Inverter Power Module Parasitics Modeling with Cross-coupling Simplification for Fast Model Extraction and Switching Characteristics Simulation

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***Abstract*—Inverter power module parasitics models are commonly used for inverter switching analysis, gate drive tuning, and EMI characterization. This paper investigates the parasitics modeling and simplification of an inverter power module. The circuit cross-coupling is characterized by Z-parameter matrix. Three types of cross-coupling modeling/simplification methods are studied in this research. The effect of cross-coupling simplification on model extraction time and circuit simulation time are evaluated. To validate the accuracy of the parasitics models, the circuit simulations are compared with the experimental results.**

Keywords—power module; parasitics; cross-coupling; simulation

I. INTRODUCTION

A. The Effect of Parasitics on Semiconductor Switching Characteristics

The switching characteristics of power semiconductors are essential to the efficiency of power converters and the power integrity of pulse width modulation (PWM). Studies on power semiconductor switching characteristics mainly focus on voltage/current transient time [1-3], overshoot and plateau in the waveforms, switching loss [4], and delay time. Dominant factors that affect the semiconductor switching characteristics include the electrical dynamic properties of semiconductor dies [5, 6], the converter load conditions [7], the gate drive transient output [8, 9], the parasitics in the converter commutating loop [10]. The switching transient time of power semiconductor has been reducing for decades because of the improvement of semiconductor fabrication [11].

The effect of parasitics on switching characteristics has been investigated on Si devices [12, 13], SiC devices [14, 15] [16-19], and GaN devices [20-22]. Generally, the capacitive parasitics that affect the switching characteristics is from the device intrinsic capacitance [23]. The inductive parasitics that affect the switching characteristics is from the conductors' loop inductance [24]. Because of the fast switching speed of most of the power semiconductors, the resistive parasitics in the power converter has a modest effect on the semiconductor switching characteristics [25]. State-of-the-art studies on resistive parasitics mostly focus on the thermal characteristics and the loss of the conductors in the power converter.

B. The Physics of Power Converter Parasitics

In a power converter circuit setup, the circulating loops can be categorized into gate drive loops and power loops. In most of the hard-switching circuitry, small gate drive loop is desired to reduce the loop inductance. The layout of the power loops in a power converter compromises to the converter parasitics control, EMI design, heat transfer, insulation, and component mechanical properties [11]. Minimizing the parasitic inductance in a commutating power loop is one of the key strategies to reduce device's switching transient time and current/voltage overshoots [26, 27].

The loop inductance includes mutual inductance and self-inductance. Due to mutual inductance, the switching transient in one circulating loop will induce transient voltage potential in all the coupled circulating loops. Optimized cross-coupling in an integrated power module is desired during the power module layout design [11].

The parallel-die strategy is commonly used in high current rating semiconductor power modules. Equivalent current sharing among the paralleled dies is desired in power module integration design. The switching transient current sharing of paralleled dies is directly related to the self-inductance of each sharing branch, and the mutual inductance/cross-coupling among branches. State-of-the-art literatures have evaluated the effect of paralleling layout on power module switching characteristics [28].

C. Parasitics Modeling and Extraction

The parasitics in a simple circuit layout, such as a straight conductor trace or a square conductive layer, can be calculated by the formulas in [29, 30]. The parasitics in a complex layout can be evaluated with finite element analysis (FEA) where the input/output characteristics can be modeled as a multi-port linear system [31]. With more ports included, the system matrix has higher order. The system matrix extracted by FEA is commonly used for circuit simulation.

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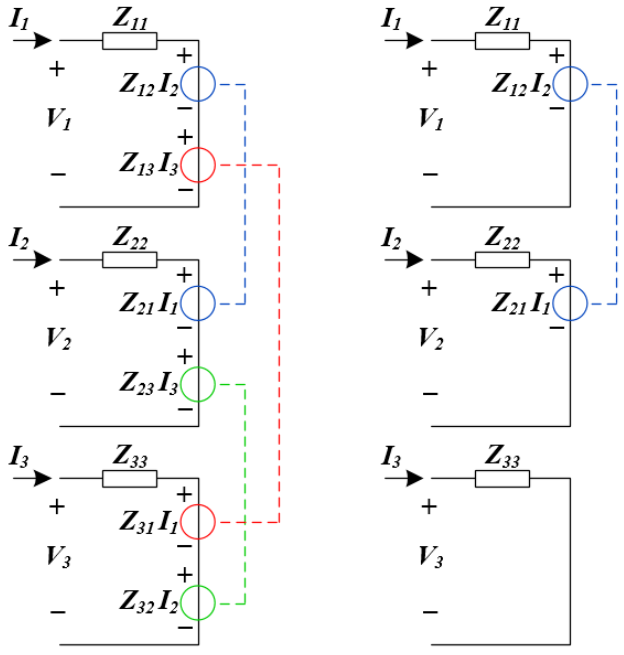
Extracting the system matrix from the CAD model and using the system matrix for circuit simulation both can require great computing time. [31] studied model simplification; [32] investigated improving simulation speed.

