Research on Parallel Operation Characteristics and Current Sharing Method of High Power IGBT

Tang Yong¹; Wang Bo² and Lin Qiu Jie³
¹, ²College of Mechanical and Electronic Engineering, Wuhan Donghu University, Wuhan 430000, Hubei Province, China.
³Naval University of Engineering, Wuhan430000, Hubei Province, China.
*E-mail address of corresponding author: tangyong_tt@163.com;

Abstract. With the development of power electronics technology, the capacity of power conversion devices is getting larger and larger, and the current level requirements for high-power IGBT are also getting higher and higher. A single device often cannot meet the requirements, and multiple IGBT need to be used in parallel. When IGBT is connected in parallel, due to the differences in device parameters, external circuit parameters and heat dissipation conditions, the current distribution is easily unbalanced, resulting in device performance waste or even damage. Therefore, the current sharing problem is the core problem to be solved in parallel connection of IGBT. In order to solve the problems such as difficulty in analyzing a single factor for coupling of various influencing factors, difficult control of temperature and high cost of circuit, this paper adopts Saber software simulation method to analyze the influence of various internal and external factors on IGBT's dynamic and static current sharing, thus obtaining the relationship between these factors and corresponding countermeasures, and obtaining an effective IGBT parallel current sharing scheme. Finally, the correctness and effectiveness of this scheme are verified by experiments.

1. Introduction
Insulated Gate Bipolar Transistor (IGBT) is a composite power semiconductor device that combines the structure of power field effect transistor (MOSFET) and bipolar power transistor (BJT). Because it has the advantages of simple driving, high power level, low power consumption and good thermal stability, IGBT become the most widely used fully controlled power electronic device[1-3]. With the development of modern power electronics technology, the current level of a single IGBT device is constantly improving, but it often cannot meet the requirements of current large-capacity power electronics power conversion devices. Considering the factors of economy, reliability and supply channels, selecting the highest level of devices is sometimes not the best solution. In this case, it is an effective way to use multiple IGBT parallel connection to meet the current requirements of a single inverter[4-5].

If the IGBT current distribution in parallel operation is not uniform, the IGBT carrying most of the current may exceed its rated current or exceed its maximum junction temperature for safe operation, causing permanent damage to the device. In addition, uneven current will also lead to uneven heating, and uneven thermal stress for a long time will lead to inconsistent IGBT service life and decrease the service life of the whole system. Therefore, the current sharing problem is the most critical problem that must be solved for reliable parallel connection of IGBT[6-7]. At present, the parallel operation of
IGBT is usually at the expense of large-scale derating, and the working current of a single IGBT is usually much lower than its rated current, which will not only greatly increase the weight and volume of the whole converter, but also reduce the reliability and power consumption, and increase the difficulty of heat dissipation, which is very disadvantageous in high-power converter devices. Therefore, on the premise of ensuring reliable current sharing, the number of devices connected in parallel should be reduced as much as possible to optimize the overall performance of the power conversion device.

There are many factors that affect IGBT parallel current sharing effect, including the device's on-state voltage drop, switching speed, internal carrier life, driving resistance, emitter inductance, operating temperature and other external conditions, and these factors are complicated and coupled to each other. If the analysis is conducted by means of test alone, it is often difficult to eliminate interference from other factors and will result in a large amount of equipment consumption[8]. In addition, for IGBT commercial devices used in engineering applications, it is difficult for conventional means to go deep into the interior to change device parameters, and because the temperature changes sharply, the influence of temperature on these parameters must also be considered, so the general experimental means cannot analyze the uneven flow phenomenon caused by the inconsistency of IGBT internal parameters.

To sum up, this paper uses the simulation method based on Saber electrical software to analyze the influence of various internal and external factors on IGBT current sharing, so as to obtain the relationship between these factors and the corresponding countermeasures, and to obtain an effective IGBT parallel current sharing scheme. Finally, the correctness and effectiveness of this scheme are verified by experiments.

2. Construction of simulation circuit

For the parallel operation simulation of high-power IGBT, this paper adopts the powerful simulation and mixed signal simulation software Saber from Synopsys. IGBT model uses Hefner model based on semiconductor physical properties in Saber component library. The model not only has high simulation accuracy, but also has a temperature interface (TJ interface in the figure) as shown in figure 1, which can set the operating temperature of IGBT and facilitate the study of the influence of temperature on IGBT parallel characteristics. The constructed simulation circuit is shown in figure 2.

