A design method of ac busbar for IGBT power assembly

Y P Xue1,2,3,4, J Liu2,3,4, W Su2,3,4, W Sun2,3,4
1University of Chinese Academy of Sciences,Beijing 100190,China
2Institute of Electrical Engineering,Chinese Academy of Sciences,Beijing 100190,China
3Key Laboratory of Power Electronics and Electric Drive,Institute of Electrical Engineering,Chinese Academy of Sciences,Beijing 100190,China
4Beijing Engineering Laboratory of Electrical Drive System & Power Electronic Device Packaging Technology,Beijing 100190,China
Email:xueyanpeng@mail.iee.ac.cn

Abstract. The design scheme of paralleling multiple IGBTs in power assembly to increase the current capacity is widely used in power electronic equipment. In order to ensure the equipment’s safe operation, the power assembly’s uneven current problem is a design difficulty. This paper analyzes the influence of ac and dc busbar stray inductance on the uneven current problem from the circuit model perspective, and put forward a method to improve the current sharing performance, which is to adjust the ac busbar stray inductance based on the dc busbar stray inductance. Taking a vehicle motor controller as the research object, designing an ac busbar with this design method. The experimental results confirmed the validity of this method.

1. Introduction
The design scheme of paralleling multiple IGBTs in power assembly to increase the current capacity is widely used in the fields of wind power converter, photovoltaic inverter and electric motor controller. If the power assembly couldn’t balance the current between each IGBT properly, it will accelerate aging of the IGBT which flowing through a larger current, even cause a damage to the equipment. Factors that affect the current sharing performance of the power assembly include: IGBT device parameter differences, IGBT driver parameter differences, IGBT parallel circuits parameter differences[1]. In order to solve the uneven current problem, there are some common methods: 1.using the same batch of IGBT devices in power assembly 2.IGBT driver design specially[2] 3.using symmetrical structure in ac and dc busbar design[3,4], et al.

This paper studies how to improve the current sharing performance of the power assembly by adjusting the ac busbar structure when the dc busbar structure is asymmetrical and can’t change. In this paper, an equivalent circuit model of power assembly including ac and dc busbar stray inductance is established, and a design method of the ac busbar is given. Under the guidance of this design method, an ac busbar is designed for power assembly of a motor controller for a vehicle. The experimental results prove the effectiveness of this design method.
2. Ac busbar design

2.1. Equivalent circuit analysis

Ac and dc busbar generally are made of a conductive metal conductor, the resistance from confluence of the busbar to the IGBT terminal is generally tens to hundreds of uΩ. Since the resistance value is too small, its influence on the uneven current problem can be neglected. Therefore, this paper only considers the influence of the stray inductance parameters of the ac and dc busbar on the uneven current problem[5],[6].

In this paper, an equivalent circuit model of power assembly including ac and dc busbar stray inductance is established, as shown in Figure 1 (a). The power assembly is made up of two IGBT modules connected in parallel. L1DC, and L2DC respectively represent the stray inductance from positive confluence of the dc busbar to IGBT1 and IGBT2, M1 represents the mutual inductance between L1DC and L2DC; L1AC and L2AC represent stray inductance from confluence of the ac busbar to the IGBT1 and IGBT2, M2 represents the mutual inductance between L1AC and L2AC ; LIGBT represents the parasitic inductance of the IGBT module, and as the distance between two IGBT modules is far, mutual inductance influence can be neglected. Can be seen from figure 1 (a), stray inductance between P and C points determine the current sharing performance of the power assembly.

![Equivalent circuit diagram](image)

**Figure 1.** Equivalent circuit:(a) detail circuit and(b) simplified circuit

When the IGBTs are turning on, voltage between P and C points :

\[ v_i = (L_{1DC} + L_{IGBT} + L_{1AC} \times L_{2DC} + L_{IGBT} + L_{2AC}) \times \frac{di_1}{dt} + (M_1 + M_2) \times \frac{di_2}{dt} \]

\[ v_i = (L_{1DC} + L_{IGBT} + L_{1AC} \times L_{2DC} + L_{IGBT} + L_{2AC}) \times \frac{di_1}{dt} + (M_1 + M_2) \times \frac{di_2}{dt} \]

