

High Robustness Operation of 4.5 kV / 1500 A IGBT Modules in a 2-Parallel Configuration for HVDC Submodules

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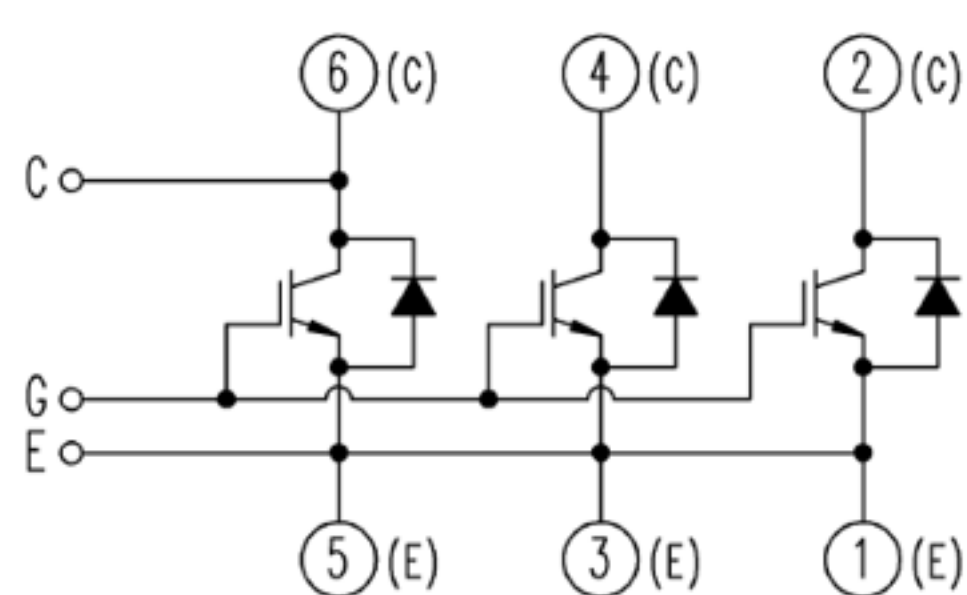
1. Introduction

HVDC systems are shifting to Voltage Source Converter-Modular Multilevel Converter(VSC-MMC) for superior controllability. High-power applications require 2-parallel operation of 4.5 kV modules to handle peak currents exceeding single-device ratings.

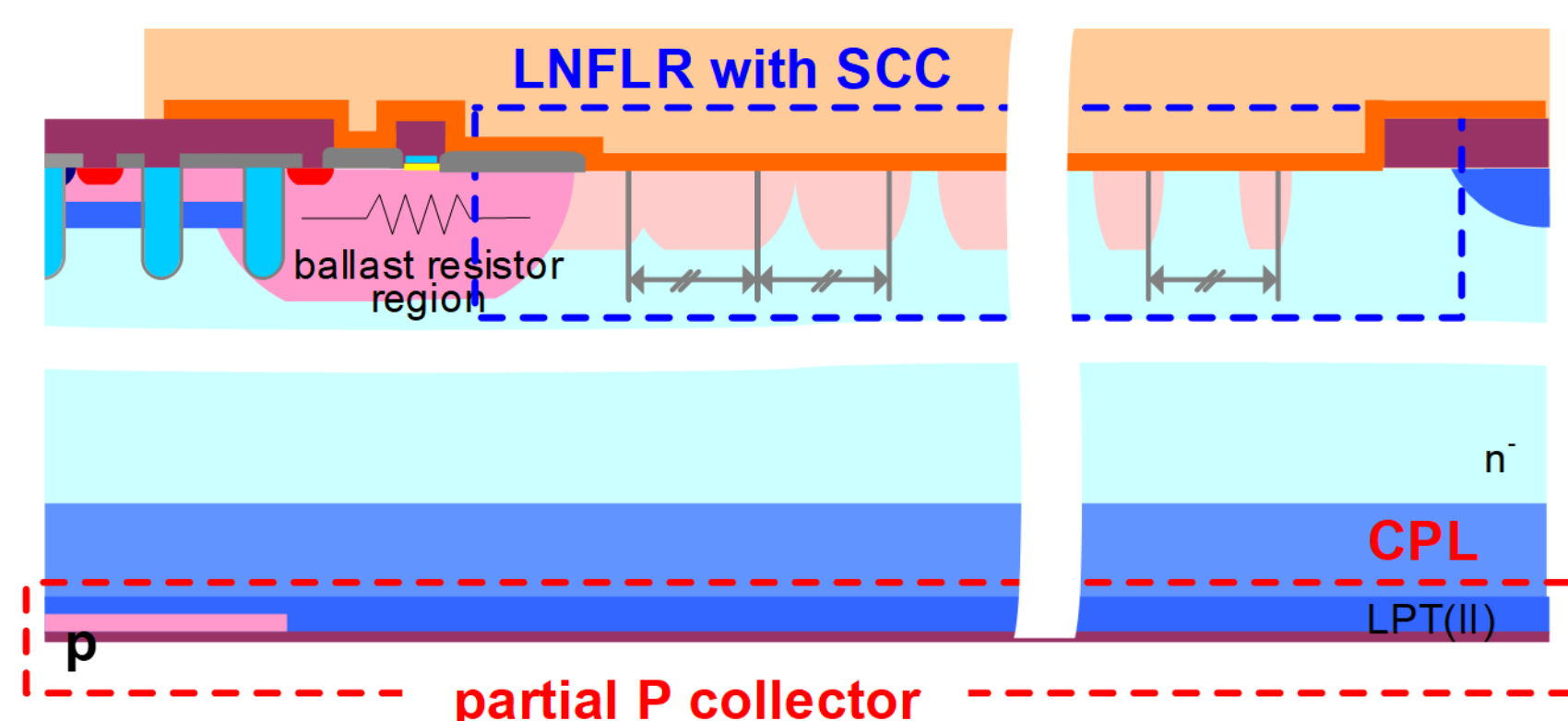
- High Power: 2-parallel 1500 A modules are vital for 3 GW class systems.
- Imbalance Risk: Current sharing variations can lead to localized overstress.
- Robustness Proof: Verifying IGBT module reliability under extreme fault scenarios.