D. Research Opportunities

The balance of detailed parasitics modeling and reducing model extraction/simulation time is essential for the model-based power electronics design/analysis; however, this topic has not been fully investigated by existing studies based on an industry standard design platform. This paper presents the parasitics modeling and simplification of a two-level, three-phase inverter power module. The mechanism of cross-coupling simplification is demonstrated with the circuit Z-parameter matrix. Three types of cross-coupling modeling/simplification methods are evaluated based on model extraction time, circuit simulation time, and simulation accuracy. The simulation and experimental results are compared.

II. Power Module Parasitics Modeling and Simplification

A. Circuit Cross-coupled Model Simplification



(a) Fully coupled (b) Simplified

Fig. 1 3x3 circuit and its simplification

A Z-parameter matrix describes the behavior of any linear electrical network that can be considered as a black box with a number of ports. A port in this context is a pair of electrical terminals carrying equal and opposite currents into and out of the network, and having a particular voltage between them. For all ports, the voltages may be defined in terms of the Z-parameter matrix and the currents by the following matrix equation.

$$V = Z\ I \tag{2.1}$$

The Z-parameter matrix for a three-port network is shown in (2.2), and the equivalent circuit for this 3×3 matrix is shown in Fig. 1(a). In this case, Z_{11}, Z_{22}, and Z_{33} are self-impedance. Z_{12}, Z_{13}, Z_{23}, Z_{21}, Z_{31}, Z_{32} are mutual-impedance. In this research, self-impedance includes resistance, self-inductance, and self-capacitance. Mutual impedance is dominated by mutual inductance. The effect of mutual capacitance on circuit simulation is subtle.

Mutual impedance is commonly used to characterize the cross-couplings between different ports in a circuit network. Circuit analyzer can choose not to characterize the weak cross-couplings in the circuit modeling. As a result, the Z-parameter matrix for a circuit can be de-ordered. Take the circuit in Fig. 1(a) as an example. If the port 3 is weakly coupled to port 1 and port 2, Z_{13}, Z_{31}, Z_{23}, and Z_{32} can be approximated to 0 as shown in (2.3). By re-writing (2.3) to (2.4) and (2.5), the equivalent circuit in Fig. 1(a) will be simplified to the circuit as shown in Fig. 1(b).

$$\begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} & Z_{13} \\ Z_{21} & Z_{22} & Z_{23} \\ Z_{31} & Z_{32} & Z_{33} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} \tag{2.2}$$

$$\begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} & 0 \\ Z_{21} & Z_{22} & 0 \\ 0 & 0 & Z_{33} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} \tag{2.3}$$

$$\begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \end{bmatrix} \tag{2.4}$$

$$V_3 = Z_{33} I_3 \tag{2.5}$$

B. Inverter Circuitry

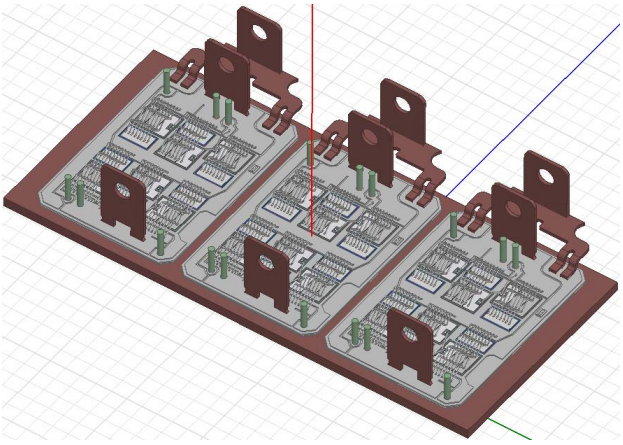


Fig. 2 Inverter power module layout (open sample)

This paper studies a two-level, three-phase inverter power module. The open-module layout is shown in Fig. 2. It can be seen that the three phases in the power module have identical layout. This research focus on the parasitics and cross-coupling within one phase and the cross-coupling between different phases are not discussed. The schematic for a single phase is shown in Fig. 3, where the dies of IGBTs and diodes are paralleled in groups of three respectively.