In general, M1 + M2 is significantly less than L1DC + LIGBT + L1AC and L2DC + LIGBT + L2AC, i1 and i2 difference doesn’t exceed 10% of (i1 + i2). For ease of analysis, the equivalent circuit of the power assembly is simplified from figure 1(a) to figure 1(b), and equation (1) can be simplified as:

\[ v_i = L_1 \times \frac{di_1}{dt} = L_2 \times \frac{di_2}{dt} \]  

(2)

In the equation(2):

\[ L_1 = L_{1DC} + L_{IGBT} + L_{1AC} \quad M_1 + M_2 \]

\[ L_2 = L_{2DC} + L_{IGBT} + L_{2AC} + M_1 + M_2 \]  

(3)

L1 and L2 represent the equivalent inductance parameter of each IGBT branch circuit in power assembly. The current unevenness can be calculated from equation(2):

\[ \varepsilon\% = \left| \frac{I_1 - I_2}{(I_1 + I_2)} \right| = \left| \frac{L_1 - L_2}{L_1 + L_2} \right| \]  

(4)

From equation (4) we can see the closer the values of L1 and L2 are, the better the current sharing performance of the power assembly will be. And from equation (3) we can see, as long as guarantee the value of L1DC + L1AC and L2DC + L2AC close to each other, we can ensure the current sharing performance. Reflected in the actual physical world, when the dc busbar structure is asymmetrical(L1≠L2), we can achieve a good current sharing performance by adjusting the ac busbar structure.
2.2. **Calculation of DC Busbar Stray Inductance**

In practical application, IGBTs in the power assembly are connected to the dc busbar respectively, and the shape of the dc busbar is often asymmetrical due to the actual space environment. Both of this two reasons make it difficult to ensure stray inductance of the dc busbar to each IGBT consistent, and the dc busbar has a large volume generally, the structure is not easy to adjust. Compared with the dc busbar, ac busbar structure is simple and easy to adjust. Therefore, in order to ensure a good current sharing performance, we can first use Q3D simulation software to calculate the stray inductance value of the dc busbar to each IGBT in the power assembly, and then adjust the structure of the ac busbar to ensure the current sharing performance following the principle of $L_{1DC+} + L_{1AC}$ and $L_{2DC+} + L_{2AC}$ values approaching.

Taking a w phase of a power assembly used by one vehicle motor controller as the research object. Dc busbar shape is shown in figure 2. The power assembly consists of two Infineon FF600R12ME4 half-bridge modules connected in parallel. The $L_{IGBT}$ between the IGBT power terminals is about 10nH. The three-phase U, V and W space layouts are arranged in order from left to right. The power input terminals of dc busbar are labeled P and N; $W_1p$ terminal is connected to the upper IGBT collector of the first IGBT half-bridge module, and $W_{1N}$ terminal is connected to the lower IGBT emitter of the first IGBT half-bridge module; $W_{2p}$ terminal is connected to the upper IGBT collector of the second IGBT half-bridge module, and $W_{2N}$ terminal is connected to the lower IGBT emitter of the second IGBT half-bridge module. There are 15 capacitor cores evenly distributed in the dc busbar, and the positive and negative terminals of the capacitors connect to the dc busbar’s positive and negative respectively.

![Figure 2. Dc busbar mechanical structure](image)

In practical application, the input terminals of the dc busbar are connected to the external power supply through two pieces of cable. At the normal switching frequency, the impedance of this pieces of cable is much larger than the impedance of the capacitors to the IGBT terminals. Therefore, during normal operation, the capacitors act as a power supply to provide instantaneous turn-on current to the IGBT. Simplify the analysis, the 15 capacitors equivalent to one capacitor. The equivalent circuit of the w phase IGBT power assembly is shown in Figure 3.

![Figure 3. W phase power assembly equivalent circuit](image)

Using Q3D simulation software to calculate the stray inductance of the dc busbar confluence point to the IGBTs in Figure 2, and the stray inductance is obtained as shown in Table 1.

| Table 1. Stray inductance of dc busbar |
|-------------------------------|-----------------|-----------------|
| $L_{1DC+}$(nH) | $L_{2DC+}$(nH) | $M_1$(nH)        |
| 10            | 12.7           | 3.7             |
2.3. AC Busbar design
According to the analysis in section 2.1, if the stray inductance of the dc busbar confluence point to the IGBTs are different, in order to ensure a good current sharing performance of the power assembly, the ac busbar structure can be adjust according to the principle that the values of $L_1$ and $L_2$ are approximative. In order to verify the effectiveness of this design method, a new ac busbar has been designed.