2. Module Specification and Characteristics

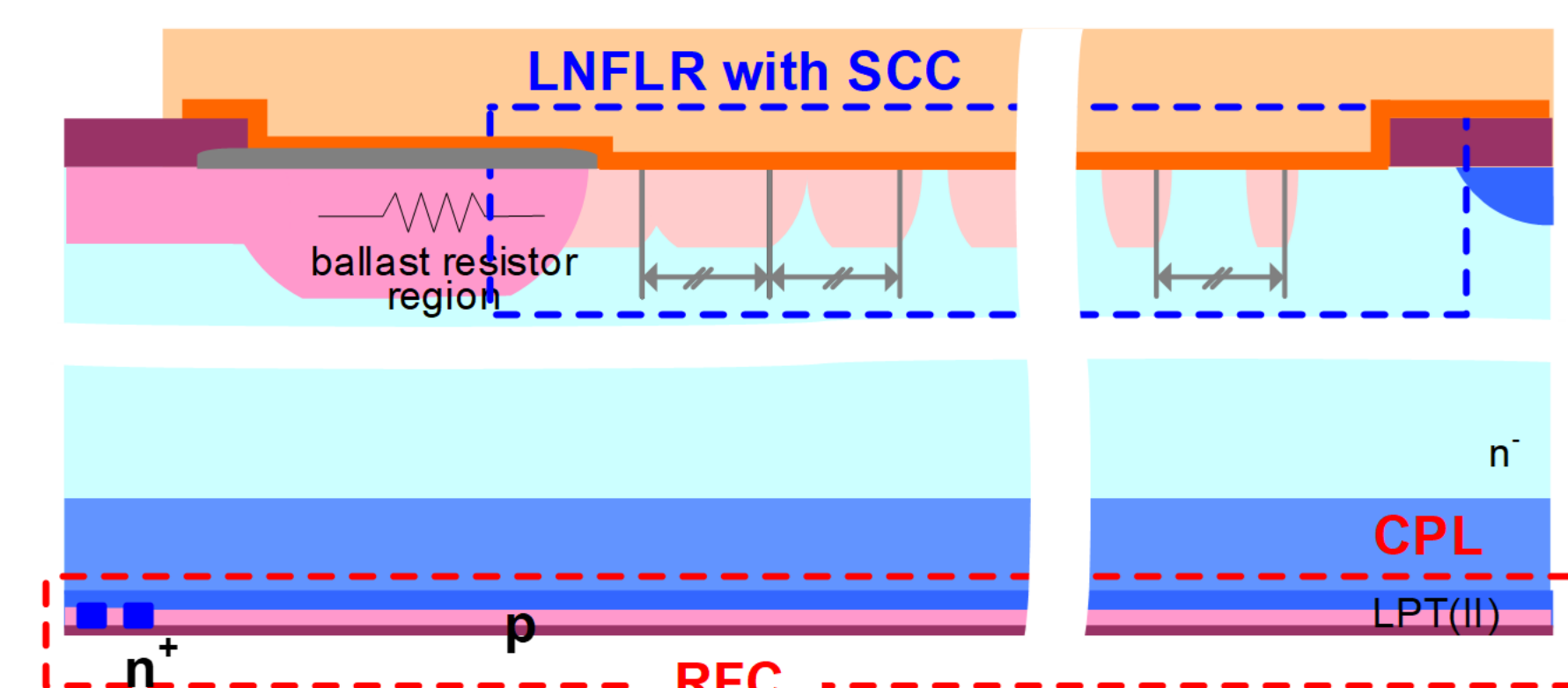
The evaluated module (CM1500HC-90XA) utilizes 7th Gen CSTBT™ and RFC diode technology. Key features include the "Partial P Collector" for wide RBSOA and "Relaxed Field of Capture(RFC) technology" for enhanced RRSOA by preventing carrier starvation.



Evaluated Module / Circuit



The structure of IGBT Chip



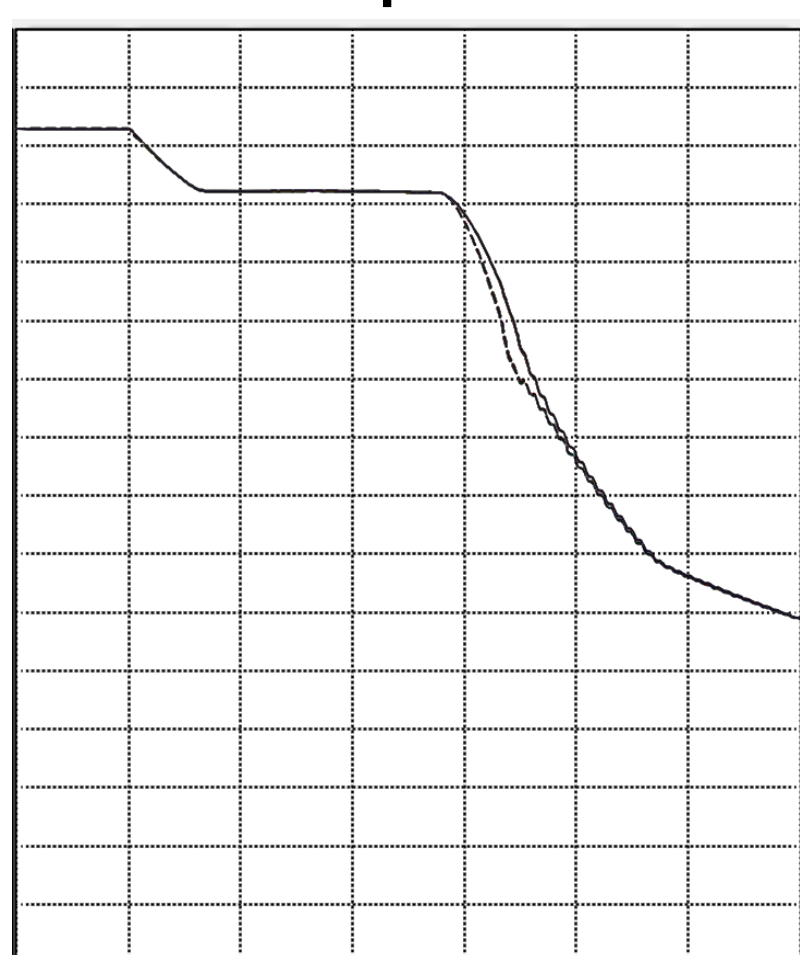
The structure of Diode Chip

3. Current-Sharing Analysis

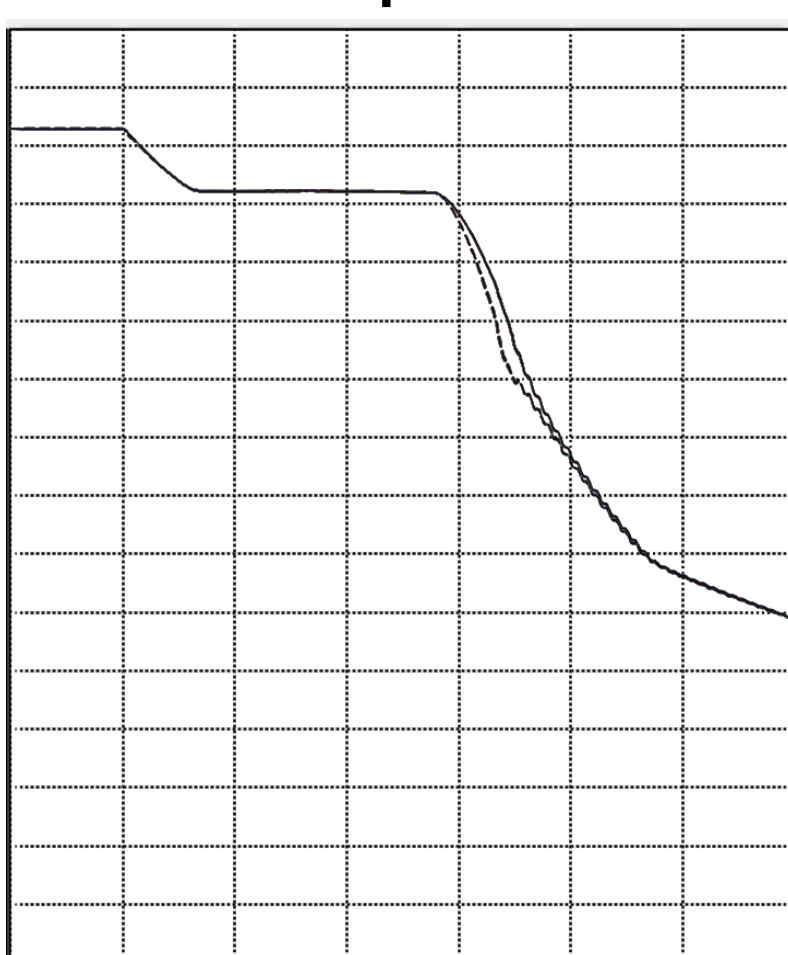
3.1 Internal Module Structure Influence

A high-fidelity simulation model was developed, incorporating parasitic inductance of busbars and wire bonds. The 18 internal chips showed a d_i/d_t within $\pm 10\%$ during turn-off, indicating a well-balanced structural layout that minimizes localized switching stress.

