Parasitic Effects Analysis of Bonding Wires Bonding Parameter of Intelligent Power Modules for Three-Phase Motor Control Applications

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Abstract. Parasitic parameter analysis is the focus of intelligent power module switch performance research. This paper will utilize the model of 600V/30A intelligent power module and extract the part of circuit layout bonding wires parasitic parameter by Ansys Q3D Extractor, expedition the relationship between physical bonding parameter and parasitic parameter in the intelligent power module circuit. An exact three-phase circuit module of high voltage intelligent power module and bonding wires package module is established. Through Ansys Q3D Extractor, test a series of bonding parameters from the three-phase circuit layout module and extract the parasitic parameters of the bonding wires. The experimental results of the parasitic parameters are analysed and compared, and the influence degree of the bonding parameters on the parasitic parameters is discussed. An improved solution is proposed for the bonding wires of the intelligent power module to reduce the voltage spike that the MOSFET chip during the turn-off process.

1. Introduction

Intelligent power module has outstanding power switch capability and be applied to motor control, hybrid vehicles, welders, alternative energy sources, current conversion industrial control or other power supplies.

As power integration being higher and switching speed getting faster, it was very important to extracting the parasitic parameters of the intelligent power module in an effective and precise method. This is because parasitic parameter of the intelligent power module makes an impact performance, such as the circuit trace and bonding wires resistance and inductance in the layout.

The parasitic parameter stores energy when the MOSFET is on [1]. If the circuit has no external cushion capacitor, the energy is released as a voltage spike when it turns off. Parasitic parameters can result in induction voltage, which increases the voltage at both terminals of the MOSFET when it is turned off, thus increasing the working voltage stress and the switching loss of the MOSFET, which will result in period destroy when it is serious. To enhance the intelligent power module performance and reduce the voltage spikes generated during the turn-off process, the parasitic parameter must be reduced.

In the circuit layout of intelligent power module, chip and PCB trace interconnection by bonding wires [2]. Bonding wires is the most universal and popular chip interconnection method because of its innate low cost, flexible fabrication, and mature manufacturing technology [3]. Nevertheless, due to
the self-inductance and mutual-inductance between the bonding wires, these parasitic parameters are limit the performance of chip.

The effect of bonding wires on its self-inductance and mutual inductance is manifestation in [4]. In [6, 7], the self-inductance and mutual-inductance of bonding wires calculated by using formula and focus on single effect. This paper fully considers the situation of multiple irregularly shaped bonding wires in parallel, and models and simulates each bonding parameter of the bonding wires. Then, we extract the parasitic of bonding wires by using Ansys Q3D Extractor.

This paper takes 600V/30A intelligent power module as the research object, analyses and studies the degree of the bonding parameters of the bonding wires on the parasitic parameters, and provides a feasible solution for reducing the influence of the parasitic parameters. This article is divided into the following parts: Section 2, briefly introduces the basic structure and principle of the intelligent power module. Section 3 explains the basic theory of conductor parasitic parameters. Section 4 analysis the experimental data and proposes an optimized solution for the modeling and simulation experiments of bonding wires. Section 5 summarizes the whole experiment, and proposes a basic method for optimal design of the bonding wires of the intelligent power module.

2. 600V/30A Intelligent Power Module Model

In the actual industry application, three-phase intelligent power module which is used widely can be divide into two parts: power inverter circuit and logic control circuit. The research object of this paper is 600V/30A intelligent power module, which consists of these two parts. The power inverter circuit consists of three bridge arms, each bridge arm contains two MOSFET power chips, and the two MOSFET chips in the bridge arm only conduct one when the intelligent power module works [9].

With the increase of working frequency of intelligent power module, parasitic parameters have more and more influence on the working circuit. Bonding wires parasitic parameter is an important part of the whole parasitic parameter of intelligent power module circuit [12]. The parasitic inductance of bonding line can be divided into self-inductance and mutual inductance. Self-inductance is caused by the change of magnetic flux caused by the change of conductor current, and mutual inductance is caused by the change of magnetic flux of adjacent conductor. Figure 1 show the schematic diagram of intelligent power module.