![Figure 1. IGBT model with temperature interface](image1)

![Figure 2. Simulation circuit of parallel operation](image2)

The circuit adopts Buck chopper circuit, with resistance and inductance connected in series as resistive and inductive loads, and anti-parallel diode freewheeling. The switch circuit consists of two IGBT's of the same structure connected in parallel, with an independent drive circuit. The drive signal is a square wave pulse with an amplitude of 15V, and the rise time and fall time are 100ns. In the circuit, the driving resistance, driving signal, emitter inductance, temperature and internal parameters of IGBT as show in the figure 2 all can be adjusted.

There are mainly two kinds of current imbalance when IGBT is connected in parallel: static current imbalance and dynamic current imbalance[9]. Among them, the non-uniform static current is mainly caused by the non-uniform on-state voltage drop VCE ( SAT ) of the device[10], while the non-uniform dynamic current is mainly caused by the non-uniform parameters of the device, driving resistance, driving speed, operating temperature, emitter inductance and other factors[11-12]. The dynamic and static parallel characteristics of IGBT are simulated and analyzed respectively below.
3. Simulation and Analysis of IGBT Static Parallel Operation Characteristics

The output characteristic curves of Z1 and Z2 IGBTs working in parallel are shown in figure 3.

![Figure 3](image_url)

Figure 3. Output characteristic curves of two IGBTs working in parallel

In figure 3, Vo1 and Vo2 are the threshold voltages of Z1 and Z2 respectively. As can be seen from figure 3, the on-state voltage drop of Z1 and Z2 can be expressed as:

\[
\begin{align*}
V_{ce\text{(sat)}} & = V_{o1} + r_1 I_{C1} \\
V_{ce\text{(sat)}} & = V_{o2} + r_2 I_{C2}
\end{align*}
\] (1)

In the formula, r1 and r2 are the on-state resistances of the two IGBTs respectively. Since the two IGBTs are directly connected in parallel, the following formula holds:

\[
\begin{align*}
V_{ce\text{(sat)}} & = V_{ce\text{(sat)}} \\
I_{C\text{tot}} & = I_{C1} + I_{C2}
\end{align*}
\] (2)

Where \(I_{C\text{tot}}\) is the total current. The currents through Z1 and Z2 can be expressed respectively:

\[
\begin{align*}
I_{C1} & = \frac{V_{o2} - V_{o1} + r_2 I_{C\text{tot}}}{r_1 + r_2} \\
I_{C2} & = \frac{V_{o1} - V_{o2} + r_1 I_{C\text{tot}}}{r_1 + r_2}
\end{align*}
\] (3)

It can be seen from equation (3) that the non-uniform distribution of static current when IGBT is connected in parallel is mainly caused by the non-uniform on-state voltage drop, which also changes with temperature, so the inconsistency of junction temperature TJ will also affect IGBT parallel connection. In order to facilitate analysis, the current unbalance rate \(\alpha\) is defined as:

\[
\alpha = \frac{I_{C1} + I_{C2}}{I_{C\text{tot}}}
\] (4)

The following is a simulation analysis of the influence of temperature inconsistency on IGBT static current sharing. As shown in figure 1, the simulation circuit keeps the temperature of IGBT 2 at 30°C, changes the temperature of IGBT1 at 60°C, and other circuit parameters remain unchanged. The simulation results are shown in figure 4.
As can be seen from figure 4, the two parallel IGBTs with inconsistent temperature at on-state time have non-uniform current, with the higher temperature IGBT receiving less current and the lower temperature IGBT receiving more current. Keeping the temperature of IGBT 2 unchanged at 30°C and changing the temperature of IGBT 1 from 30°C to 120°C in steps of 10°C, the simulation results are shown in Table 1.

### Table 1. On-state current sharing at different temperature

| IGBT2 temperature (°C) | IGBT1 temperature (°C) | IGBT1 On-state current (A) | IGBT2 On-state current (A) | Unbalance rate α |
|------------------------|------------------------|----------------------------|----------------------------|------------------|
| 30                     | 30                     | 24.865                     | 24.865                     | 0.00%            |
| 30                     | 40                     | 24.84                      | 24.89                      | 0.20%            |
| 30                     | 50                     | 24.797                     | 24.932                     | 0.54%            |
| 30                     | 60                     | 24.74                      | 24.989                     | 1.00%            |
| 30                     | 70                     | 24.672                     | 25.057                     | 1.55%            |
| 30                     | 80                     | 24.594                     | 25.134                     | 2.17%            |
| 30                     | 90                     | 24.509                     | 25.218                     | 2.85%            |
| 30                     | 100                    | 24.418                     | 25.309                     | 3.58%            |
| 30                     | 110                    | 24.322                     | 25.404                     | 4.35%            |

As can be seen from the data in Table 1, the greater the temperature difference between parallel IGBTs, the greater the non-uniform fluidity in its on-state. In the actual circuit, factors such as different heat generation and heat dissipation of the two parallel IGBT modules will cause different temperatures of the IGBT, thus changing the on-state voltage drop of the IGBT and further affecting the static current sharing effect when the IGBT is connected in parallel. Therefore, it is necessary to select IGBT with the same on-state voltage drop for parallel connection, and also to ensure the consistency of heat dissipation conditions as much as possible.