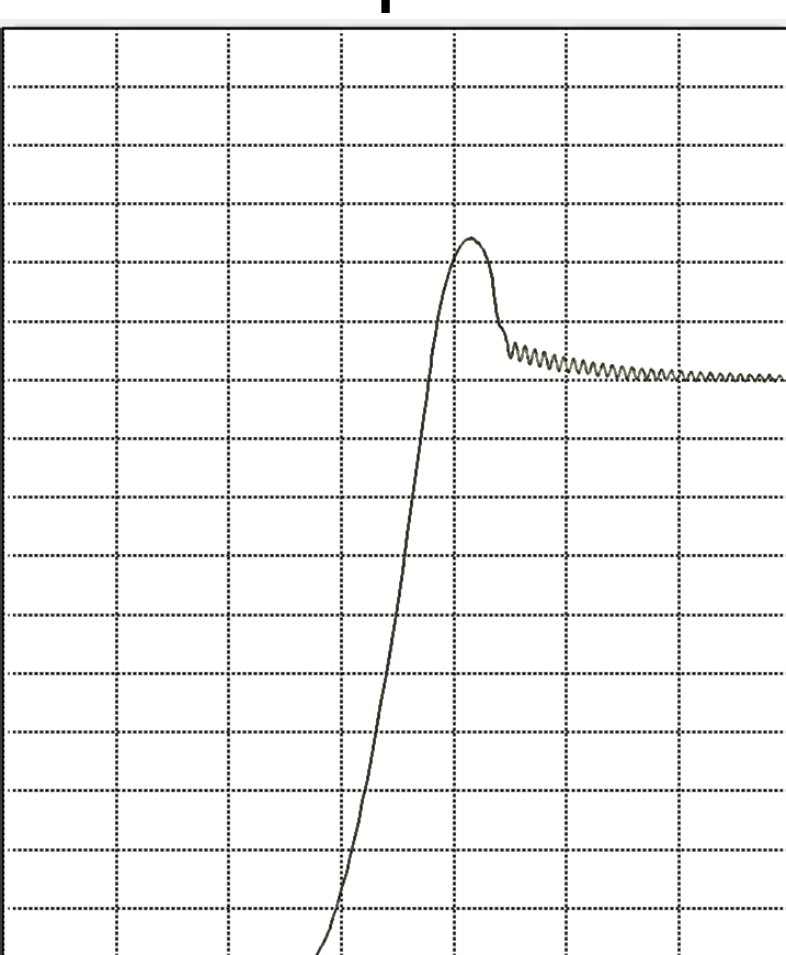
$V_{GE} : 2.5V/div$
Time : $1\mu s/div$



$I_C : 25A/div$
Time : $1\mu s/div$



$V_{CE} : 250V/div$
Time : $1\mu s/div$



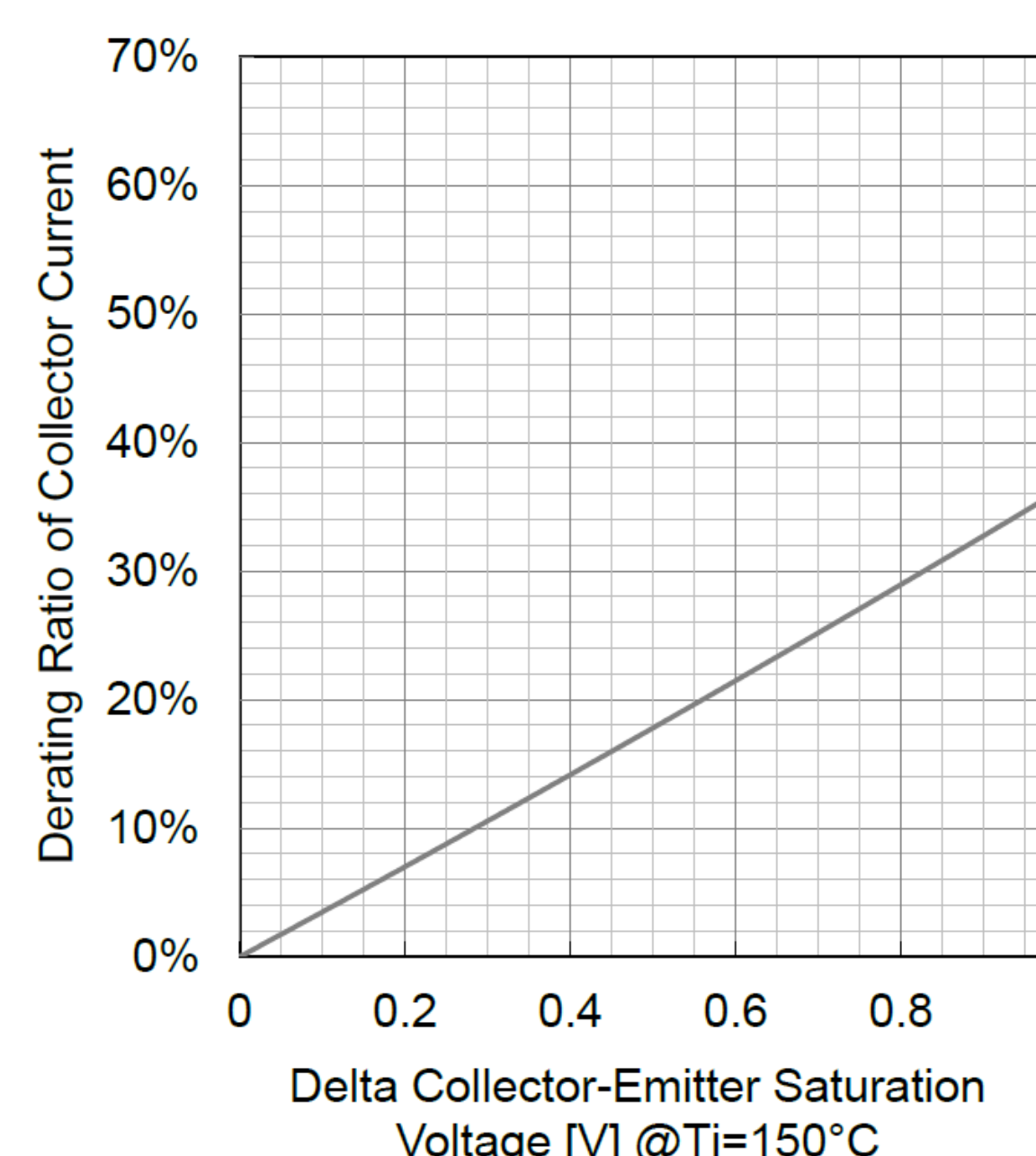
Internal chip(18 chips) current imbalance during turn-off

