.**

Keywords—IGBT; semiconductor device modeling; inverters; electromagnetic interference; inductance measurement; parasitic capacitance;

I. Introduction

For high efficiency and high power density, switching mode power converters have been widely used. Recently, the desire for smaller size and lower cost forces the switching frequency of the devices in the converters to increase, as much as the system allows. However, the high frequency switching has drawbacks in electromagnetic interference (EMI) problems, as well as in switching losses. Multiple harmonics resulting from the switching operations make large peaks in specific frequencies. Such peaks have a negative impact on other connected components in the form of common mode current, as shown in Fig. 1. Especially, in high power applications, the high frequency switching generates large *dv/dt* and *di/dt*, which are noise sources in the system. Consequently, a power inverter composed of several switching devices has been a source of EMI in the power electronic system.

In medium power industry, the insulated gate bipolar transistor (IGBT), which has the capability of high switching speed and high current flowing, has been widely used as switching device in power converters. In traditional power electronic studies, the semiconductor switching device is often considered as ideal switch with just two operations of turning-on and turning-off. However, the output square waveforms of the real system involve not only the rising and falling time, but also many other transient phenomena such as overshoot voltage, reverse recovery current, tail current, and oscillations. For this reason, an accurate high frequency IGBT model is required to analyze EMI from a power inverter.

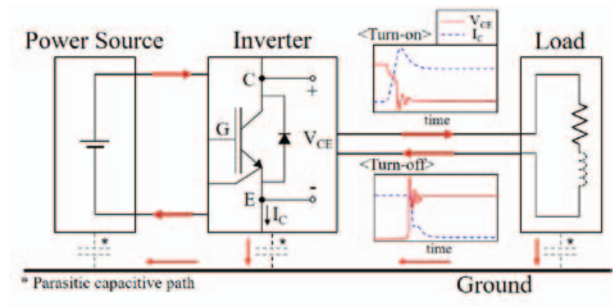


Fig. 1. EMI noise generation from the switching operations of inverter; high power inverter waveforms contain many transient phenomena, which influence other components through parasitic capacitive paths.

Conventional IGBT models which can be used in circuit simulations can be summarized by two categories [1]. Firstly, the physics based mathematical models can have high level of accuracy up to high frequency with considerations of physics inside the semiconductors, but it is difficult to construct such model and extract the model parameters [2]. Secondly, the behavioral IGBT models use fitting algorithms with respect to external characteristics of IGBT, but the high frequency transient phenomena are relatively inaccurate [3]. This paper proposes a semi-mathematical IGBT model using datasheet information and measurement data. It is a simple model with existing MOSFET and BJT model, but high accuracy can be obtained by applying measurement data in the model. Measured C-V curves and impedances are used to extract parasitic capacitances and parasitic terminal inductances, respectively. For time domain measurement, a PCB test board is designed, and the parasitic components on the designed PCB test board are extracted using ANSYS Q3D. To validate the IGBT model, output voltage and current are compared with the measurement data and analyzed in frequency domain up to 10MHz.

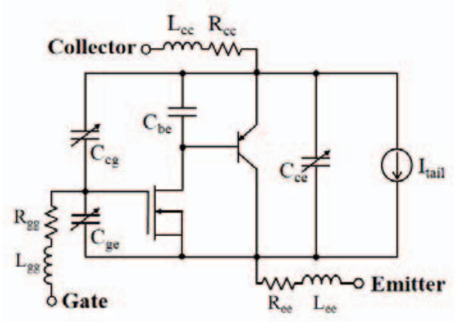


Fig. 2. The proposed IGBT model based on datasheet and measurement; there are MOSFET and BJT components for DC characteristics, and others for transient phenomena.

II. The Proposed IGBT Model Based on Datasheet and Measurement

To implement and simulate the semi-mathematical IGBT model, ANSYS Simplorer 2015 is used [4]. Among three different IGBT models provided in ANSYS Simplorer, which are average, basic dynamic [5], and advanced dynamic model, the last option was adopted to customize all of the parameters. To simplify the model, the parasitic capacitances are modeled as three capacitors, collector-gate (C_{CG}), collector-emitter (C_{CE}) and gate-emitter (C_{GE}) capacitance. Any other additional components in the original advanced dynamic model are disabled. The final circuit of the proposed IGBT model is presented in Fig. 2. This IGBT model has only a few components, but high accuracy can be obtained by using measurement data for transient model parameters. Since the equivalent circuit of the model reflects the structure of IGBT device, high frequency characteristics can be simulated with the model. The equivalent circuit consists of MOSFET, BJT, parasitic capacitances, terminal inductances, terminal resistances and a tail current source. The DC characteristics are modeled by MOSFET and BJT components using datasheet information. Other components correspond to transient characteristics, and their values are determined using measurement data in the following chapters.

