Study on Laminated Bus Bar for High-pulse Power Converter Module

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Abstract. Aiming at the problems of high switching overvoltage of power semiconductor devices and unbalanced current of parallel power devices in high-pulse power converters, this paper proposes a laminated bus bar of symmetrical path on the basis of the theoretical analysis and key points of laminated bus bar. The finite element simulation software was used to analyze the stray inductance of laminated bus bars. The actual stray inductance and overvoltage of the converter commutation circuit were measured by single pulse experiment. The results show that the laminated bus bar of symmetrical path can effectively reduce stray inductance, suppress switching impulse overvoltage and improve the current balance of the parallel power devices. It is of great significance to analyze the performance of laminated bus bar of symmetrical path, and it can be used for high-pulse power conversion technologies.

Keywords: Laminated bus bar; High-pulse power; Switching overvoltage; Stray inductance.

1. Introduction
Laminated bus bar is an electrical connection bar. It consists of multilayer thin copper bars and separated by high insulation materials between the copper bars. It is widely used in converters, there are applications in special power conversion equipment such as traditional industry and high-power wind power generation[1]-[3].

The high-pulse power converter module adopts the device parallel method to improve the current output capability[5]. And the high overvoltage of Insulated Gate Bipolar Transistor (IGBT) and the imbalance of the current in the parallel IGBT become design difficulties. For a two-level power module, the switching voltage spikes of the IGBT is \( V_o = V_o + L \frac{di}{dt} \). The switching speed of the IGBT can reach \( us \) level, and the peak pulse current of the power device of the high-pulse power converter can reach tens of thousands of amps level. If a conventional design method of laminated bus bar is used, the stray inductance value of the commutation circuit fails to meet the requirements of suppressing the peak surge voltage, which will cause the voltage peak of the power semiconductor device to exceed the device's safe operating area and damage IGBT[4]. And the unsymmetrical shape of conventional laminated bus bars makes the distribution parameters of main circuit inconsistent, which results unbalanced current of parallel IGBTs[5].

The research is the design of laminated bus bar in high-pulse power converter. It is found that the stray inductance of the designed laminated bus bar of symmetrical path is about \( 4nH \), which corresponds to the stray inductance of commutation circuit of about \( 12nH \). It retains a voltage safety margin of 350V and achieves the symmetry of peripheral circuit of the parallel IGBTs to improve the current balance of the parallel IGBTs, which can fully meet the requirements of pulse-power conversion technology.
2. Laminated Bus Bar Inductance Suppression Principle
Schematic diagram of laminated bus bar is Figure 1, the upper and lower copper bars have the same size. The length, width and height of a single layer are a, b and c, and the thickness of the insulating layer is h. Ref.[6] explains the physical characteristics and gives its equivalent inductance formula:

(1) Internal inductance: It is caused by the internal magnetic chain of the conductor copper bar, and it is related to the frequency of the current flowing through the conductor copper bar. When the frequency is large, the internal inductance is very small to be ignored. When the frequency is small, the internal inductance can be expressed as:

\[ L_i = \frac{\mu_0 \mu_r b}{8\pi} \]  

(2) External inductance: It is mainly generated by the external magnetic links of the positive and negative copper bars of the laminated bus bar. When \( h \ll 2c \) and \( h \ll (b + c) \), the external inductance can be estimated as:

\[ L_e = \frac{2\mu_0 \mu_r a}{\pi} \ln\left(1 + \frac{c}{b+c}\right) \]  

And when \( c \ll b \), the above formula is simplified to:

\[ L_e = \frac{2\mu_0 \mu_r ac}{\pi} \]  

So the laminated bus bar stray inductance is:

\[ L = L_i + L_e \]  

Where \( \mu_0 \) is the permeability of the vacuum, and \( \mu_r \) is the relative permeability of the copper layer. When IGBT is turned on and off, the current flowing through the laminated bus bar is an instantaneous high-frequency current, which will form a mirror current in the adjacent copper bar. When the distance between the ground plane and the signal path plane is much smaller than the width of the conductor, under the skin effect, the high-frequency current will be mainly distributed on the plane of the two copper bars near the inside, and a pair of currents in opposite directions will be obtained. Forming an unbalanced path in Figure 2.