3.2 Influence of Static Characteristics

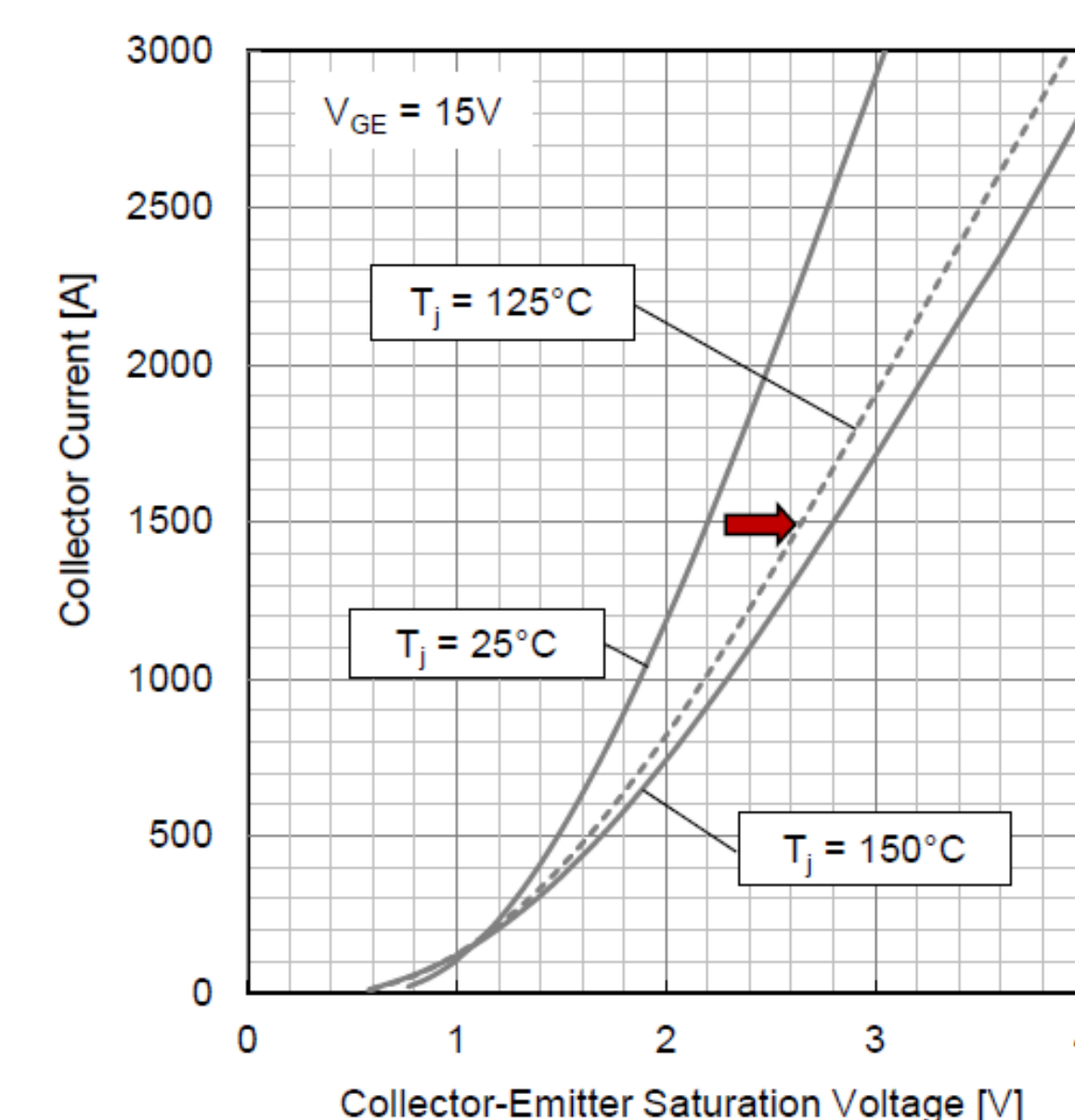
Current sharing is governed by the equality of V_{CE} . A positive temperature coefficient ($\alpha > 0$) provides a critical self-stabilization effect:

$$V_{CEsat}(T_j) = V_{CEsat}(T_{ref}) \cdot [1 + \alpha(T_j - T_{ref})]$$

The module carrying more current heats up, increasing its V_{CEsat} and diverting current to the cooler module, ensuring stable parallel operation.



