# **BOID S POUR Systems** <sup>®</sup> Parallel Operation: Influence of Power Module Parameters

The challenge of IGBT module paralleling is to understand the necessary de-rating of power converters under consideration of different module parameters. This understanding is important for proper module parallel operation inside the thermal and safe operation limits. This article describes the methodology of how to analyze the influence of module parameters on current sharing and switching energy imbalance for parallel operation of power modules.

> By N. Soltau, E. Wiesner, Mitsubishi Electric Europe B.V., Ratingen, Germany Y. Ando, J. Sakai, K. Hatori, Mitsubishi Electric Corporation, Fukuoka, Japan

### Introduction

The current imbalance during module operation can be caused both by the characteristics of the paralleled power modules, such as the different forward voltage and by the design of the power converter itself. The interface of power modules, such as power connection on DC and AC side, the design of gate driver, and the gate driver connection to the power modules, have an influence on static and dynamic current imbalance of modules connected in parallel. An overview of the various factors that influence the performance of the power modules connected in parallel is shown in figure 1.

In the chapters below, the focus is on the analysis of the IGBT and diode characteristics with regard to current imbalance in parallelconnected power modules. For the following analysis, uniform cooling conditions are considered.



*Figure 1: Factors affecting the performance of power modules connected in parallel* 

# **Evaluation Setup and Test Sample**

Each rolling stock manufacturer has its own unique converter design, so it would be difficult for semiconductor manufacturers to make representative power module analysis without standardized test setup. This difficulty was discussed in Horizon 2020 Project "Shift2Rail" [2]. The project members agreed to define a standardized interface between semiconductor supplier and power converter manufacturer to discuss de-rating for power modules. The reference setup is shown in figure 2. One of the goals for reference setup is to reduce the influence of external components on the cur-



Figure 2: Reference test setup for paralleling evaluation

rent imbalance of parallel connected power modules as much as possible. On the DC side, each power module has an individual DClink capacitor; the AC power connection is made via a wide busbar with a central load connection under the modules. Only one central gate driver is used in combination with a low-inductive interface board to control the paralleled modules.

The reference test setup was chosen for investigation of module parallel connection in the following chapters. CM450DA-66X module in the LV100 package is a representative X-Series power module that was selected as device under test for performing the evaluation and analysis. The X-Series line-up with silicon chipset and aluminum base plate is shown in table 1. These power modules feature the latest X-Series 7th Gen. cutting edge chip set with CSTBT™(III) trench IGBT and RFC diode. Both IGBT and diode chips have a positive temperature coefficient for forward voltage over a wide current range. This feature is beneficial for thermal balancing between the parallel connected modules during operation if the temperature is not evenly distributed across the heatsink. The NTC temperature sensor, which is integrated into the module, allows the monitoring of case temperature for each individual parallel connected module. In addition, the dual-power modules of the X-series

Chip	Package / Baseplate	1.7 kV	3.3 kV	4.5 kV	6.5 kV
X-Series (Si)	6 <u>kViso</u> / Aluminium	CM1200DA-34X (1200 A Dual)	CM450DA-66X (450 A Dual) CM600DA-66X (600 A Dual) CM600E1A-66X (600 A Chopper)	-	-
	10 kViso / Aluminium	-	CM450DE-66X (450 A Dual) CM600DE-66X (600 A Dual)	CM450DE-90X (450 A Dual)	CM300DE-130X (300 A Dual) (under feasibility)

Table 1: LV/HV100 X-Series line-up

use a new innovative aluminum base plate with integrated AIN ceramic insulation, the so-called MCB (Metal Casting direct Bonding) baseplate. The new baseplate structure has a significantly smaller junction to case thermal resistance compared to conventional structure, which allows output-power increase or reduction of the operating junction temperature. In addition, Mitsubishi Electric's X-Series power modules offer features for demanding railway application such as high CTI value of housing material, partial discharge measurement, high quality control and traceability.

# Correlation of Power-Module Parameters and Parallel-Switching Waveforms

To investigate the impact of different IGBT power module parameters on the current sharing, parallel connections of ten different pairs of power modules have been measured. Afterwards, linear regression analysis is performed to correlate characteristics of switching waveforms and power-module parameters. Please find more information in [3].

The devices under test are 3.3 kV / 450 A (CM450DA-66X) power modules in the LV100 package. These devices show a natural distribution in their electrical parameters. Hence, collector-emitter saturation voltage ranges from 2.61 V to 2.81 V, gate-emitter threshold voltage ranges from 6.56 V to 7.70 V, and diode forward voltage ranges from 2.20 V to 2.45 V. The ten pairs have been analyzed in terms of their switching characteristics during turn-on, turn-off and reverse recovery.

#### **Turn-Off Switching Analysis**

Figure 3 shows two exemplary turn-off measurement results. When IGBT device parameters are similar, nice current sharing can be achieved. On the contrary, in case of different power module parameters, the load current unequally shares between power modules.