Figure 1. Schematic diagram of laminated bus bar.

Figure 2. Unbalanced path.
According to the principle of magnetic field superposition and electromagnetic theory, when the upper and lower conductors flow are name size and opposite current, the electromagnetic induction intensity at a certain point in space is the vector sum of the electromagnetic induction intensity produced by the two conductors. The high-frequency magnetic fields in the space around the bus bar cancel each other, which is equivalent to the stray inductance of laminated bus bar being suppressed to a certain extent.

3. Laminated Bus bar Design Points
In order to reduce the stray inductance of laminated bus bar, according to the principle of the second section, the design of laminated bus bar requires that current flow path on the single-layer copper bar is short, and the section of the current flow is thin and long. In other words, on the basis of meeting the physical connection and mechanical strength requirements, laminated bus bar should be short, wide, and thin, and the distance between copper bar layers should be small. The size and number of openings and slots in laminated bus bar should be less. For the necessary openings and slotting on the width edge, the position should be close to the middle area of laminated bus bar, and the slotting position on the length edge should be near the corner area of laminated bus bar [7].

In addition to the overall design points above, the location layout of the connection terminals of devices and laminated bus bar should be reasonably designed. When the IGBT is turned off, the current on the commutation circuit will flow through the inside of the laminated bus and IGBT. The position of the connection terminals must be designed to ensure that the current forms an unbalanced path and the conductor flows a large and reverse current [8]. Reducing the size of the bus bar terminal to outside, shorten terminal spacing, and the terminal part connecting the positive and negative bus bars is designed as a laminated structure, which can reduce the stray inductance of laminated bus bar[9].

For the unbalanced current characteristics of parallel IGBTs, the structure of laminated bus bar close to IGBTs is particularly important. The mutual inductance on this part of laminated bus bar has a strong influence. The essence of mutual inductance is the interaction of electromagnetic field. As long as the current path is controlled, the loop inductance can be effectively changed[10]. In order to improve the consistency of the distribution parameters of the peripheral circuits of the IGBTs, the copper bars used to connect the parallel IGBTs on the single-phase bridge arms are symmetrical to the left and right, ensuring that the paths of the currents flowing through the copper bars connected to the parallel IGBTs are symmetrical and consistent.

4. High-pulse Power Converter Module Laminated Bus Bar Design

4.1. Main Circuit Topology of High-pulse Power Converter Module
High-pulse power converter module performance parameters: DC voltage 600V, maximum AC output voltage peak is 185V, AC output maximum phase current effective value is 7kA, phase current peak value is 12kA in redundant operating conditions, adopting three-phase AC output and intermittent pulse work system.

![Figure 3. Topology of main circuit of power module and distribution of copper bars.](image)

According to the design input parameters, the main circuit device model is calculated and determined. It is required to use six capacitors of 5000µF-1200VDC in parallel to form DC-side support capacitor. The manufacturer gives the capacitance parasitic reactance of about 20nH; the IGBT is Infineon.
FZ3600R17HP4_B2, including IGBT and anti-parallel diodes, as shown V11 and D11 in Figure 3, which internal parasitic inductance is 6nH; IGBT driver uses Concept 1SP0635X2X1-17, and its active clamping voltage is 1320V. Figure 3 shows the main circuit topology of the high-power converter module. The DC bus voltage is 600V, the parallel IGBTs increase the output current, so the output pulse power can increase doubled.

4.2. High-pulse Power Converter Module Laminated Bus Bar Design
According to the design points about the laminated bus bar, the high-pulse power converter module is designed to low the stray inductance in the commutation circuit, to ensure that the switching overvoltage spikes of IGBTs is less than the active clamping voltage of the drive board 1320V. The consistency of the distributed parameters of the parallel IGBT peripheral circuits is required to ensure the parallel IGBT current balance. The design results in laminated bus bar of symmetrical path, as shown in Figures 4 and 5.