Delta V_{CEsat} Derating ratio curve



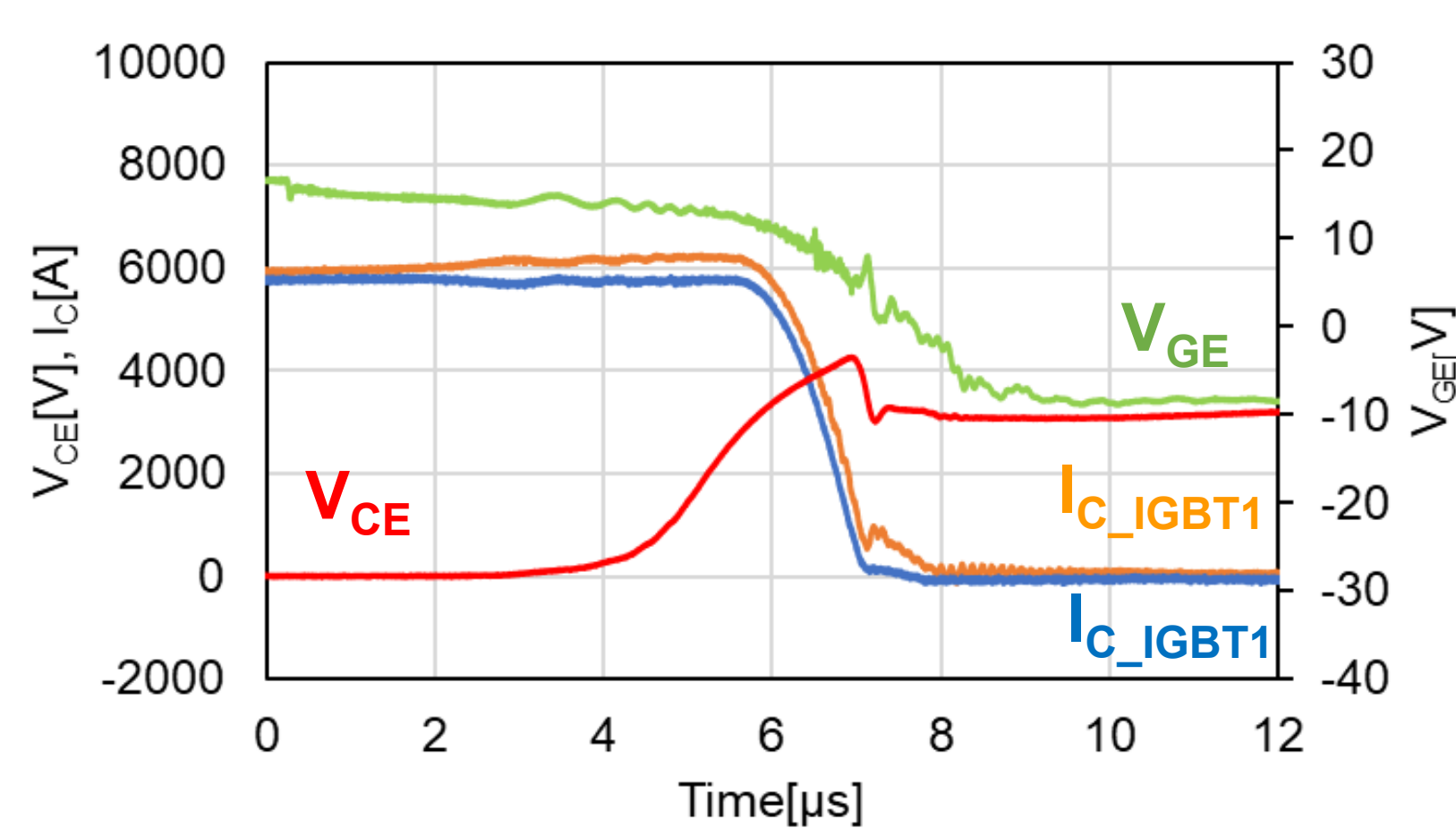
$V_{CE} - I_C$ curve

4. Robustness Assessment and Switching Characteristics

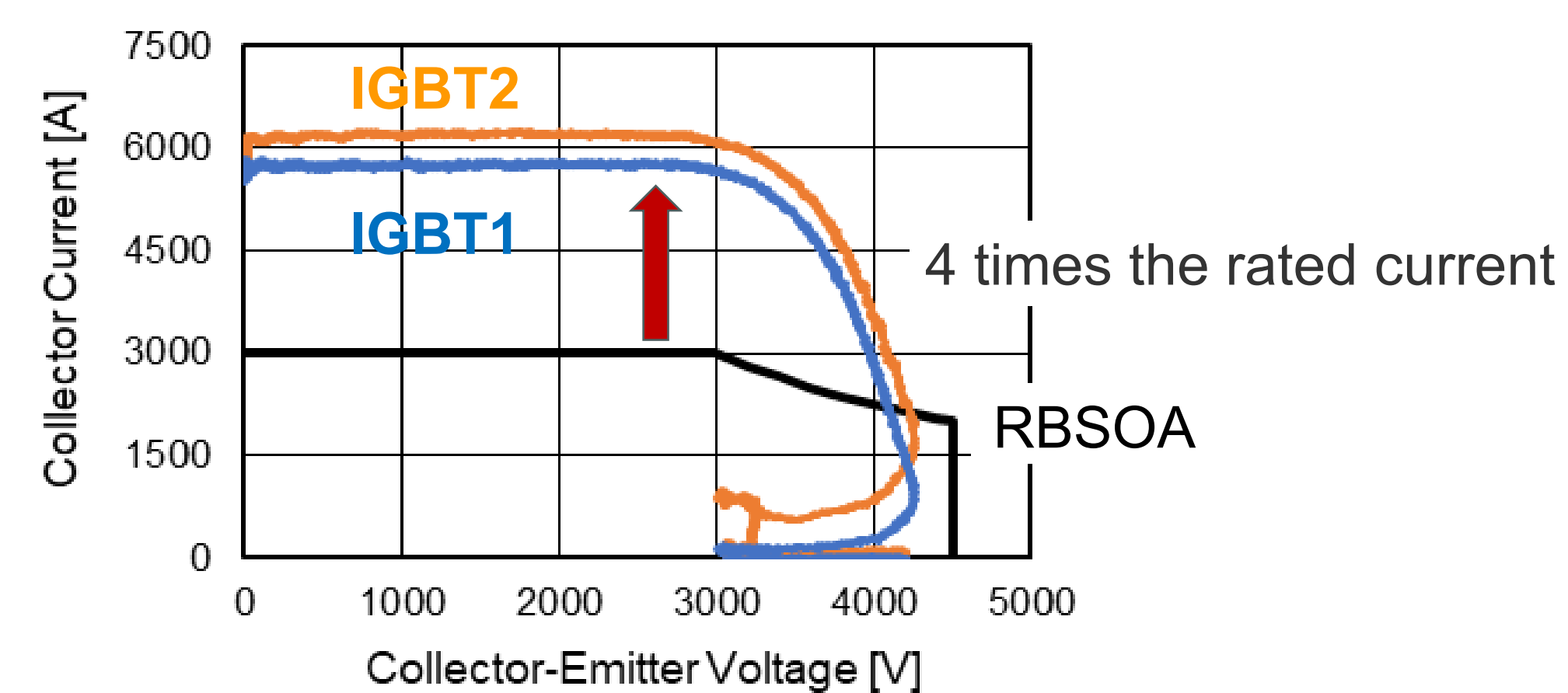
4.1 RBSOA: Dynamic Avalanche Capability

RBSOA is a key indicator of device robustness against dynamic avalanche during high-current interruption. To verify reliability in practical HVDC applications, 2-parallel switching tests were conducted with a total current of 12,000 A (4 times the rated current) at $T_j = 150^\circ\text{C}$.

→ **Successful turn-off at 12,000 A total. The verified 6,000 A per module provides a margin of more than double the expected peak load, ensuring robust system-level protection even under severe fault scenarios.**