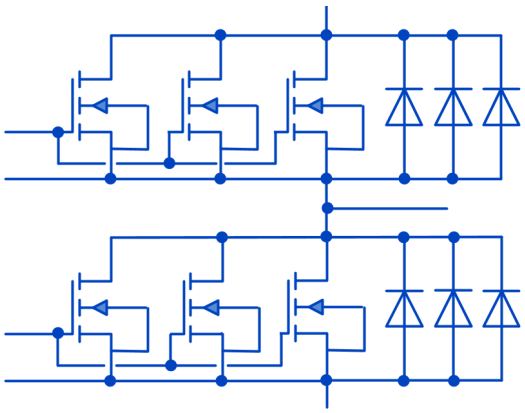
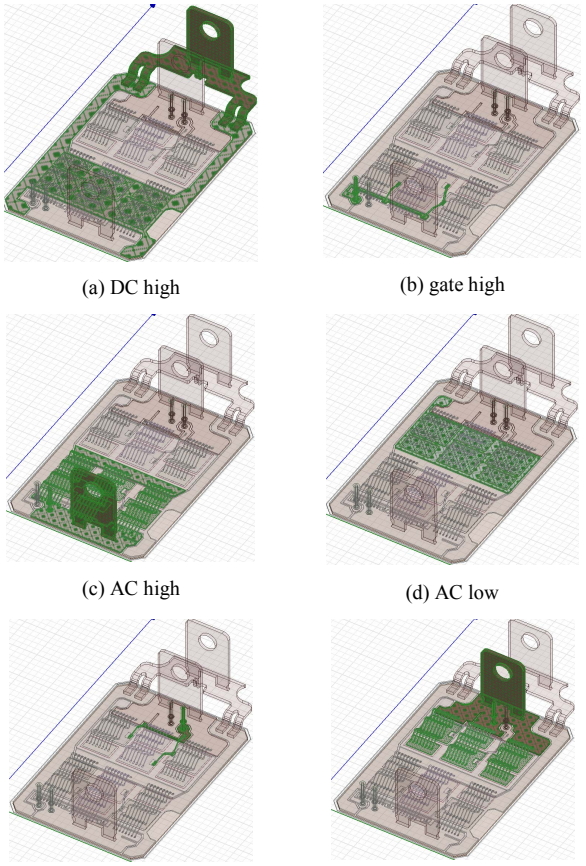


Fig. 3 Inverter power module single phase schematic

C. Power Module Parasitics Modeling



(a) DC high (b) gate high

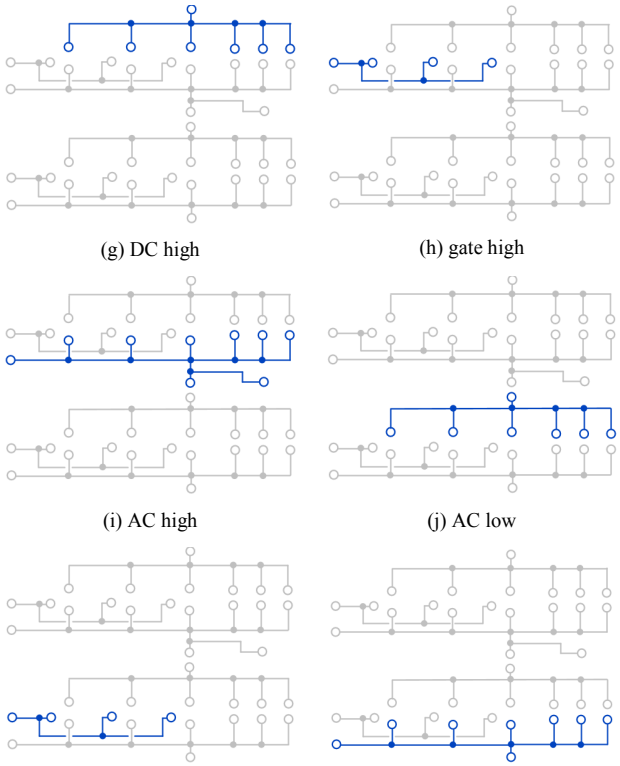
(c) AC high (d) AC low

(e) gate low (f) DC low`

Fig. 4 Identified nets for the power module single phase: nets shown in the layout