### 4. Simulation and Analysis of IGBT Dynamic Parallel Operation Characteristics

During the switching process of IGBT working in parallel, the IGBT that is turned on first has current passing through it early, which will bear most of the current. And then the IGBT that is turned off last will cut off late, which will also bear most of the current, resulting in dynamic non-uniform current in parallel. Because the total current of the switching-on transient is small, the effect of non-uniform current during switching-on is not obvious, and the influence on the IGBT is not large, this paper mainly studies the non-uniform current of the switching-off transient of parallel IGBT. The main factors that affect the current balance at switching time are gate driving resistance and speed, external circuit parameters such as emitter stray inductance and temperature of parallel modules [11]-[12].

#### 4.1 Influence of Driving Resistance on IGBT Dynamic Parallel Current Sharing

The turn-on delay time, turn-off delay time, rise delay time and fall delay time in the IGBT switching process are all directly related to the gate drive resistance. Since the drive resistance of each drive circuit cannot be guaranteed to be identical in parallel circuit, it will have an impact on IGBT parallel current sharing. In the simulation circuit shown in figure 2, the driving resistance of IGBT2 is kept...
unchanged at 5Ω, and the driving resistance of IGBT1 is changed to 6Ω, while other circuit parameters are unchanged. The simulation results are shown in figure 5.

![Figure 5](image)

**Figure 5.** Influence of different driving resistance on dynamic parallel current sharing

As can be seen from figure 5, the non-uniform current caused by inconsistent driving resistance mainly acts in the initial phase of the IGBT turn-off transient, at which time IGBT2 acts first, the current drops, IGBT1 current rises, and it bears a large current. The current distribution of IGBT1 and IGBT2 is more balanced in the current drop phase and current tailing phase. Keeping the gate driving resistance of IGBT2 constant at 5Ω and changing the gate driving resistance of IGBT1 in steps of 0.5Ω, the simulation results and calculated non-uniformity are shown in table 2.

| IGBT2 driving resistance (Ω) | IGBT1 driving resistance (Ω) | Turn-off current (A) | unbalance rate α |
|-----------------------------|-----------------------------|----------------------|------------------|
| 5                           | 5                           | 24.865               | 1                |
| 5                           | 5.5                         | 25.964               | 4.42%            |
| 5                           | 6                           | 27.055               | 8.81%            |
| 5                           | 6.5                         | 28.012               | 12.66%           |
| 5                           | 7                           | 28.876               | 16.13%           |
| 5                           | 7.5                         | 33.727               | 35.64%           |
| 5                           | 8                           | 34.649               | 39.35%           |
| 5                           | 8.5                         | 35.549               | 42.97%           |
| 5                           | 9                           | 36.453               | 46.60%           |

According to the data in table 2, the greater the difference in gate driving resistance of parallel IGBT, the greater the impact on the turn-off transient of IGBT. Once the difference in resistance exceeds 30 %, the degree of non-uniform current will expand rapidly, resulting in more serious non-uniform current sharing.

### 4.2 Influence of Driving Speed on IGBT Dynamic Parallel Current Sharing

If the parallel IGBT uses different driving signal sources, the driving signals will be out of sync, which will affect the switching time of IGBT and the dynamic current distribution during parallel connection. In that simulation circuit shown in figure 2, the drive signal of IGBT2 is kept unchanged, and the drive signal of IGBT1 is delayed by 10 %, i.e., 10ns, with other circuit parameter unchanged. The simulation results are shown in figure 6.

![Figure 6](image)

**Figure 6.** Influence of different driving speed on dynamic parallel current sharing
As can be seen from figure 6, the uneven current caused by the inconsistent driving speed mainly acts on the initial phase of the IGBT turn-off transient. At this time, due to the delay of the driving signal of IGBT1, IGBT2 acts first, the current drops, and IGBT1 current rises, bearing a large current. The current distribution of IGBT1 and IGBT2 is more balanced in the current drop phase and current tailing phase. Keeping the driving signal of IGBT2 unchanged and changing the signal delay time of IGBT1 in steps of 5 ns, the simulation results and calculated non-uniformity are shown in table 3.