RBSOA waveform

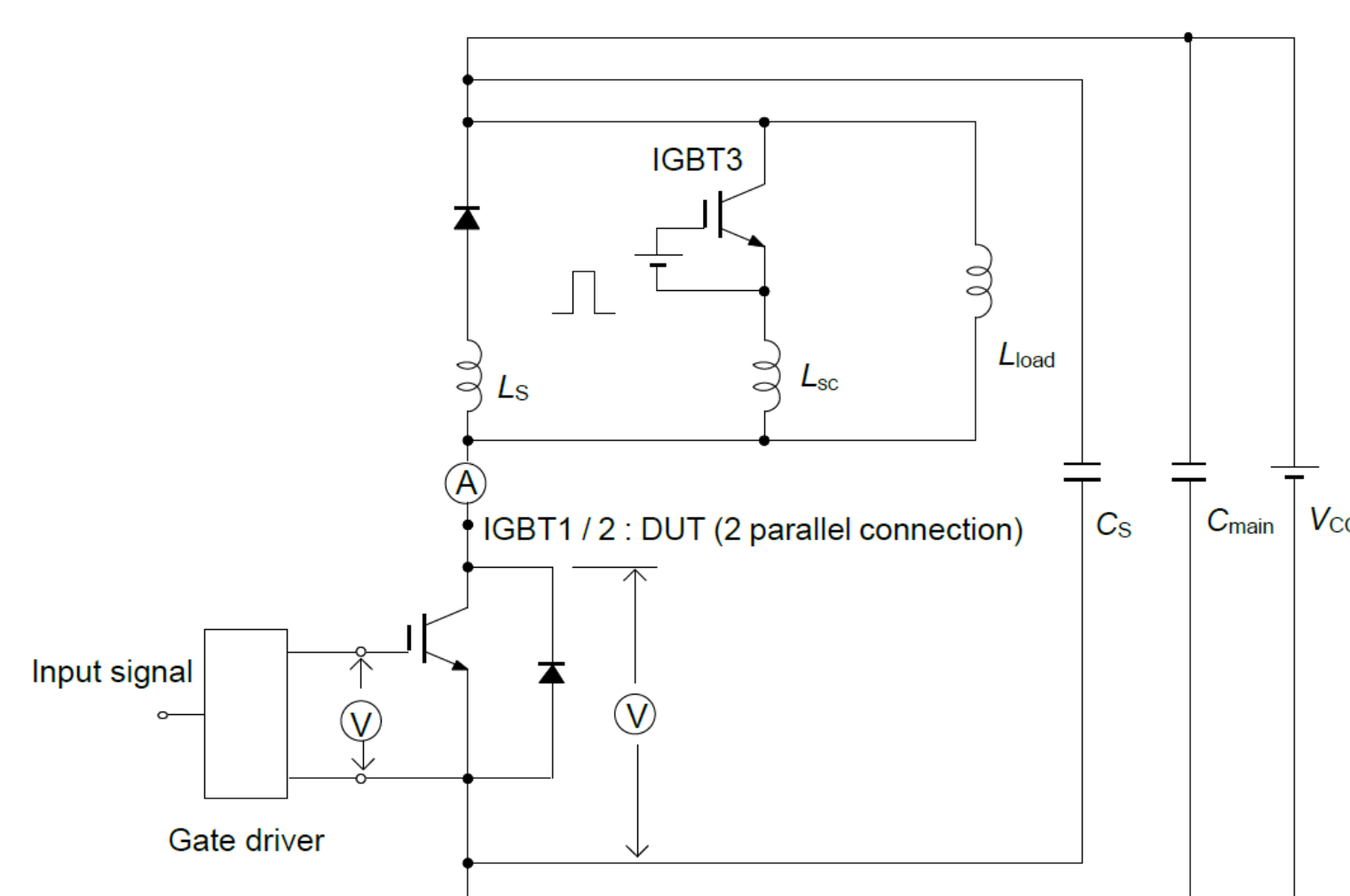


RBSOA I-V plots

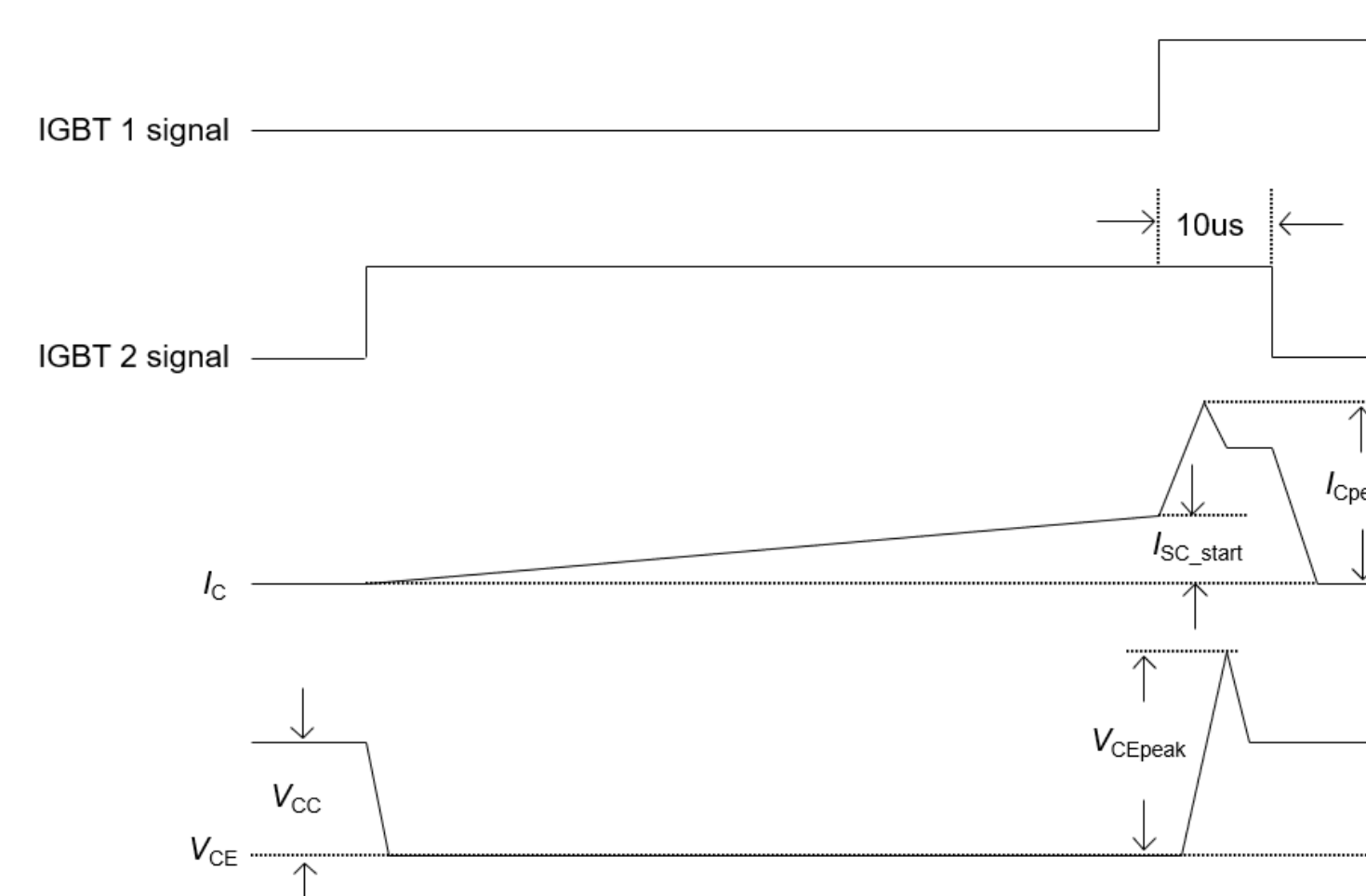
4.2 Short-circuit Type 2: Protection during Conduction

Short-circuit Type 2 simulates a fault during the steady-state ON period. The IGBT naturally limits the fault current through its desaturation characteristic.