In the power module parasitics analysis, each group of the connected conductive components is modeled as a "net". The identified nets for the single phase of the power module is shown in Fig. 4 (a) to (f), and the corresponding parts in the schematic is shown in Fig. 4 (g) to (l). By modeling all the mutual impedance in the single phase layout, a fully cross-coupled model (also referred to as the "FC model") can be derived as shown in the schematic in Fig. 5. Note that all the nets shown in Fig. 5 are cross-coupled, and a 34×34 Z-parameter matrix is derived.

The aforementioned cross-coupled model simplification (part A of section II) is applied to the single phase of the power module. By splitting the fully cross-coupled model to a high-side model (a 17×17 matrix) and a low-side model (a 16×16 matrix) as shown in Fig. 6, the mutual impedance across the high-side model and the low-side model are set to zero. As a result, any circuit behavior on the high-side model will not affect the low-side model and vice versa. These two split models together are also referred to as the half-split model (the HS model).



(g) DC high (h) gate high

(i) AC high (j) AC low

(k) gate low (l) DC low

Fig. 4-continued Identified nets for the power module single phase: nets shown in the schematic

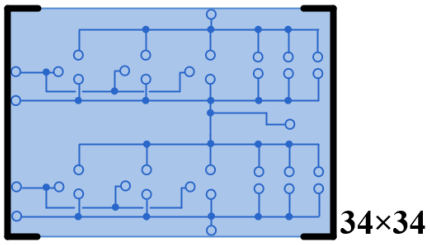


Fig. 5 Fully coupled model (FC model)

By completely removing the cross-coupling between/among any nets in Fig. 4, six independent parasitic models can be derived as shown in Fig. 7. The six parasitic models correspond to one 8×8 matrix, one 7×7 matrix, two 6×6 matrices, and two

3×3 matrices. These six models are also referred to as independent-parasitic model (IP model).

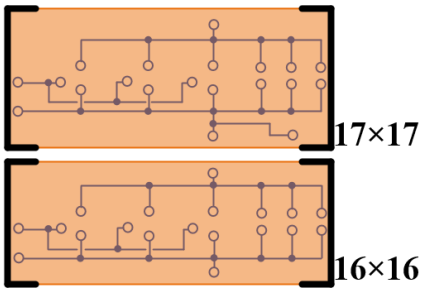


Fig. 6 Half-split model (HS model)

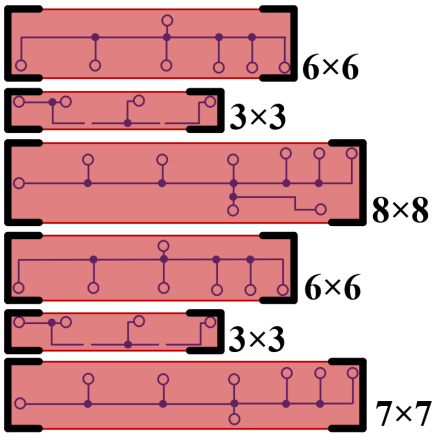


Fig. 7 Independent-parasitic model (IP model)

