Modeling and Optimization of Bus-bar Local Stray Inductors in Converter

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Abstract. Taking a two level inverter laminated bus as the research object, a mathematical model of local stray inductance is established. The ANSYS Q3D finite element simulation software is used to extract the self-inductance and mutual inductance of local stray inductances in laminated bus-bars. The equivalent local stray inductance is calculated according to the stray inductance mathematical model. The size and generation factors of the local stray inductance of the bus-bar are analysed, and the bus-bar structure is improved. By reducing the local stray inductance between the bus capacitors to IGBT module, the operational status of the converter circuits of the power converter is effectively improved. A double pulse test circuit is built to extract the local stray inductance of the bus-bar before and after optimization. The experimental results show that the improved bus-bar stray inductance is obviously reduced, the correctness of the theoretical analysis is verified, and it is helpful to optimize the bus-bar structure.

1. Introduction

The stray inductance of the IGBT device dynamics test platform has a great influence on the switching characteristics[1, 2]. Accurate extraction of the stray inductance in the test circuit is very important for analyzing the switching characteristics of the device[3, 4]. In [5], it is proposed to extract the stray inductance by simultaneously using the current and voltage waveforms of the turn-off and turn-on transients. Based on the package structure and electrical characteristics of the crimp IGBT, some scholars have designed and built a dynamic switching characteristic test platform for the crimp-type IGBT module based upon the dual-pulse test principle. The experiment was carried out to verify the suppression of the turn-off voltage spike of the device by the laminated bus-bar technology and the snubber capacitor[6].

The power converter has multiple current flow circuits. Due to the structural characteristics of the bus-bars, the stray inductances of different current flow circuits are also different. The unreasonable design of a certain bus-bar is likely to cause excessive stray inductance in some converter circuits, resulting in higher voltage spikes and losses of some IGBTs in the system, and an increased probability of failure. In [7], a bus-bar with a half-bridge structure was used as the research object to establish an equivalent mathematical model that affects the stray inductance of the non-uniform flow between the power terminals of the IGBT module in the IHM-B package. The distribution of the inductance has a large effect on the degree of uneven current flow into the power terminals of the module. Therefore, it is not only necessary to analyze the total stray inductance, but the study of local
stray inductance is more helpful to the optimization of the bus-bar structure [8-12]. In [13], the multiple stages of the switching transient process in the current flow circuit were analyzed. On this basis, the method using the turn-on transient processes combined with the integral algorithm were proposed to extract the stray inductance. However, the effective implementation of this method is based on the need to be able to determine the most favorable stage of stray inductance extraction during switching transients.

In this paper, the local stray inductance value of the single-phase bus-bar of the two-level inverter is extracted by mathematical modeling and ANSYS simulation. The local stray induced potential of the phase is measured according to the double-pulse test circuit. The correctness of the mathematical model of the stray inductance of the bus-bar is verified, and the cause of the excessive local stray inductance is analyzed. The bus-bar structure has been improved based on the aforementioned results. Finally, the improved bus-bar is verified by experiments. The results show that the local stray inductance is significantly reduced.

2. Local stray inductance distribution and modeling

2.1. Local stray inductance distribution

The schematic of the connection between the inverter bus-bar and the IGBT module is shown in figure 1. Modules A, B, and C are three IGBT modules. This packaged IGBT module is a half-bridge structure, and each module can be used as a single-phase bridge arm for a two-level inverter. The six ports of the IGBT module are a, b, c, d, e1, and e2, respectively. Among them, ports a and b are the collector terminals of the upper arm IGBT which is connected to the upper bus-bar. Ports c and d are the emitter terminals of the lower arm IGBT, and are connected to the lower bus-bar. Ports e1 and e2 are bridge arm output terminals and serve as output terminals of the inverter. The DC side capacitor bus-bar of the inverter is connected to the bus-bar of the IGBT module through ports C1 and C2. Ports S1 and S2 are the external DC power ports.

In the control algorithm for inverter, the output pulse of each step on the control board only changes the state of a certain IGBT switch of a certain phase. In this paper, the local stray inductance of the A-phase circuit bus-bar in figure 1 is taken as an example for analysis. The analysis method of the stray inductance of the B and C phase circuits is the same as that of the A phase circuit.

The stray inductance measurement circuit of phase A is shown in figure 2. The device T1 of the upper bridge arm is the control object, and the T2 is reliably turned off. La, Lb, Lc, and Ld are the self-inductance of the bus-bar local stray inductance between the ports C1 and C2 and the IGBT module ports a, b, c, and d, respectively. Mab, Mac, Mad, Mbc, Mbd, and Mcd are the mutual inductance between the local stray inductances. Lload is the load inductance.