![Figure 1. Power inverter circuit schematic of intelligent power module](image)

In this paper, to make the study more clarity with industry standard package, the 600V/30A three phase MOSFET intelligent power module be used for research object. The major structure of the intelligent power module will be revealed in the below.

From Fig.1, it can be seen that there are 6 high-voltage MOSFET chips and 6 reverse continuous current diodes in the intelligent power module inverter circuit, and the MOSFET chips and diodes are welded on the heat sink. MOSFET chip and diode are connected with PCB copper wire through two parallel bonding wires.

In the intelligent power module lay out module, parasitic parameters are mainly concentrated in the inverter circuit, and bonding wires have a great impact on parasitic parameters, the change of bonding
parameters of bonding wires will affect the parasitic parameters. In this paper, we only study the influence of the bonding parameters of the bonding wires on the parasitic parameters.

The power inverter circuit contains three full-bridge circuit that converts DC to AC. Figure 2 shows the physical model of the intelligent power module, which can intuitively show the physical structure of the intelligent power module.

Figure 2. Intelligent power module model

Figure 3 and Figure 4 show the experimental part is parasitic circuit model of the intelligent power module emulation. The two experimental parts of P-P_W and U'-U are the power conversion circuit and power supply circuit of the 600V/30A intelligent power module. The U'-U experiment part is to reduce the influence of the bonding wires parasitic inductance on the power chip voltage spike, and the P-P_W experiment part is to reduce the influence of the bonding wires parasitic parameters on the loop stray inductance. These two experimental parts can well reflect the changes in the parasitic parameters of the bonding wires and are more representative. Ansys Q3D Extractor performs electromagnetic field simulation using a combination of the FEM and the method of Moments (MoM). This tool performs a DC and an AC analysis and avoids the meshing of the air and the simulation result consider proximity and skin effects.
Figure 5 is a basic model of the bonding wires of the research object of the article. For the sake of cost, the material of the bonding wire studied in this article is aluminium. The bonding wires of connection the MOSFET chips and the PCB trace impacts the power converter circuit performance. The next section discusses the derivation and analysis of parasitic parameters.

3. Analytical Derivation of Parasitic Parameters

Parasitic parameter minimization is part of focus in intelligent power module layout design. Inductance is the inherent parameter of conductor, and it’s has important impact to working steady state with the working frequency rising. Inductance is caused by a sudden change in the current in the conductor. When the current changes, inductance will produce induced voltage to prevent the change of current.

For the circular regular bonding wires with the length \( l \) and the diameter \( d \) in the free space, the formula of inductance \( L \) is as follows:

\[
L = \left( \frac{\mu_0}{2\pi} \right) \times \left[ \ln \left( \frac{\alpha}{d} \right) + \mu_r \frac{\tanh \left( \frac{4d}{d_s} \right)}{4} - l \right]
\]

Series resistance can be calculated as follows:

\[
R = \begin{cases} 
\left( \frac{4\rho l}{\pi d^2} \right) \cosh \left[ 0.041 \left( \frac{d}{d_s} \right)^2 \right] & \frac{d}{d_s} \leq 3.394 \\
\left( \frac{4\rho l}{\pi d^2} \right) \times \left( 0.25 \frac{d}{d_s} + 0.2654 \right) & \frac{d}{d_s} \geq 3.394
\end{cases}
\]

In the formula, \( \mu_0 \) is the permeability of air medium \((\mu_0=4\pi \times 10^{-7} \text{H/m})\); \( \mu_r \) and \( \rho \) is the relative permeability and resistivity of materials for bonding wires; \( d_s \) is the skin depth of bonding wires.

Two or more parallel bonding wires to achieve bonding can abate the series inductance and enhance the bonding reliability, and affect mutual inductance and heat dissipation between bonding wires. Mutual inductance between parallel bonding wires should be taken into account when calculating parasitic inductance of multiple parallel bonding wires.