According to the data in table 3, the greater the drive speed difference of the parallel IGBT drive circuit, the greater the impact on the IGBT turn-off transient process and dynamic current sharing. Therefore, the drive signal of the parallel IGBT should preferably use the same drive circuit. However, when one drive circuit cannot provide enough power to drive multiple IGBTs, it is often necessary to use multiple independent drive circuits. In order to achieve a better current sharing effect, the difference in drive speeds of the independent drive circuits is controlled within 5% according to the simulation results.

| IGBT1 driving speed delay(ns) | IGBT2 driving speed delay(ns) | unbalance rate α |
|-------------------------------|-------------------------------|-----------------|
| 0                             | 24.856                        | 0               |
| 5                             | 26.953                        | 8.44%           |
| 10                            | 29.027                        | 16.78%          |
| 15                            | 32.783                        | 31.89%          |
| 20                            | 37.034                        | 48.99%          |
| 25                            | 36.43                         | 46.56%          |
| 30                            | 38.643                        | 55.47%          |

4.3 Influence of Temperature on IGBT Dynamic Parallel Current Sharing

The dynamic working characteristics of IGBT are greatly influenced by temperature, because the semiconductor physical constants of IGBT and the internal parameters of the device, including carrier migration rate, intrinsic excitation concentration, excess carrier life, threshold voltage and cross-conductivity, will change with the change of temperature, resulting in IGBT shutdown voltage spikes, current trailing time, switching speed and other performance indicators have changed. The difference of the transient process of IGBT at different temperatures is most significant by the life parameters of the internal excess carrier, and the life parameters of the excess carrier increase with the increase of temperature, which will lead to the slow compounding speed of the excess carrier, which causes the IGBT shutdown process to become slow and the current trailing time to be prolonged [13]-[14]. Using the simulation circuit shown in figure 2, the temperature of the IGBT2 is 30℃, the temperature of the set IGBT1 is 60℃, the other circuit parameters remain unchanged, and the simulation results are shown in figure 7.

![Figure 7](image_url)

**Figure 7.** Influence of Temperature on IGBT Dynamic Parallel Current Sharing

As can be seen from figure 7, the uneven flow caused by temperature inconsistency exists in the whole process of shutdown transient, including the initial shutdown stage, current drop stage and current tailing stage, all of which have different degrees of influence. In the initial phase of the
shutdown transient, IGBT2 operates first, the current drops, and IGBT1 current rises, bearing a large current. During the current dropping phase and current tailing phase, IGBT1 receives a large current. Keeping the temperature of IGBT2 unchanged and changing the temperature of IGBT1 in steps of 10°C, the simulation results and calculated non-uniformity are shown in table 4.

| IGBT2 temperature (°C) | IGBT1 temperature (°C) | IGBT1 turn-off current (A) | unbalance rate (α) | Current tailing time(s) |
|------------------------|------------------------|---------------------------|-------------------|------------------------|
| 30                     | 30                     | 24.865                    | 0.00%             | 2.0973u                |
| 30                     | 40                     | 25.176                    | 1.25%             | 2.2079u                |
| 30                     | 50                     | 25.471                    | 2.44%             | 2.3842u                |
| 30                     | 60                     | 26.282                    | 5.70%             | 2.6145u                |
| 30                     | 70                     | 26.932                    | 8.31%             | 2.752u                 |
| 30                     | 80                     | 27.526                    | 10.70%            | 2.9413u                |
| 30                     | 90                     | 28.069                    | 12.89%            | 3.0364u                |
| 30                     | 100                    | 28.569                    | 14.90%            | 3.2378u                |
| 30                     | 110                    | 29.03                     | 16.75%            | 3.38u                  |

From the data in the table 4, it can be seen that the temperature difference within 10°C has little influence on the IGBT switching transient. With the increase of the temperature difference, the degree of non-uniform flow of the parallel two tubes becomes more serious, and the IGBT with low temperature bears a larger current.

4.4 Influence of Emitter Stray Inductance on IGBT Dynamic Parallel Current Sharing

When the current of IGBT collector suddenly changes, the existence of emitter inductance will prevent the current from changing, resulting in an increase in switching time. If the emitter inductance is not controlled, it will lead to non-uniform current of parallel devices. Using the simulation circuit shown in figure 2, the emitter inductance of IGBT2 is kept unchanged at 1u, the emitter inductance of IGBT1 is changed at 1.2u, and other circuit parameters remain unchanged. The simulation results are shown in figure 8.