III. Model Extractin Time and Circuit Simulation Time

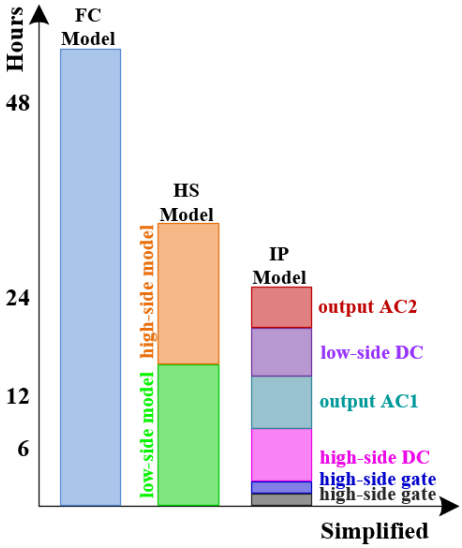


Fig. 8 Model extraction time

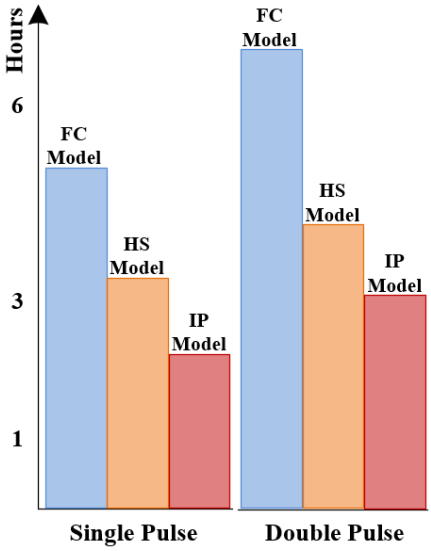


Fig. 9 Circuit simulation time

In this research, all the analysis are conduct on an independent workstation. The model extraction for the three types of parasitics model (the FC model, the HS model, and the IP model as discussed in part C, section II) is conducted under ANSYS Q3D. The model extraction time for the FC model, the HS model, and the IP model is shown in Fig. 8. It can be seen that with more cross-coupling included in the model, the overall model extraction time is longer.

The extracted single phase parasitics model are configured into simulation circuitry for inverter turn-off transient analysis (single-pulse simulation) and turn-on transient analysis (double-pulse simulation). The circuit simulation time for single-pulse testing and double-pulse testing are shown in Fig. 9. It can be seen that with more cross-coupling included in the model, both the turn-off transient and the turn-on transient take longer circuit simulation time.

Note that model extraction tools like ANSYS Q3D have functions to simplify the Z-parameter matrix of the extracted model. However, the physics behind the matrix simplification is not always explicit to the users.

IV. Simulation and Experimental Result

In this paper, the experimental results are derived from a two level three-phase prototype inverter setup with the DC bus voltage at 380-Volt. The simulation results are based on the FC model, the HS model, and the IP model. The setup of the simulation model is the same as the prototype inverter setup.

Fig. 10 shows the simulation result for the turn-on transient analysis (double-pulse simulation). To compare the details of the three models, waveforms in the dashed box in Fig. 10 are zoomed in and shown in Fig. 11, Fig. 12, and Fig. 13. It can be seen that the FC model captures more transient details while the result from the IP model is smoother. Subtle difference can be observed in V_{CE} and V_{GE} by comparing the simulation result from the aforementioned three models. In the simulated I_C waveforms, the overshoot generated by the FC model is more

accurate when comparing to the experimental waveform in Fig. 14.