Since the stray inductance between the capacitor terminals of the capacitor bus-bar to the C1 and C2 ports is small, it can be ignored for analysis. Through the transient process of the T1 switch, the voltage and current waveforms on the local stray inductances of the bus-bar can be measured to calculate the stray inductance.
2.2 Mathematical modeling of local stray inductance

According to the volt-ampere characteristics of the inductor, the S-domain relationship between the potentials $u_{L1}$ and $u_{L2}$ induced by the local stray inductance and the currents $i_a$, $i_b$, $i_c$, $i_d$ are shown in equation (1), which characterizes the coupling relationship of the branches of the switching transient.

$$
\begin{bmatrix}
  L_{a} & M_{ab} & -M_{ac} & -M_{ad} \\
  M_{ab} & L_{b} & -M_{bc} & -M_{bd} \\
  -M_{ac} & -M_{bc} & L_{c} & M_{cd} \\
  -M_{ad} & -M_{bd} & M_{cd} & L_{d}
\end{bmatrix}
\begin{bmatrix}
i_a \\
i_b \\
i_c \\
i_d
\end{bmatrix}
=\begin{bmatrix}
i_{L1} \\
i_{L2}
\end{bmatrix}
$$

Since both ports a and b are the collectors of the IGBT module on the upper bridge arm, both ports c and d are the emitters of the lower arm, so the local stray inductance in figure 2 can be simplified to the inductance distribution shown in figure 3.

![Figure 3. Simplified distribution of stray inductance in bus-bar.](image)

In figure 3, $L_{C1,ab}$ is the equivalent self-inductance of port $C_1$ to the ports a and b, and $L_{C2,cd}$ is the equivalent self-inductance of port $C_2$ to the ports c and d. $M_{abcd}$ is the mutual inductance of these two inductors. The current $i_s$ is the bus current. Then, the S-domain relationship between the voltage and the current in the circuits is:

$$
\begin{bmatrix}
i_{L1} \\
i_{L2}
\end{bmatrix}
=\begin{bmatrix}
L_{C1,ab} & M_{abcd} \\
-M_{abcd} & L_{C2,cd}
\end{bmatrix}
\begin{bmatrix}
i_s \\
i_a \\
i_b \\
i_c \\
i_d
\end{bmatrix}
$$

The current relationship in figure 2 and figure 3 satisfies the following equation:

$$
\begin{bmatrix}
i_s \\
i_a \\
i_b \\
i_c \\
i_d
\end{bmatrix}
=\begin{bmatrix}1 & 1 & 0 & 0 \\
0 & 0 & 1 & 1
\end{bmatrix}
\begin{bmatrix}
i_a \\
i_b \\
i_c \\
i_d
\end{bmatrix}
$$

Based on the equations (1)-(3), the self-inductive $L_{C1,ab}$, $L_{C2,cd}$, and mutual inductance $M$ can be calculated to obtain a simplified stray inductance matrix model:

$$
\begin{bmatrix}
L_{C1,ab} & -M_{abcd} \\
-M_{abcd} & L_{C2,cd}
\end{bmatrix}
=\begin{bmatrix}1 & 1 & 0 & 0 \\
0 & 0 & 1 & 1
\end{bmatrix}
\cdot
\begin{bmatrix}1 & 0 \\
1 & 0 \\
0 & 1 \\
0 & 1
\end{bmatrix}
$$

Let $L_1$ and $L_2$ be the equivalent local stray inductance of the A-phase bus-bar, then:
4

\[
\begin{bmatrix}
    u_{L_1} \\
    u_{L_2}
\end{bmatrix} = S \begin{bmatrix}
    L_1 & 0 \\
    0 & L_2
\end{bmatrix} \begin{bmatrix}
    i_{L_1} \\
    i_{L_2}
\end{bmatrix}
\]

The following equation can be obtained from the equation (2) and the equation (5).

\[
\begin{bmatrix}
    L_1 \\
    L_2
\end{bmatrix} = \begin{bmatrix}
    L_{C1, ab} & M_{abcd} \\
    -M_{abcd} & L_{C2, cd}
\end{bmatrix} \begin{bmatrix}
    1 \\
    1
\end{bmatrix}
\]

The actual measured stray inductance of the bus-bar is \( L_1 \) and \( L_2 \).