![Figure 8. Influence of Emitter Stray Inductance on IGBT Dynamic Parallel Current Sharing](image)

As can be seen from figure 8, the non-uniform current caused by the inconsistency of emitter inductance mainly acts on the current falling stage and current tailing stage at the turning-off time, and IGBT1 receives a large current in the current falling stage and current tailing stage. In order to reduce the dynamic non-uniformity, it is necessary to minimize the difference in emitter lead inductance and minimize the emitter lead inductance.

5. Experimental verification

Considering the simulation results, two IGBT parallel experimental circuits as shown in figure 9 are constructed by using the same type and batch of devices, using the same drive signal, selecting the drive resistors with the same resistance, ensuring the same heat dissipation conditions and controlling the emitter inductance as small as possible. The circuit adopts Buck structure, the main bridge arm uses two IGBT modules T1 and T2 connected in parallel, and the diodes T3 and T4 are used as
freewheeling. The BSM50GB60DLC IGBT of EUPEC 600V/50A is selected as the experimental device. The operating voltage Ud is 300V, the duty cycle is 0.5, the switching frequency is 5 kHz, the total load current is 100A, the load resistance R is 1.5 Ohms, and the load inductance L is 0.9 mH. The IGBT turn-off current-sharing waveform obtained from the experimental test is shown in figure 10.

As can be seen from figure 10, after adopting the above parallel connection measures, the current of the two IGBTs can be evenly distributed in the dynamic and static processes, and the dynamic and static current sharing can achieve good results.

6. Conclusion
In this paper, various factors affecting the dynamic and static current sharing effect of IGBT parallel connection are simulated and analyzed, and the effect of on-state voltage drop, driving resistance, switching speed, temperature, emitter inductance and other factors on current sharing is obtained, and an effective solution is proposed. Finally, the effectiveness of the method is verified through experiments, which has practical engineering application value for guiding IGBT parallel connection work.

Acknowledgments
Project supported by Youth Foundation of Wuhan Donghu University(2018dhzk004).

References
[1] Majumdar G, Minato T. Recent and future IGBT evolution[C]// Power Conversion Conference, Nagoya, Japan, 2007:355-359.
[2] Cai Hui, Zhao Rongxiang, Chen Huiming, et al. Study on multiple-frequency IGBT high frequency power supply for induction heating[J]. Proceding of the CSEE, 2006, 26 (2): 154-158 (in Chinese).
[3] Tang Yong, Chen Ming, Wang Bo. Switching Transient Model of Field-Stop IGBT[J]. Proceedings of the CSEE, 2011, 31 (30): 54-60.
[4] N. Y. A. Shammas, R. Withanage, D. Chamund. Review of series and parallel connection of IGBTs[J]. Circuits, Devices and Systems, IEE Proceedings, 2006, 153(1): 34-39
[5] L. M. Selgi, G. Sorrentino, L. Fragapane, et al. Preliminary experimental evaluation on PT-IGBT in parallel connection[C]. European Conference on Power Electronics and Applications, Aalborg, 2008, 1-8
[6] XIN L Y, SUN K K, GONG Z, et al. Current Balancing Design of Paralleled-IGBT in Power Assembly[J]. High Power Converter Technology, 2017(1): 18-23
[7] J. C. Joyce. Current sharing and redistribution in high power IGBT modules[D]. University of Cambridge, 2001
[8] LI H, YANG G, YANG T, et al. Application Research on Parallel-using of 6.5 kV High-voltage IGBT[J]. Electric Drive for Locomotives, 2011(4): 14-16.
[9] R. Letor. Static and dynamic behavior of paralleled IGBTs[J]. IEEE Transactions on Industry Applications, 1992, 28(2): 395-402
[10] Lizama, R. Alvarez, S. Bernet, et al. Static balancing of the collector current of IGBTs connected in parallel[C]. Industrial Electronics Society, IECON 2014 - 40th Annual Conference of the IEEE, Dallas, 2014, 1827-1833
[11] N. Chen, F. Chimento, M. Nawaz, et al. Dynamic characterization of parallel-connected high-power IGBT modules[C]. Energy Conversion Congress and Exposition, Denver, 2013, 4263-4269
[12] U. Schlapbach. Dynamic paralleling problems in IGBT module construction and application[C]. International Conference on Integrated Power Electronics Systems. IEEE, Nuremberg, 2010, 1-7
[13] X. Wang, Z. Zhao, L. Yuan. Current sharing of IGBT modules in parallel with thermal imbalance[C]. Energy Conversion Congress and Exposition, Atlanta, 2010, 2101-2108
[14] LING C,HU A,TANG Y. Research on Temperature Characteristic of IGBT Parallel Connection Dynamic Current Imbalance[J]. Power Electronics,2011(11): 121-123.