In the following analysis, there are two types of ac busbar, one is the previously used ac busbar labeled as a-busbar, the other is a newly designed busbar labeled as b-busbar.

2.3.1. a-busbar

![A-busbar mechanical structure](image)

Using Q3D simulation software to calculate the stray inductance from the ac busbar confluence point to each IGBT terminal. The results are shown in Table 2. $L_{1AC}$ is smaller than $L_{2AC}$, this is because there is a part of distance the current flows reversely when it flows from IGBT1 to the ac busbar confluence point. This reverse current weakens the magnetic flux generated by IGBT1 current, so the inductance is smaller. The current direction is shown by the dashed line in Figure 4.

| Table 2. Stray inductance of a-busbar |
|--------------------------------------|
| $L_{1AC}$ (nH) | $L_{2AC}$ (nH) | $M_2$ (nH) |
| 28.5 | 32.8 | 27.5 |

2.3.2. b-busbar

![B-busbar mechanical structure](image)

Using Q3D simulation software to calculate the stray inductance from the ac busbar confluence point to each IGBT terminal. The results are shown in Table 3. $L_{2AC}$ is smaller than $L_{1AC}$, this is because there is a part of distance the current flows reversely when it flows from IGBT2 to the ac busbar confluence point. This reverse current weakens the magnetic flux generated by IGBT2 current, so the inductance is smaller. The current direction is shown by the dashed line in Figure 5.

| Table 3. Stray inductance of b-busbar |
|--------------------------------------|
| $L_{1AC}$ (nH) | $L_{2AC}$ (nH) | $M_2$ (nH) |
|  |  |  |

4
Substituting the data in Table 2 and Table 3 and $L_{IGBT}$ into equation (3) and (4), we get the equivalent inductance of each IGBT branch circuit and current non-uniformity of the power assembly. The data is shown in Table 4.

|     | $L_1$(nH) | $L_2$(nH) | $\Delta L$(nH) | $\varepsilon$(%) |
|-----|-----------|-----------|---------------|----------------|
| a-busbar | 79.7      | 86.7      | 7             | 4.2            |
| b-busbar | 81.5      | 79.6      | 1.9           | 1.2            |

From the data in Table 4, it can be found that adopting the new busbar scheme can significantly reduce the difference of the equivalent inductances between the two IGBT branch circuits and improve the current sharing performance of the power assembly.

3. Experiment

Double-pulse chopper experiment is used to verify the current sharing performance of the power assembly under the two ac busbar schemes. The main parameters of the circuit are shown in Table 5, the experiment circuit is shown in Figure 6, and the experimental waveform are shown in Figure 7. Due to the limitation of the experimental environment, it actually measures the current flowing out from the IGBT. In the Figure 7, the rising current represents the current flowing out from the IGBT when the upper IGBTs are turned on, and the falling current represents the current flowing though the diode of the lower IGBT module. From the experimental results, a-busbar current non-uniformity is 4.5%, and calculated value is 4.2%; b-busbar current non-uniformity is 1.1%, and calculated value is 1.2%.

| Power Supply(V) | Load Inductance(uH) | IGBT |
|-----------------|---------------------|------|
| 400             | 13                  | FF600R12M |

![Figure 6. Double-pulse chopper experiment](image)

![Figure 7. IGBT current wave](image)
4. Conclusion
This paper presents a method to improve the current sharing performance when the dc busbar is asymmetric. The design method can ensure a good current sharing performance of power assembly by adjusting the ac busbar structure. And the experimental results proved the effectiveness of this design method.

Acknowledgements
This work was funded by Beijing Science and Technology Project(No. Z161100001416004).

References
[1] Xin LY, Sun KK, Gong Z, Chen YP, Tang LG 2017 J.High power converter technology. (1) 18-23
[2] Xiao YW, Tang YY, Chen YF 2015 J.Journal of power supply. (2) 64-70
[3] Yang XY, Liu WZ, Ma CQ, Zhang XT 2013 J.Power electronics. 47(5) 100-103
[4] Wu JX, Zhang HH, Chen YF 2017 J.High power converter technology.(2) 27-32
[5] Geng CF, Zhang JW, He FY 2017 J.Power electronics. 51(7) 86-88
[6] Zhang JW, Cheng Z, Tan GJ 2017 J.Power electronics. 51(7) 77-79