

System-Level Short-Circuit Failure Mechanisms of IPMs in Practical Motor-Drive Applications ①

Yu-Quan Su, Shao-Nan Wang, Hao Lan

Semiconductor Technologies Co., Ltd., China

StarPower Semiconductor Ltd., China

Abstract

To evaluate the short-circuit (SC) reliability of high-density intelligent power modules (IPMs) in appliance motor drives, this paper investigates the system-level transient behaviors and failure mechanisms under P-to-phase and phase-to-phase SC conditions using a practical 1.5-HP air-conditioner test platform. Experimental results show that under P-to-phase Type II SC, the gate voltage elevation induced by the Miller effect creates a positive feedback loop, drastically amplifying the peak SC current. Post-protection, the energy stored in line parasitic inductances forces a freewheeling path, leading to catastrophic thermal destruction of the internal freewheeling diode (FRD). Under phase-to-phase SC, dominated by the negative feedback from the low-side emitter parasitic inductance, the DC bus voltage exhibits a highly asymmetric dynamic redistribution, forcing the low-side IGBT to sustain the majority of the voltage stress. Finally, design guidelines indicate that next-generation IPMs must optimize both the IGBT short-circuit capability under elevated gate voltages and the transient current robustness of internal FRDs. This study provides practical insights for highly reliable IPM optimization and system-level protection.

System-Level Test Platform

An SC test platform was constructed based on an actual air-conditioner variable-frequency control board and the complete appliance to evaluate the SC failure characteristics of IPMs under realistic motor-drive conditions. This platform is capable of reproducing SC conditions, such as P-to-phase and phase-to-phase, through physical wiring connections.