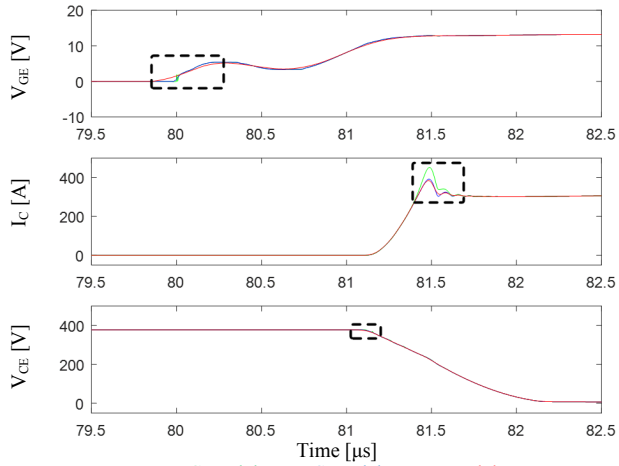


Fig. 10 Turn-on transient simulation

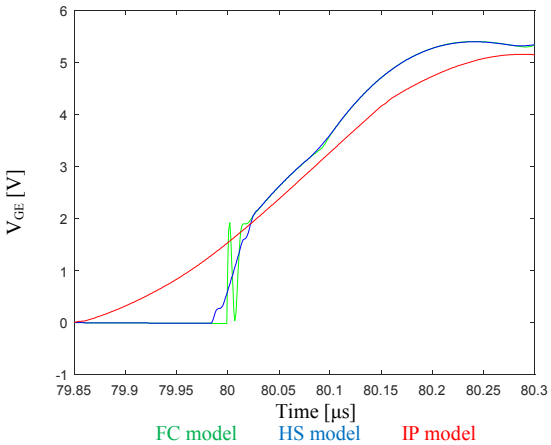


Fig. 11 Turn-on transient simulation, zoomed in V_{GE}

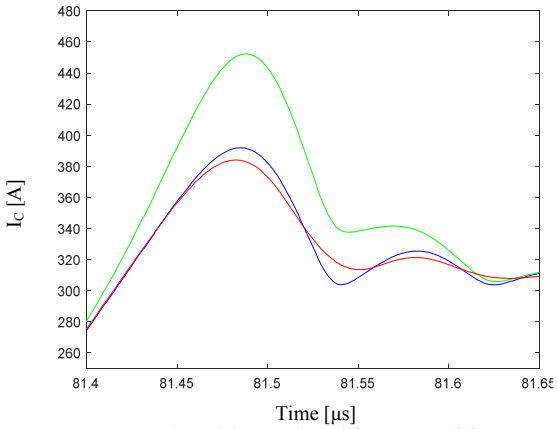


Fig. 12 Turn-on transient simulation, zoomed in I_C

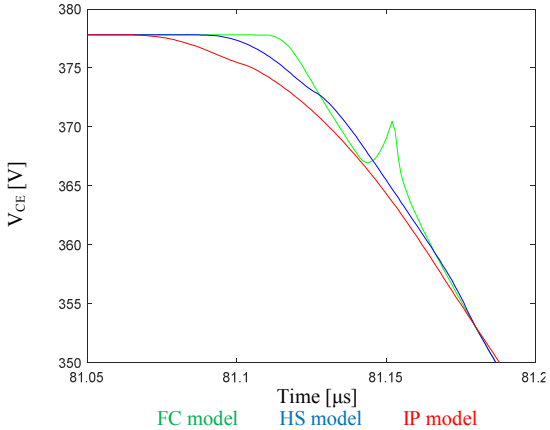


Fig. 13 Turn-on transient simulation, zoomed in V_{CE}

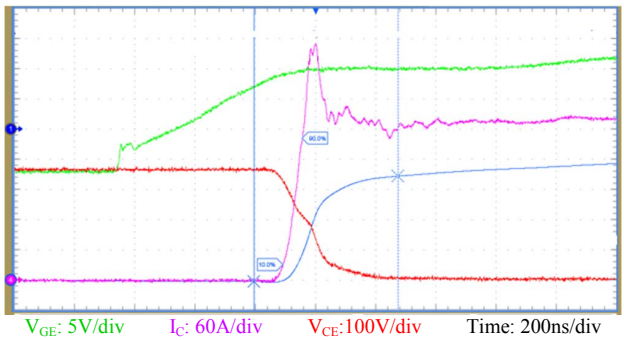


Fig. 14 Turn-on transient experimental result

Fig. 15 shows the simulation result for the turn-off transient analysis (single-pulse simulation). To compare the details of the three models, waveforms in the dashed box in Fig. 15 are zoomed in and shown in Fig. 16, Fig. 17, and Fig. 18. It can be seen that the FC model generates waveforms with more details. The details from the HS model is slightly less when compared with the FC model. The transient details from IP model are modest. Subtle difference can be observed in V_{GE} and I_C by comparing the simulation result from the aforementioned three models. In the simulated V_{CE} waveforms, the overshoot generated by the FC model is more accurate when comparing to the experimental waveform in Fig. 19.