III. Extraction of Parasitic Impedances in Inverter

It is important to minimize the parasitic impedances for stable operations of the inverter circuit. For this purpose, the IGBT module F4-50R06E1A3, which has 4 IGBT dies and 4 freewheeling diodes, is used. Fig. 3 shows the full bridge inverter circuit of the IGBT module. A PCB test board for the IGBT module is designed to construct the measurement setup and precisely characterize the circuit parameters. The IGBT module also has physical length between each semiconductors, which means there are parasitic impedances inside the package. The transient phenomena are dependent on each parasitic capacitances in IGBT device. Since these parasitic elements on the measurement setup have significant effects on high frequency characteristics, it is important to extract and include these components to simulation.

A. Parasitic components on PCB

The test PCB is designed with 2 layers using PADS 2007, as presented in Fig. 4. It consists of the power planes for positive and negative DC voltages, the power lines for gate and emitter voltages of each IGBTs, and the power planes for the output voltages. The parasitic components' values are characterized by ANSYS Q3D. As the result of simulation, the values are summarized in TABLE I. For an inverter simulation, the PCB is imported as a sub-circuit to ANSYS Simplorer.

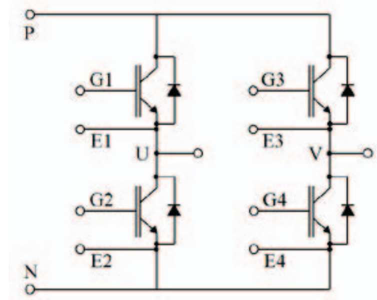
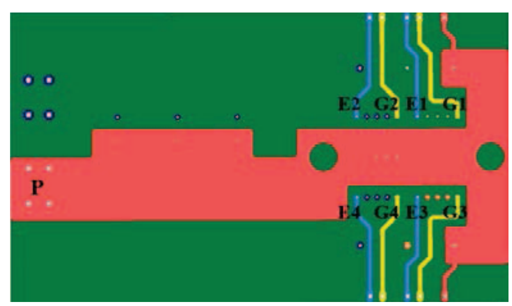


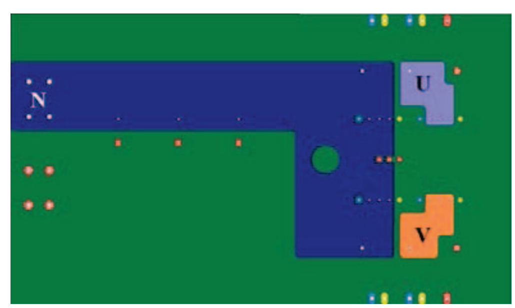
Fig. 3. Full bridge inverter circuit of the IGBT module, Infineon F4-50R06W1E3; 4 IGBT dies and 4 anti-paralleled diodes are packaged in the IGBT power module.

B. Inductances in IGBT package

An IGBT package has various inductances in many locations, such as direct copper bonded substrates, bonding wires and terminals. It is known that the terminal inductances are dominant over others in IGBT package [6]. The parasitic inductances are measured using Agilent 4294A Impedance Analyzer, and included in the IGBT model as terminal inductances. Parasitic package capacitances between substrates and heatsink can also have critical impacts on high frequency characteristics of IGBT, but such effects are minimized by floating the heatsink from ground.



(a)



(b)

Fig. 4. The PCB for inverter circuit of IGBT module (a) Top layer (b) Bottom layer; the power planes for connecting IGBT terminals to power supply and measurement equipment have parasitic resistances, inductances, and capacitances.

TABLE I. PARASITIC COMPONENTS ON THE PCB

	Resistances	Inductances
P	2.459 mΩ	56.504 nH
N	2.231 mΩ	54.546 nH
G1,G3 / E1,E3	12.69 mΩ /10.31 mΩ	29.55 nH / 25.37 nH
G2,G4 / E2,E4	10.52 mΩ / 10.44 mΩ	25.83 nH / 25.66 nH

	Capacitances		Capacitances
P-N	111.46 pF	G3-V	5.253 pF
G1-U,	5.609 pF	E3-V	4.136 pF
E1-U	4.139 pF	G4-N	3.680 pF
G2-N	3.754 pF	E4-N	5.468 pF
E2-N	5.496 pF		

C. Internal capacitances in IGBT device

Similar to a MOSFET, an IGBT structure has intrinsic capacitances, such as oxide capacitances, depletion capacitances and diffusion capacitances. As mentioned before, these capacitances are modeled as three capacitors in the IGBT model. The C_{CG} can be represented by series of the gate-drain oxide capacitance and the capacitance of depletion region in drain. It is one of the most important factor for the transition time of the IGBT. The C_{GE} is formed by the gate-source oxide capacitance and the capacitance of the depletion region in the collector of IGBT. The C_{CE} is shown in the depletion region of base-collector region [7, 8].