3. Local stray inductance simulation

In order to verify the correctness of the local stray inductance model of the bus-bar, the ANSYS Q3D software was used to simulate the bus-bar model shown in figure 1, and the stray inductance parameters were extracted. In order to be non-general, phases B is selected for simulation shown in figure 4.

![Figure 4. Simulation of bus-bar model.](image)

![Figure 5. Simulation of bus-bar simple model.](image)

Based on the above-mentioned stray inductance matrix and the local stray inductance parameters of the B-phase bus-bar obtained by simulation, the self-inductance and mutual inductance matrix of the local stray inductance of the bus-bar can be obtained as follows:

\[
\begin{bmatrix}
    L_a & M_{ab} & -M_{ac} & -M_{ad} \\
    M_{ab} & L_b & -M_{bc} & -M_{bd} \\
    -M_{ac} & -M_{bc} & L_c & M_{cd} \\
    -M_{ad} & -M_{bd} & M_{cd} & L_d
\end{bmatrix} = \begin{bmatrix}
    57.35 & 41.94 & -23.65 & -8.37 \\
    41.94 & 38.17 & -17.43 & -17.16 \\
    -23.65 & -17.43 & 80.61 & 67.59 \\
    -8.37 & -17.16 & 67.59 & 68.29
\end{bmatrix}
\]

According to equation (4), the simplified stray inductance self-inductance and mutual inductance matrix in figure 3 can be obtained:

\[
\begin{bmatrix}
    L_{C1, ab} & -M_{abcd} \\
    -M_{abcd} & L_{C2, cd}
\end{bmatrix} = \begin{bmatrix}
    39.86 & -13.26 \\
    -13.26 & 77.28
\end{bmatrix}
\]

In order to verify the feasibility and effectiveness of the simplification of the bus-bar spur model, the above bus-bars were also simulated by ANSYS Q3D. The simplified stray inductance parameters are the equivalent self-inductance of port C1 to terminals a and b and the equivalent self-inductance of port C2 to terminals c and d, respectively. For the whole of the laminated bus-bar, the port C1 is set as the excitation of the positive bus-bar, and the port C2 is the sink of the bus-bar. The corresponding terminals of the IGBT are respectively the sink and the excitation of the corresponding bus-bar. Then, the simulation results are shown in figure 5.

The simplified stray inductance can be obtained by the simulation:

\[
\begin{bmatrix}
    L_{C1, ab} & -M_{abcd} \\
    -M_{abcd} & L_{C2, cd}
\end{bmatrix} = \begin{bmatrix}
    38.79 & -13.84 \\
    -13.84 & 76.53
\end{bmatrix}
\]

Comparing equations (8) and (9), it can be seen that the results are almost the same, which proves the feasibility of the simplified method of local stray inductance in figure 3. Furthermore, the correctness of the stray inductance model is also verified.
Substituting the data of equation (9) into equation (6):

\[
\begin{bmatrix}
L_1 \\
L_2 \\
\end{bmatrix} = \begin{bmatrix}
24.95 \\
62.69 \\
\end{bmatrix}
\quad \text{(10)}
\]

It can be seen from equations (9) and (10) that since the bus-bar is a laminated structure, the mutual inductance generated between the local stray inductances in the current flow circuits partially offsets some of the self-inductance. Thereby, the equivalent local stray inductance value is made smaller than the self-inductance value. However, compared with the volume of the bus-bar, the simulated local stray inductance value is larger.

The self-inductance \( L \) of the copper row and the mutual inductance \( M \) of the laminated copper row are as follows.

\[
L = \frac{\mu_0 \mu_r l}{\pi} \left( \frac{1}{8} + \frac{2h}{h + w} \right) \left( d \ll h \parallel d + h \ll w \right) \quad \text{(11)}
\]

\[
M = \frac{\mu_0 \mu_r l h}{\pi} \cos \phi \left[ \frac{4(d + h)^2 + kw^2}{(d + h)^2 + kw^2} \right]^{1/2} \quad \text{(12)}
\]

Wherein: \( l, w, d \) are the length, width and thickness of the copper row; \( h \) is the insulation distance between the copper rows; \( \mu_0 \) is the vacuum permeability; \( \mu_r \) is the relative permeability of the insulating layer; \( k \) is the correction coefficient.