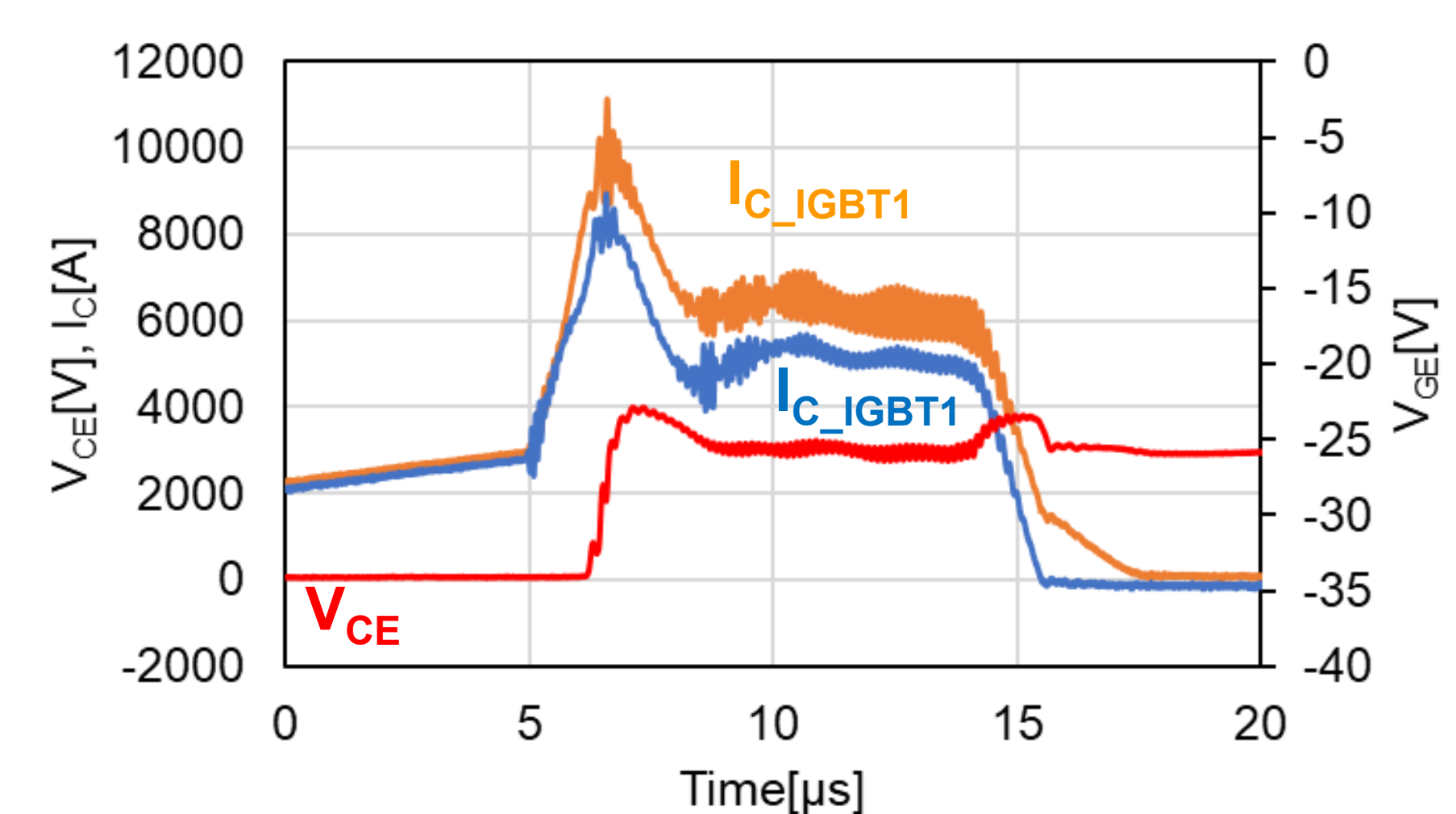
→ **Parallel-connected modules successfully suppressed the fault current and safely executed turn-off at $V_{CC} = 3000\text{ V}$ without any destructive failure. This confirms superior robustness and reliable self-protection even under high-voltage fault conditions.**