With linear regression analysis of the ten pairs, the correlation between IGBT power module parameters and switching characteristics is determined. It is found that the difference in steady state current  $\Delta I_C$  correlates with the difference in collector-emitter voltage only. Other power module parameters are found to be insignificant (determination coefficient < 95%). Linear regression analysis leads the following relationship for the current imbalance. Please refer to [3] for further details.

$$\frac{\Delta I_C}{I_{Cavg}} \approx -0.56 \, \mathrm{V}^{-1} \cdot \Delta V_{\mathrm{CEsat}} \tag{1}$$

#### **Turn-On Switching Analysis**

Figure 4 shows turn-on switching waveforms with two power modules connected in parallel. If power module parameters are similar, the current will share equally





(a) similar device parameters

Figure 3: Exemplary turn-off waveforms (green: V<sub>GE</sub> 10V/div, blue: I<sub>C1</sub> 150A/div, yellow: I<sub>C2</sub> 150A/div, red: V<sub>CE</sub> 500V/div, 2.0 us/div)



(b) different device parameters

5 µs

2% VCC

*I*C,1 *I*C,2  $\Delta I_{\rm C}$ 

(a) similar device parameters

Figure 4: Exemplary turn-on waveforms (green: V<sub>GE</sub> 10V/div, blue: I<sub>C1</sub> 300A/div, yellow: I<sub>C2</sub> 300A/div, red: V<sub>CE</sub> 500V/div, 2.0 us/div)





(a) similar device parameters



Figure 5: Exemplary reverse-recovery waveforms (blue:  $I_{C1}$  300A/div, yellow:  $I_{C2}$  300A/div, red:  $V_{CE}$  500V/div, 2.0 us/div)

between both power modules. However, when power modules are different, unequal current sharing between power modules is to be expected.

It is found that current sharing correlates with gate-emitter threshold voltage difference  $\Delta V_{GE(th)}$  and difference in forward voltage of the complementary free-wheel diodes  $\Delta V_{EC}$ . Linear regression analysis leads the following relationship for the current imbalance. Please refer to [3] for further details.

$$\frac{\Delta I_C}{I_{\text{Cavg}}} \approx -0.18 \text{ V}^{-1} \cdot \Delta V_{\text{EC}} - 0.18 \text{ V}^{-1} \cdot \Delta V_{\text{GE(th)}}$$
 (2)

#### **Diode Reverse-Recovery Switching**

Exemplary switching results of diode re-

verse recovery are shown in figure 5. Again, the current shares equally between two power modules if the power-module parameters are similar. If the power module parameters are different, differences in the static current and in the peak reverse recovery current becomes visible.

Linear regression analysis shows that the static current sharing correlates solely on difference of diode forward voltages  $\Delta V_{EC}$ . Other power-module parameters are found to be insignificant. The following relationship for the current imbalance is found. Please refer to [3] for further details.

$$\frac{\Delta I_{\rm E}}{I_{\rm Eavg}} \approx -0.78 \, {\rm V}^{-1} \cdot \Delta V_{\rm EC} \tag{3}$$

# **De-rating Calculation up to Six-Times** Paralleling

Based on derating factors for currents and energies, that were derived in previous chapter, the required derating in case of parallel connection of more than two modules can be defined. For this, it will be assumed that one of the paralleled modules has a minimum characteristic (resulting in maximum switching energy or current) while all other modules have the maximum characteristics (leading to minimum switching energy or current). By using the following equation, the derating ratio for the collector current for more than two parallel connected modules can be calculated as an example.

The parameter n is the number of parallel connected modules. The parameter x is the identified imbalance ratio from the measurement of two parallel connected modules (for example  $(\Delta I_C/I_{Cavg}\ according$ to (1) and (2) or  $(\Delta I_E/I_{Eavg})$  according to (3)). As a result, the de-rating dependency on the grouping parameter can be defined as shown in figure 6. The figure already illustrates that confidence intervals, as determined by the regression analysis, become also very helpful regarding the derating ratio of multiple power modules.

The previous analysis shows that if small parameter variation is guaranteed, a small derating ratio and good current sharing is achievable. This is demonstrated by figure 7. It shows switching type test results of a

$$\frac{I_{C,\max}}{I_{C,avg}} - 1 = \frac{I_{C,\max}}{\left((n-1)I_{C,\min} + I_{C,\max}\right)/n} - 1 = \frac{n \cdot I_{C,\max}}{\left((n-1)\frac{1-x}{1+x}I_{C,\max} + I_{C,\max}\right)} - 1 = \frac{n}{\left((n-1)\frac{1-x}{1+x} + 1\right)} - 1$$
(4)



Figure 6: Collector current derating ratio versus forward voltage difference

 $\Delta V_{\text{CEsat}}$ @150°C in V

6-times parallel connection. The current homogenously shares among the six power modules which leads to good balance of losses and optimal utilization of available chip area.

#### Conclusion

This article explains a methodology to investigate the influence of power-module parameters on the switching characteristics of a parallel connection. For each switching type, IGBT turn-off, turn-on and diode reverse recovery, the influence of the different device parameters is investigated. Considering only the significant parameters, a model is provided to calculate differences in switching characteristics on arbitrary device parameters. It is shown how the results are transferred to parallel connection with more than two devices. Finally, homogeneous current sharing between six devices in a parallel connection is confirmed. The switching waveforms proof that with welldesigned converter layout and well-paired LV100 modules ideal current sharing is achieved.

#### References

- [1] T. Wiik, "D1.2, New generation power semiconductor, Common specification for traction and market analysis, technology roadmap, and value cost prediction," Roll2Rail, H2020 - 636032, 2016.
- [2] A. Nagel, J. Weigel, et. al., "Paralleling reference setup," Shift2Rail, Pinta, H2020 - 730668, 2019.
- [3] Y. Ando, J. Sakai, K. Hatori, N. Soltau and E. Wiesner, "Influence of IGBT and Diode Parameters on the Current Sharing and Switching-Waveform Characteristics of Parallel-Connected Power Modules," 2022 24th European Conference on Power Electronics and Applications (EPE'22 ECCE Europe), 2022, pp. 1-11.



#### www.mitsubishielectric.com



# Figure 7: Switching waveforms for 6-times parallel connection (conditions: $V_{cc} = 1800V$ , $I_c = 2700A$ (450A per device), $T_j = 150^{\circ}$ C, $V_{GE} = +15V / -9V$ , $R_{G(on)} = 2.7\Omega$ , $R_{G(off)} = 62\Omega$ , $C_{GE} = 33nF$ )

2700