Figure 4. 3D Map of laminated bus bar of symmetrical path.

Figure 5. Three views of laminated bus bar of symmetrical path.
The laminated bus bar is 1180mm long, 108mm wide, 187mm overall height, 78mm shoulder height, and 9mm connection hole diameter. The laminated bus bar consists of positive, negative, A-phase, B-phase, and C-phase copper bars, and there are ABC three-phase output connection copper terminals. The laminated bus bar is a two-layer copper bar, which is convenient for the symmetrical design of the copper bus path.
Laminated bus bar is left-right symmetry and front-back symmetry as a whole. The copper bars connected to parallel IGBTs on a single-phase branch are left-right symmetry and front-back symmetry so that the current path on the commutation circuit is symmetrical, and the path length of the parallel IGBTs current flowing on the single-phase bridge arm is consistent.

4.3. Simulation Analysis of Laminated Bus Bar
Ansoft Q3D was used to simulate the stray inductance of laminated bus bar[11]. The source and sink on the connection port of the laminated bus bar and IGBTs are set in the software, and the end-to-end connection forms a loop path. The simulation setup for A-phase loop is shown in Figure 6. A-phase commutation circuit path: Capacitor positive electrode (source1) to A-phase upper bridge IGBT collector (sink1), and then from A-phase upper-bridge IGBT emitter (source2) to A-phase lower bridge IGBT collector (Sink2), and finally from the A-phase lower bridge IGBT emitter (source3) to
the capacitor negative (sink3), forming a completely closed loop. The laminated bus bar of symmetrical path is two-layered, and the current on the upper and lower copper bars is equal in size and opposite directions, which can reduce the stray inductance on the laminated bus bar as much as possible.

![Figure 6. Source and Sink settings of a phase loop simulation signal.](image)

The simulation shows that the stray inductance value of the A-phase circuit of the laminated bus bar is 3.841nH, and the stray inductances on the positive and negative copper bars are 1.959nH and 1.818nH. Similarly, the stray inductance of phase B and C loops is simulated, as shown in Table 1.

| Positive copper | Negative copper | Connection copper | phase circuit |
|-----------------|-----------------|-------------------|---------------|
| A-phase         | 1.959           | 1.818             | 0.064         | 3.841         |
| B-phase         | 1.606           | 1.596             | 0.206         | 3.408         |
| C-phase         | 1.863           | 1.928             | 0.062         | 3.853         |

The result shows that the stray inductances of the positive and negative copper bar in each phase are almost equal, and the symmetrical bilateral structure design is verified. The commutation loops of A-phase and C-phase are almost equal, and the symmetrical structure design of the left and right is verified. The stray inductances of copper bars and commutation circuit of B-phase are smaller than that of A and C. It is verified that the shorter the path of the commutation circuit, the lower the stray inductance of the laminated bus bar.

The simulation value of the stray inductance of A-phase commutation circuit is approximately:

$$L1 = L_{\text{in}} + 2 \times \frac{L_{\text{IGBT}}}{2} + \frac{L_{c}}{6} = 3.841 + 2 \times \frac{6}{2} + \frac{20}{6} = 13.174 \text{nH}$$  \(5\)

5. Laminated Bus Bar Single Pulse Experiment

![Figure 7. Single pulse experiment schematic.](image)
This article focuses on the IGBT turn-off process, so single-pulse experiment is used \[12\]. The experiment schematic is shown in Figure 7. The experiment tests the single-pulse case with a peak off current of 12kA.

In the experiment, the IGBT 1-1 and 1-2 were always turned off, and the IGBT 2-1 and 2-2 in parallel were turned on with a single trigger. By increasing the turn-on width of a single pulse, the IGBT 2-1 and 2-2 was turned off when the short-circuit current reached 12kA. And it measure the change of the collector-emitter voltage \( V_{ce} \) of IGBT2-1 and 2-2 during the entire test. The A phase of the power module is tested in the situation that the input DC voltage is 600V and the short-circuit current is 12kA.