Two bonding wires transversal surface is circular and the mutual inductance between the bonding wires can be calculated as follows:

\[
L_M = 5d \left( \ln \left( \frac{2d}{s} \right) - 1 + \frac{s}{2d} \left( \frac{s}{2d} \right)^2 \right)
\]

Where \( L_M \) represents the mutual inductance value between the conductors, and the unit value is nH; \( s \) is the spacing between the conductors in inches; \( d \) represents the relative length between the conductors, in inches.

The inductance of the two parallel jumpers is calculated as follows:

\[
L_{\text{parallel}} = \frac{L_1 + L_2 - L_M^2}{L_1 + L_2 - 2L_M}
\]

In the formula, \( L_1, L_2 \) is the self-inductance of two bonding wires; \( M \) is the mutual-inductance of two bond wire.

From the above theories and formulas, it can be seen that the bonding parameters of the bonding wires have an effect on the parasitic parameters, and the effects of each bonding parameter are different. Exploring the effects of each bonding parameter is of great significance in optimizing the parasitic parameters.
The inductance of a conductor can be calculated by the formula given above for a regular conductor, and the inductance of an irregular shape conductor needs the help of algorithms and software.

The bonding wires model was established, and the bonding wires model was connected to the PCB trace of the intelligent power module. The Ansys Q3D Extractor was used to simulate and solve the model and extract parasitic parameters of the bonding wires. The bonding wires model is focus on four aspects: number, length, diameter, space between the bonding wires. Each parameter on modelling, other parameter is invariant.

4. Modeling Simulation and Results Discussion

The modeling and simulation experiments are performed for the bonding wires with different bonding parameters, and the parasitic parameter data is obtained as follows. The rated working frequency of the research object in this article is 20KHz. When setting the solving frequency, set the rated working frequency to be close to the actual working state. From the extraction results data shown in Table 1 and Table 2, the parasitic parameter of the bonding wires decreases with number of bonding wires increase. From Table 1, the number of bonding wires is 3, compared to 2, the parasitic inductance decreased by 0.506 nH, 4 compared to 3, the parasitic inductance decreased by 0.339 nH, 5 compared to 4, the parasitic inductance decreased by 0.22 nH. The data in Table 2 show that the reductions in parasitic parameters are 0.667 nH, 0.448 nH, and 0.22 nH, respectively. The resistance of the bonding wires is higher than the actual resistance due to the skin effect. The parasitic inductance reduces because more bonding wires represent stronger current shunting capacity and more mutual inductance, mutual can offset part of self-inductance. As can be seen from Tables 1 and 2, the larger the number of bonding wires, the smaller the decrease in parasitic inductance. From these data, it can be concluded that the larger the number of bonding wires, the less the effect of mutual inductance becomes, which indicates that the larger the number of bonding wires, the better.

| Number of wires | Inductance (nH) | Resistance (Ω) |
|----------------|----------------|---------------|
| 2              | 8.589          | 0.707         |
| 3              | 8.083          | 0.709         |
| 4              | 7.744          | 0.712         |
| 5              | 7.524          | 0.715         |

In the layout design of intelligent power module, the area used for bonding wires is special limited. The number of bonding wires is limited, and the diameter of bonding wires also directly affects numbers. When the diameter of bonding wires is required, the number of bonding wires has been limited. The excessive number of bonding wires could affect the heat dissipation of intelligent power module.

| Number of wires | Inductance (nH) | Resistance (Ω) |
|----------------|----------------|---------------|
| 2              | 6.445          | 0.822         |
| 3              | 5.778          | 0.825         |
| 4              | 5.330          | 0.830         |
| 5              | 5.150          | 0.833         |

In these figures as follow, the (a) denotes the P-P\(_w\) and the (b) denotes the U'-U. The diameter of the bonding wires determines the current carrying capacity and also affects the self-inductance of the bonding wires. It can be seen from the experimental data that the larger the diameter of the bonding wires, the smaller the parasitic inductance generated. The following figure, the length of (a) bonding wires is 7 mm, the length of (b) bonding wires is 12 mm. The data in Figure 7 indicates that the diameter of the bonding wires is inversely related to the parasitic inductance. In practical production applications, when space is limited, the number of bonding wires needs to be determined to calculate
the diameter of the bonding wires. Make the diameter of the bonding wires as large as possible within the allowable range.