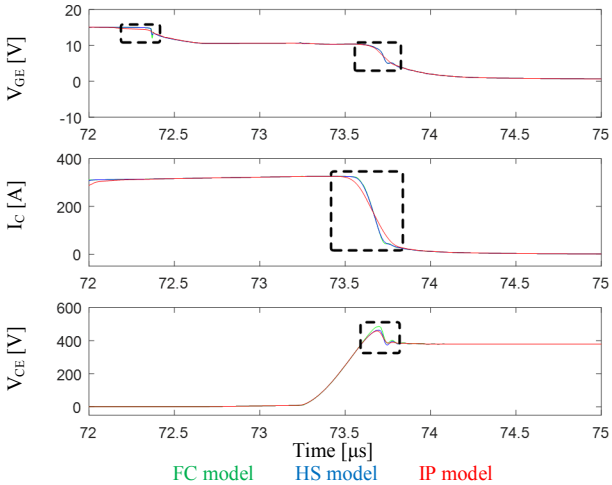


Fig. 15 Turn-off transient simulation

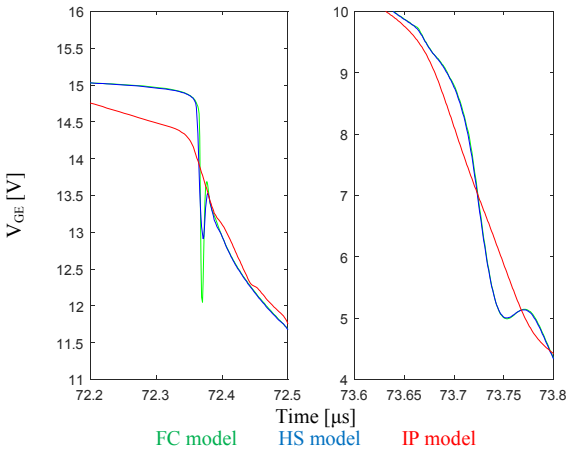


Fig. 16 Turn-off transient simulation, zoomed in V_{GE}

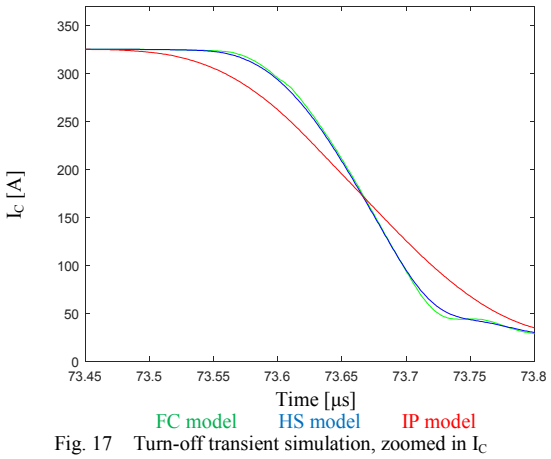


Fig. 17 Turn-off transient simulation, zoomed in I_C

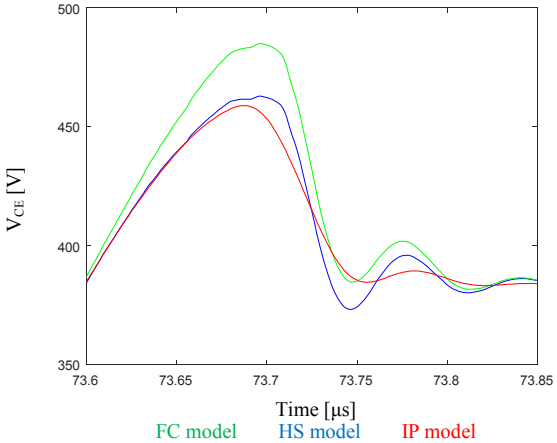


Fig. 18 Turn-off transient simulation, zoomed in V_{CE}

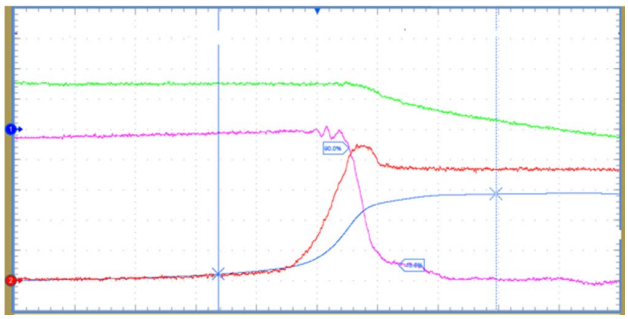


Fig. 19 Turn-off transient experimental result

V. CONCLUSIONS

The key conclusions of the paper are summarized as follows:

- By simplifying the cross-coupling in the parasitics model, the Z-parameter matrix for a circuit can be de-ordered.
- Parasitics cross-coupling simplification can effectively reduce the model extraction time and circuit simulation time.
- Parasitics models with properly simplified cross-coupling can be used simulate the inverter switching properties.

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