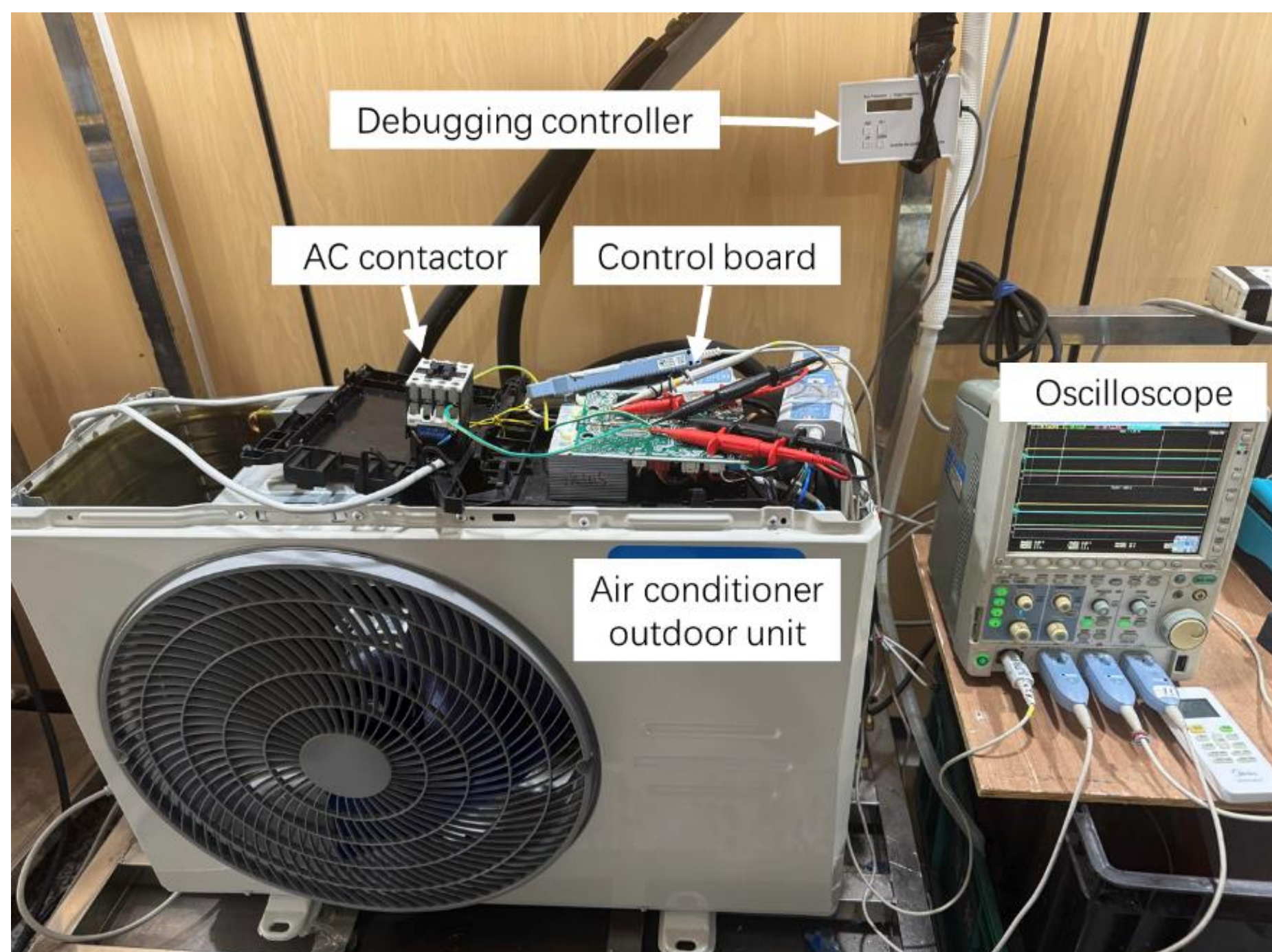


Fig. 1-a The test platform employs a commercial air-conditioner variable-frequency control board running a sensorless Field-Oriented Control (FOC) algorithm to simulate actual working condition prior to the SC event.

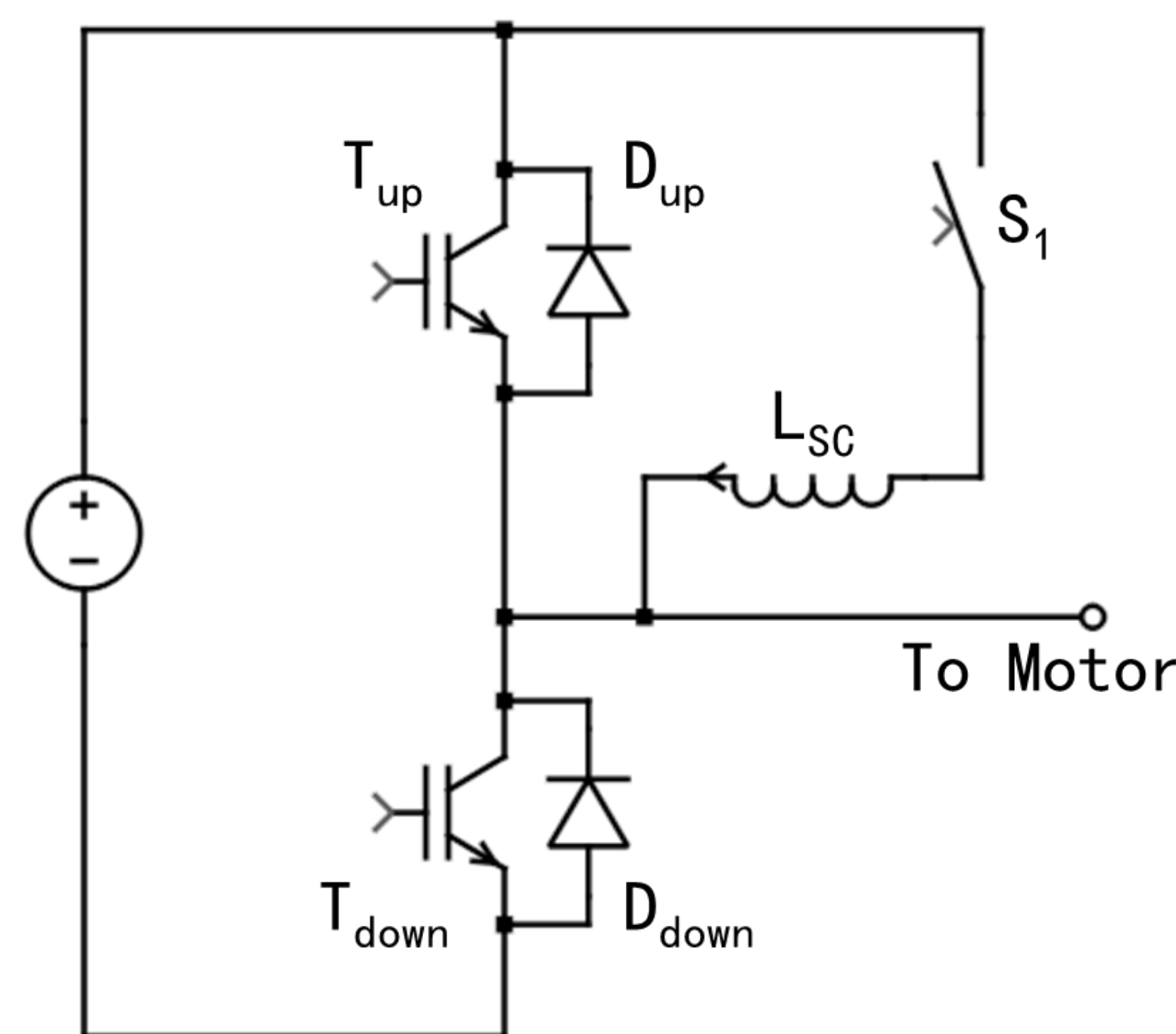


Fig. 1-b Circuit topology of P-to phase SC experiment. The shorting contactor is connected between the bus and one phase output line of the inverter, with the line's parasitic inductance denoted as L_{sc} .