From equations (11) and (12), the self-inductance \( L \) of the local stray inductance is proportional to the length \( l \) of the copper row. However, as the width of the copper strips increases, the self-inductance \( L \) decreases. The larger the distance \( h \) between the laminated copper rows, the smaller the mutual inductance \( M \) is. Based on the above conclusions, the structure of the bus-bar can be optimized. The schematic diagram of the improved bus-bar structure is shown in figure 6. Compared with the bus-bar of figure 1, the improved bus-bar combines the capacitor bus-bar with the IGBT module bus-bar into a unitary bus-bar through a higher bending process. In addition, the upper bus-bars are stacked to the lower bus-bars to a greater extent.

Figure 6. Diagram of Bus-bar structure optimization.

The improved bus-bar is simulated by ANSYS Q3D. The self-inductance \( L'_{C1\_ab}, L'_{C2\_cd} \) and mutual inductance \( M' \) matrix of the local stray inductance are:

\[
\begin{bmatrix}
L'_{C1\_ab} & -M' \\
-M' & L'_{C2\_cd} \\
\end{bmatrix} = \begin{bmatrix}
29.43 & -18.82 \\
-18.82 & 32.21 \\
\end{bmatrix}
\quad \text{(13)}
\]

Bringing the data of equation (13) into equation (6), the equivalent local stray inductances \( L'_1 \) and \( L'_2 \) are obtained:

\[
\begin{bmatrix}
L'_1 \\
L'_2 \\
\end{bmatrix} = \begin{bmatrix}
10.61 \\
13.39 \\
\end{bmatrix}
\quad \text{(14)}
\]

Comparing equations (9) and (13), it can be seen that after the bus-bar is improved, the mutual inductance of the stray inductance increases, and the self-inductance value decreases a lot. So that the local stray inductance value in equation (14) is much smaller than the formula (10). The main reason is that the width of the copper bus-bar of the modified bus-bar is greatly increased at the bend compared
with the narrow copper row at the bus-bar ports C1 and C2 of figure 1, and the current density flowing through the copper bar is greatly reduced. Thus, the self-inductance value is lowered.

4. Experiment verification

Based on the schematic diagram of the stray inductance measurement circuit shown in figure 2, the double pulse test method is used in the IGBT switching transient. Experiments were performed to obtain stray inductances (L1, L2, L’1, and L’2) before and after the bus-bar improvement. When the T1 of the power device IGBT is turned from on to off, the local stray inductance induced potential and current waveform of the original bus-bar are as shown in figure 7. The improved bus-bar local stray inductance induced potential and current waveform are shown in figure 8. The current flowing through the stray inductance of the bus-bar and the improved bus-bar are iS and i’S, I1, I2, I’1, and I’2 are the currents flowing through the stray inductance of the bus-bar and improved bus-bar at t1 and t2, respectively. The local stray inductance induction potential of the bus-bar is the maximum at time t0. U1, U2, U’1, and U’2 are the induced potentials of the local bus-bar stray inductances L1, L2, L’1, and L’2 before and after the improvement, respectively.

In figure 7 and 8, for convenience of analysis, the time from t1 to t2 is 100 ns, and the time t0 is the midpoint of time t1 and time t2. During the period from t1 to t2, the slope of the current drop can be regarded as a constant value, which is the slope of the current at time t0.

The local stray inductance of the bus-bar before and after optimization are calculated shown in table 1.

| Bus-bar          | L1 (nH) | L2 (nH) |
|------------------|---------|---------|
| Non-optimized    | 45.28   | 85.32   |
| Optimized        | 22.67   | 26.19   |

Comparing the values of equations (10) and (14) with the values in table 1, it can be seen that the measured value of the original bus-bar stray inductance is higher than the simulated value by about 22nH, and the improved measured value is higher than the simulated value by about 13nH. It can effectively reduce the stray inductance of the laminated bus-bar using the stray inductance simplified modeling method described in this paper to optimize the bus-bar. And the simulation is consistent with the actual measurement results, simplifying the modeling method is feasible.

5. Conclusion

In this paper, the reasons for the large stray inductance of the bus-bar are analyzed. The mathematical model of the bus-bar stray inductance is constructed, and the structure of the bus-bar is optimized. Through the simulation and experimental analysis of the local stray inductance of the bus-bar before and after the optimization, the following conclusions are drawn: the degree of lamination and integrity of the bus-bar are important factors to reduce the local stray inductance. The mutual inductance can be increased to reduce the local stray inductance by stacking the bus-bar. Integrating the capacitor bus-bar with the IGBT module bus-bar into a whole bus-bar not only eliminates the inductance of the
screw used for fixing between the bus-bars, but also increases the width of the bus-bar at the bend, thereby reducing the stray inductance at that location.

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