| Diameter (mm) | R (Ω) | L (nH) |
|--------------|------|--------|
| 0.30         | 8.0  | 0.08   |
| 0.35         | 8.2  | 0.10   |
| 0.40         | 8.4  | 0.12   |
| 0.45         | 8.6  | 0.14   |
| 0.50         | 8.8  | 0.16   |
| 0.700        | 6.2  | 0.20   |
| 0.702        | 6.3  | 0.22   |
| 0.704        | 6.4  | 0.24   |
| 0.706        | 6.5  | 0.26   |

Figure 6. Inductance and resistance with change of bonding wires diameter

| Space (mm)  | R (Ω) | L (nH) |
|-------------|------|--------|
| 0.08        | 8.60 | 0.08   |
| 0.10        | 8.65 | 0.10   |
| 0.12        | 8.70 | 0.12   |
| 0.14        | 8.75 | 0.14   |
| 0.16        | 8.80 | 0.16   |
| 0.18        | 8.85 | 0.18   |
| 0.20        | 8.90 | 0.20   |

Figure 7. Inductance and resistance with change of bonding wires space

| Length (mm) | R (Ω) | L (nH) |
|-------------|------|--------|
| 11.3        | 6.52 | 0.08   |
| 11.4        | 6.54 | 0.10   |
| 11.5        | 6.56 | 0.12   |
| 11.6        | 6.58 | 0.14   |
| 11.7        | 6.60 | 0.16   |
| 11.8        | 6.62 | 0.18   |
| 11.9        | 6.64 | 0.20   |

Figure 8. Inductance and resistance with change of bonding wires length

In addition to the number and diameter of the bonding wires, there are two parameters, namely the length and spacing of the bonding wires, which have an important effect on the parasitic inductance. Figure 7 (a) (b) presents the relationship between the parasitic parameter of bonding wires with the space of bonding wires. It is no change that self-inductance of bonding wires when the diameter of bonding wires fixed. The loop inductance of bonding wires can be faded due to the space between parallel bonding wires increased. Figure 8 (a) (b) presents the relationship between the parasitic parameter of bonding wires with the length of bonding wires. The diameter and space of bonding wires is fixed valued, the loop inductance increase with the length changed.

It can be concluded from the above data that the diameter of bonding wires has a great influence on its parasitic inductance, and the spacing between bonding wires has a little influence on its parasitic inductance. Through the experimental analysis and combined with the actual situation, the optimized bonding parameters of the bonding wires are respectively the number of three, diameter 0.5mm, spacing 0.18mm. The optimized bonding wires can effectively reduce the parasitic inductance. The parasitic inductances of the bonding wires optimized by P-P and U-U experiments are 7.671 nH and 5.342 nH, respectively. This solution can make full use of the existing package area and reduce heat dissipation while reducing parasitic inductance as much as possible.
Figure 9. Off voltage simulation result graph

In Figure 9, the voltage spike caused by the original bonding wires during the turn-off process is 626.76V, and the voltage spike caused by the optimized bonding wires during the turn-off process is 620.86V, and the peak overvoltage has dropped by 22%.

Through the analysis and research of the simulation experiment results, it can be known that the number, diameter and length of the bonding wires have the greatest influence on the parasitic inductance, and the proportion weight is the highest, which is given priority in actual design and production.

5. Conclusions

The parasitic parameter of bonding wires is part of the parasitic parameter of the whole intelligent power module, which have a significant impact on the normal operation of the intelligent power module. In this paper, through modeling and simulation experiments on the bonding wires, the effects of various bonding parameters on the parasitic inductance of the bonding wires are studied. At the same time, the influence weights of the bonding parameters on the parasitic parameters are analysed. The bonding wires optimization scheme proposed for the research object in this paper can greatly reduce the voltage spikes generated by the power chip during the turn off process, and also provide a design optimization idea for the bonding wires design of other intelligent power module products.

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