![Figure 8: Vce waveform under single pulse turn-off 12000A.](image)

As shown in Figure 8, when the peak of the single-pulse turn-off current \( I_p \) reaches 12kA, the \( V_{ce} \) waveform is measured. The maximum turn-off voltage \( \Delta U \) of the IGBT device is about 368V, and the off-time of the IGBT (FZ3600R17HP4_B2) is 0.315us. During this time, the current flowing through the IGBT is reduced from 0.9\( I_p \) to 0.1\( I_p \). It can be known that the stray inductance of the commutation circuit measured by the test is approximately:

\[
L_2 = \frac{\Delta U}{\Delta I} = \frac{368}{12000 \times 0.8} = 12.075 \text{nH}
\]  

(6)

It is found that the difference between the test results and the simulation results is small, and the stray inductance of the commutation circuit is about 12\( nH \).

The DC bus voltage is 600V, and the maximum off-voltage peak of the IGBT is 368V in Figure 8, so the maximum voltage of the collector and emitter of the IGBT is 968V. Active clamping voltage of IGBT driver is 1320V which leave the large safety margin for IGBT. It indicates that the power converter module has passed a single-pulse test with a short-circuit current of 12kA.

It can be seen from Figure 8 that the shutdown overvoltage waveforms of A-phase parallel IGBT2-1 and IGBT2-2 are the red and blue lines. When the IGBT with 12kA current is turned off, the turn-off overvoltage waveforms of the two are relatively Consistent, and the peaks appear almost simultaneously. It is considered that the trigger delay between the master and slave drive boards is small, in other words, the consistency of the drive circuit is well. On the other hand, the turn-off overvoltage peak difference between the parallel IGBT 2-1 and 2-2 is about 50V, which indicates that the parallel IGBT current balance is well. Assuming that the turn-off overvoltage of parallel IGBTs is \( \Delta V_1 \) and \( \Delta V_2 \), the device operation consistency estimation can be performed:

\[
\Delta V_1 = L_2 \frac{di_1}{dt}, \quad \Delta V_2 = L_2 \frac{di_2}{dt}
\]  

(7)

The stray inductances of the single IGBT commutation circuits with IGBT 2-1 and 2-2 in FIG. 7 are little difference. Therefore, the following relationships can be approximated from equations (7):

\[
\frac{\Delta I_1}{\Delta I_2} \approx \frac{\Delta V_1}{\Delta V_2} = \frac{368}{318} = 116\%
\]  

(8)

It can be seen that after using a symmetrically stacked bus bar design, the test found that the current balance through the parallel IGBTs reached 116%.
6. Conclusion

In this paper, a laminated bus bar of symmetrical path suitable for high-pulse power converter modules is designed, and Ansoft Q3D simulation analysis and single-pulse test are performed to verify the feasibility of the laminated bus bar of symmetrical path. The technical difficulties about high switching overvoltage and unbalanced current of parallel IGBTs of high-pulse power converter module are solved.

The laminated bus bar of symmetrical path has the following characteristics:

1. Low stray inductance, reducing the stray inductance of the commutation circuit, effectively reducing the IGBT switching overvoltage. In a single pulse experiment with a turn-off current peak of 12kA, the turn-off voltage peak 968V that the IGBT withstands is far less than the active clamping voltage of the driver board of 1,320V, leaving a safety margin of 350V.

2. The laminated bus bar surrounding the parallel IGBTs on the single-phase bridge arm are symmetrical left and right, and the current paths are symmetrical, which promotes the stray inductance of the parallel IGBTs commutation circuit to be almost the same. In the 12kA single-pulse experiment, the turn-off voltage peak difference of the parallel IGBTs was less than 50V, and the current balance through the parallel IGBTs reached 116%.

Utilizing the unique advantages of the laminated bus bar of symmetrical path, it not only reduces the IGBT switching overvoltage, but also improves the current balance of the parallel IGBTs. It can effectively improve the performance of high-pulse power converter module and can be used for reference in similar high-pulse power conversion technologies.

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