Short-circuit type 2 circuit diagram



Short-circuit type 2 pulse sequence

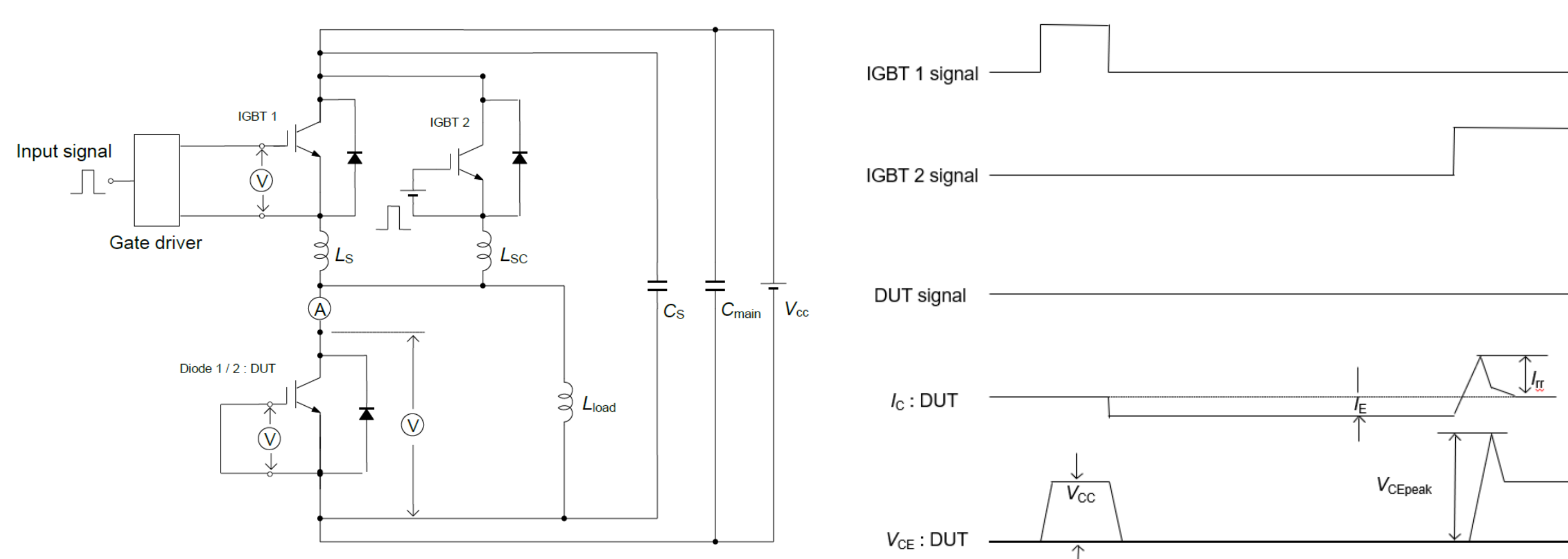


Short-circuit type 2 waveform

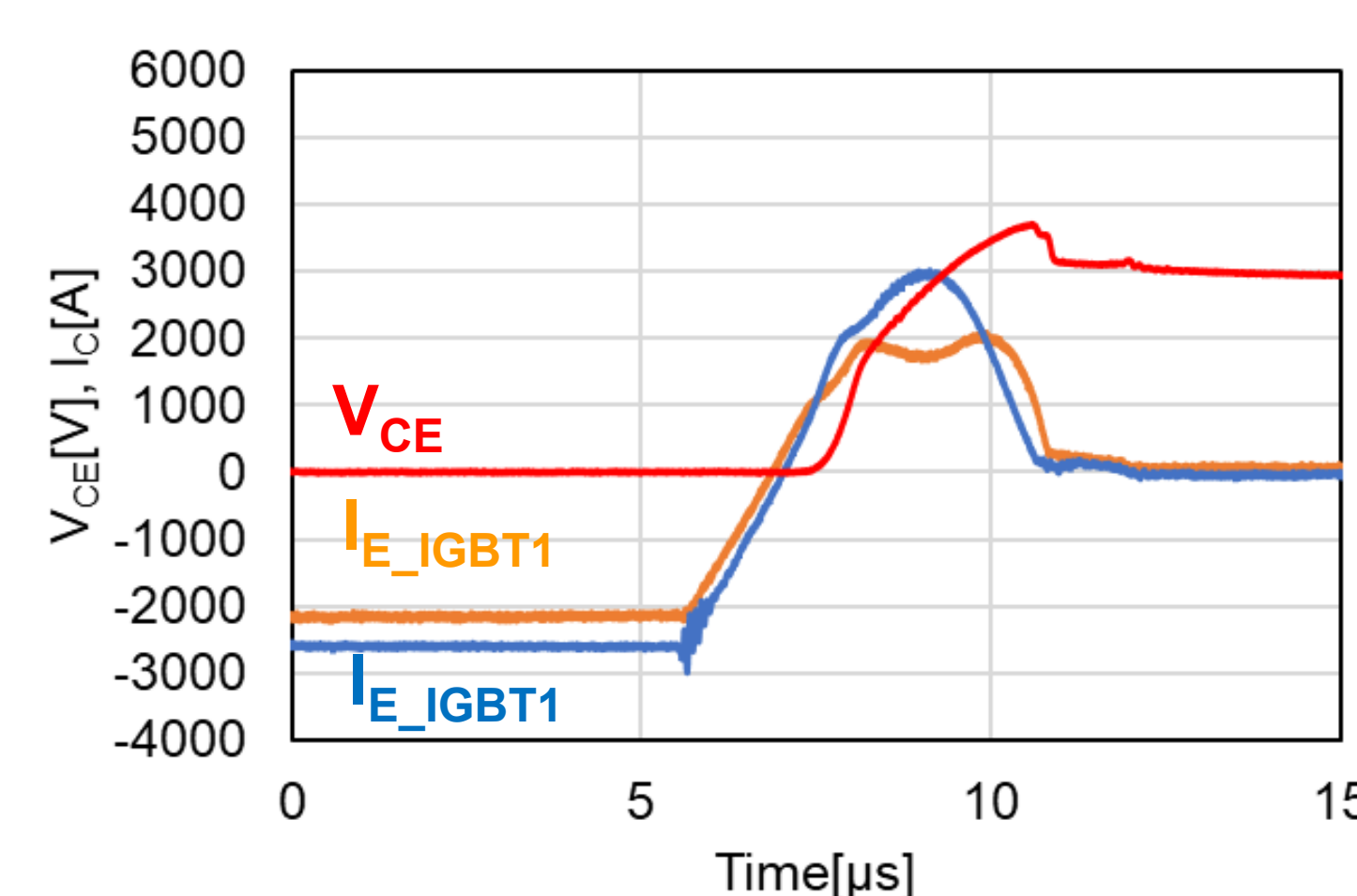
4.3 Short-circuit Type 4: Turn-on into Short-circuit

This is one of the most severe stress events, combining high di/dt at turn-on with intense peak reverse recovery power (P_{rr}) in the diode. The RFC diode technology incorporates a unique back-side structure that provides moderate hole injection during the tail period, effectively preventing "carrier starvation." The experimental results confirmed a P_{rr} of 8.7 MW in 2-parallel configuration.

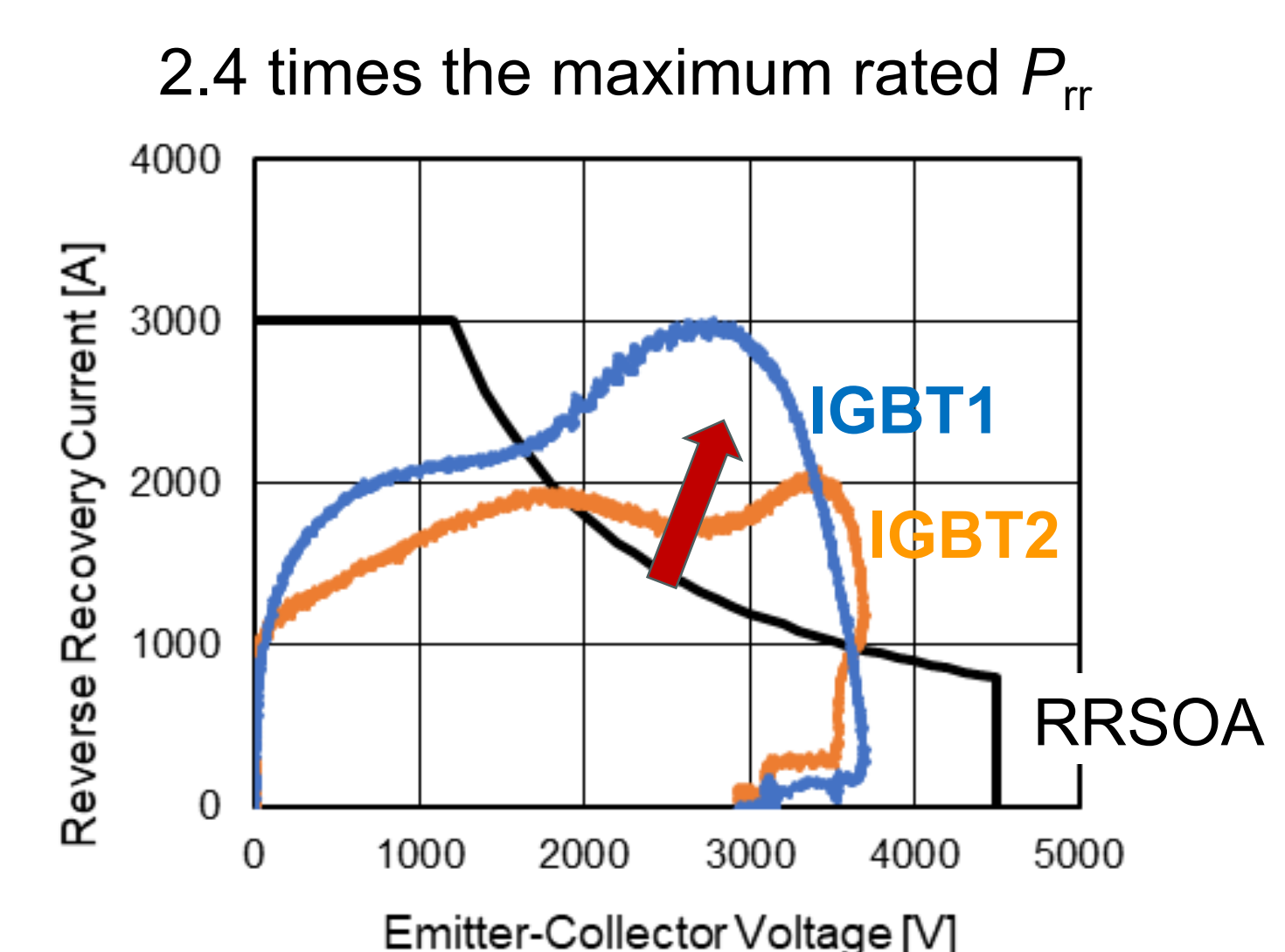
→ **Peak P_{rr} reached 8.7 MW, which is 2.4 times the maximum rating (3.6 MW). This demonstrates an exceptional safety margin for HVDC protection.**



Short-circuit type 4 circuit diagram & Pulse sequence



Short-circuit type 4 waveform



RRSOA I-V plots

5. Conclusion

- Robustness assessment of two 4.5 kV / 1500 A IGBT modules in parallel confirmed uniform current sharing (within $\pm 10\%$).
- Verified safety margins: 12,000 A RBSOA interruption and 8.7 MW Short-circuit Type 4 P_{rr} (2.4x the rating).
- IGBT modules enable a simplified and robust protection design for MMC-based VSC systems, reducing device screening needs.
- The 2-parallel operation is proven to be a reliable and robust solution for demanding HVDC applications.