Since the depletion capacitances are dependent on the applied voltage, C-V curves are measured using E4980A Precision LCR meter and 4200-SCS Semiconductor parameter analyzer with variance of the DC bias. The C_{CG} and C_{CE} are modeled by equation (1) using C_{CG}-V_{CG} and C_{CE}-V_{CE} curve, respectively. C_{GE} is also modeled with the C_0, α, δ, and V_{shift} parameters in ANSYS Simplorer using measured C_{GE}-V_{GE} curve. The modeling results with fitting parameters are presented in Fig. 5.

$$C(V) = C_0\,[\delta + (1-\delta)/(1 + V/V_D)^{\alpha}] \ \text{at}\ V > 0 \qquad (1)$$

IV. MEASUREMENT OF VOLTAGE AND CURRENT OF INVERTER

The measurement setup for the time domain waveforms of the inverter circuit is shown in Fig. 6. First of all, high voltage of 60V from a DC power supply is applied to the DC capacitors. To control the full bridge IGBT inverter, two gate driver PCBs are connected to each of the half bridges. The gate driver makes -5V and 15V as negative and positive gate voltages. The control signals are generated by the DSP board and transmitted to the gate drivers. The switching frequency is 20 kHz and there is 1μs dead time to prevent arm-short during operations. Two 10Ω power resistors with the 1kW power rating connected in parallel are used as a load for the inverter circuit. At last, the voltage across the load resistor and the current flowing through the load resistor are measured using Tektronix DPO7254 oscilloscope with P5210 voltage probe

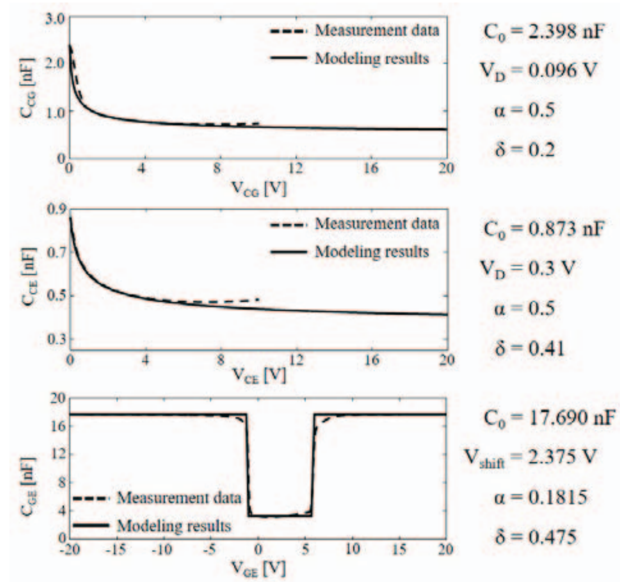


Fig. 5. The results of voltage dependent capacitances modeling of IGBT; the voltage dependency of each internal capacitance in IGBT device is fitted to the measurement data by four parameters in ANSYS Simplorer.

and PEM CWT03 Ultra-mini rogowski current probe, respectively. The time domain data are extracted with the sampling time of 2ns.

V. COMPARISONS OF VOLTAGE AND CURRENT BETWEEN THE SIMULATION AND MEASUREMENT RESULTS

After the modeling of all components in the inverter circuit and the load resistor, the results of simulation and measurement data are compared in frequency domain for verification of the model. The inverter model is simulated with transient solver and the results are extracted with the same sampling time as the measurement. The time domain data in both cases are converted into frequency domain data using Fourier transform in MATLAB. Fig. 7 shows the comparisons between simulation and measurement. To highlight the accuracy of the proposed IGBT model, the inverter simulation result using the system level IGBT model provided by ANSYS Simplorer is also included in the comparison. This model simply describes linear switching behaviors with a fixed resistance, 1mΩ, during the conduction state [4].

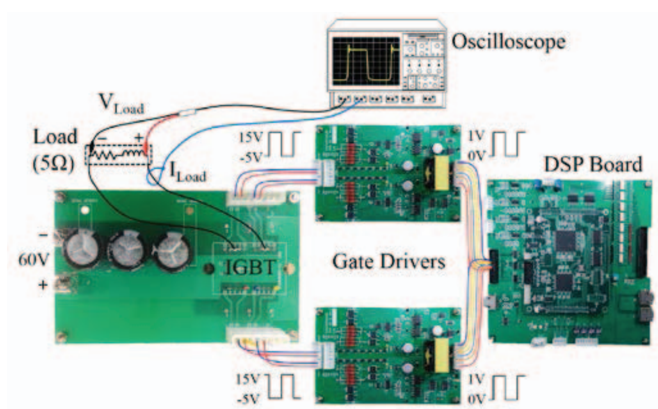
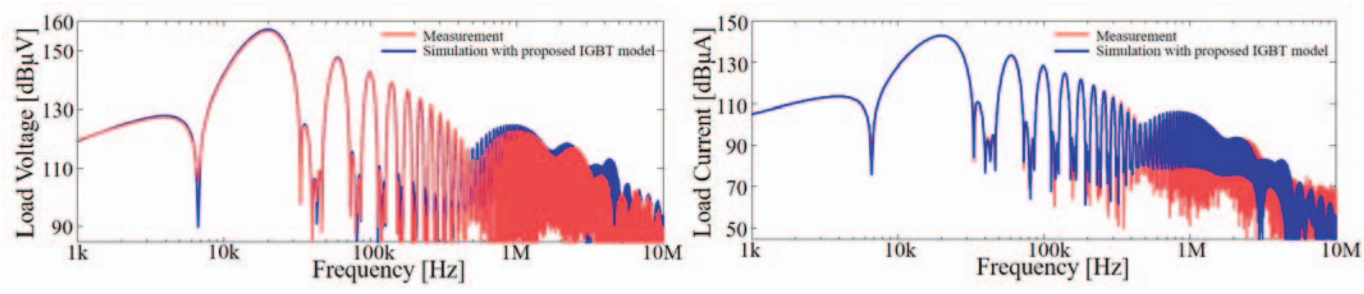


Fig. 6. Measurement setup for the output voltage and current; the gate drivers amplify the control signals from a DSP board to IGBT gate-emitter power.



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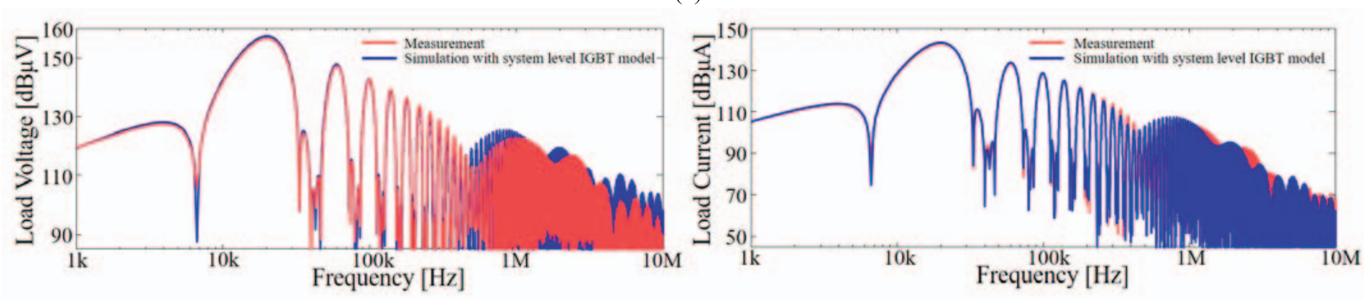

(b)

Fig. 7. Spectrum of load voltage and load current (a) Comparison between measurement and simulation with the proposed IGBT model (b) Comparison between measurement and simulation with the system level IGBT model; the proposed IGBT modeling shows better correlation to the measurement than the system level IGBT model. Since there is no parasitic components in the system level IGBT model, it has higher high frequency value in voltage and current.

The graphs of the voltage spectrum shows that the simulation results with the proposed IGBT model has better correlation to the measurement data than those with the system level IGBT model, especially in MHz ranges. The system level IGBT model has higher levels of voltage and current at high frequency because internal capacitances and terminal inductances are not considered. The dead time of 1µs makes spectral bounds rather than constant slope. The difference of the peak frequency between simulation and measurement around 1MHz is because the dead time of the inverter circuit was not exactly 1µs in measurement. The current spectrum of measurement near 10MHz shows noise level without any bounds. A current probe with lower noise is necessary to validate the proposed IGBT model up to higher frequency.

VI. Conclusions

In this paper, a simple and accurate high frequency IGBT model based on datasheet and measurement is proposed for the analysis of EMI from an inverter. Datasheet information is used to model basic operations of the IGBT, and the measurement data of C-V curves and impedance graphs are utilized in modeling high frequency transient phenomena during switching. To create a simulation environment similar to the measurement setup for full-bridge inverter circuit, parasitic components on the PCB for the IGBT module are extracted and the lumped components including wires are modeled by fitting with the impedance curves up to 30MHz. For verification, the measurement data are compared to the simulation results using two kinds of IGBT models, which are the proposed IGBT model and the system level IGBT model. The proposed IGBT model shows more similar values in the MHz frequency range than the system level IGBT model.

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