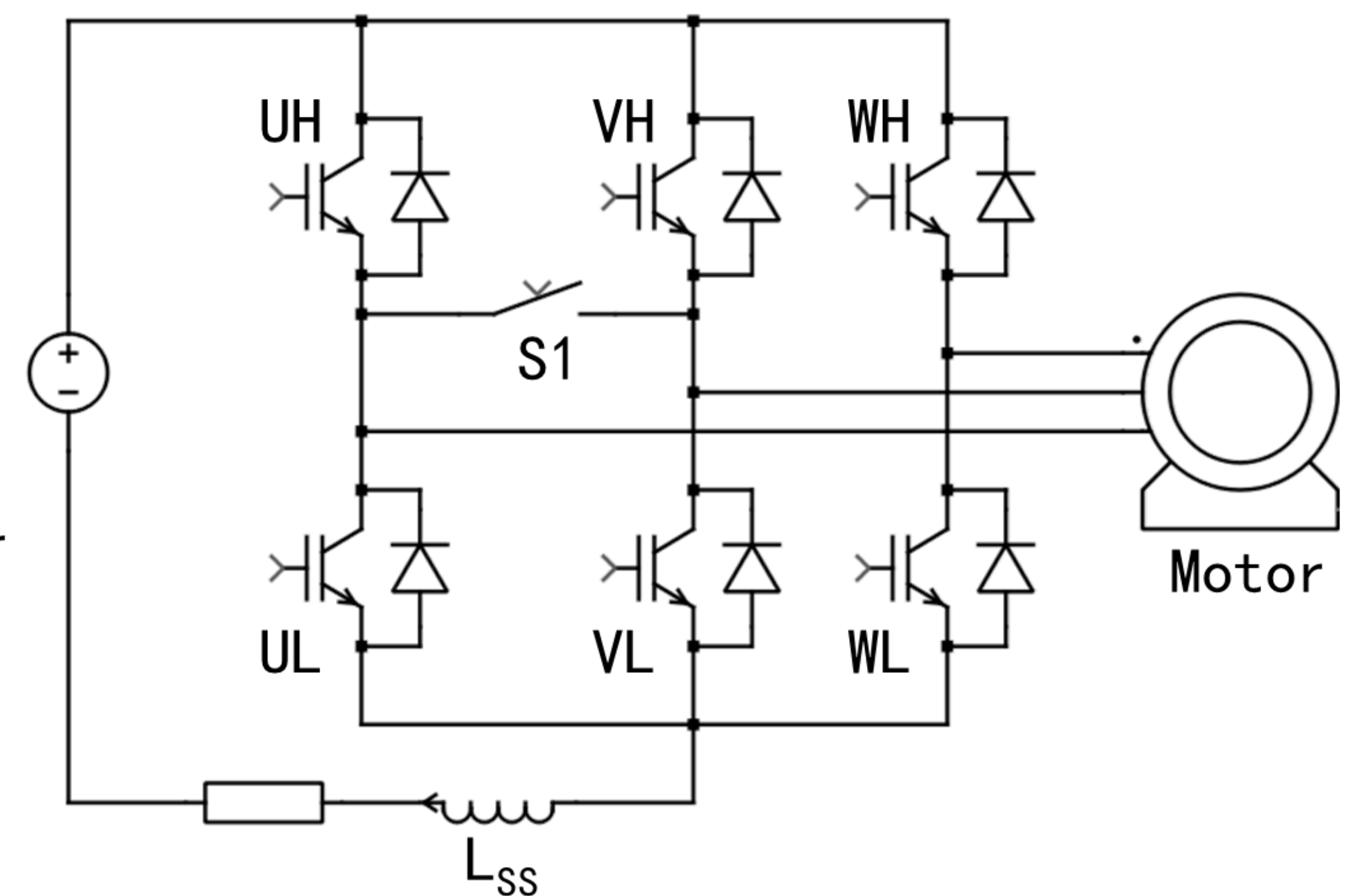


Fig. 1-c Circuit topology of phase-to phase SC experiment. The shorting contactor is connected between the U phase and V phase, simulating an SC current flowing through the VH and UL IGBTs.

P-to-Phase SC Behavior

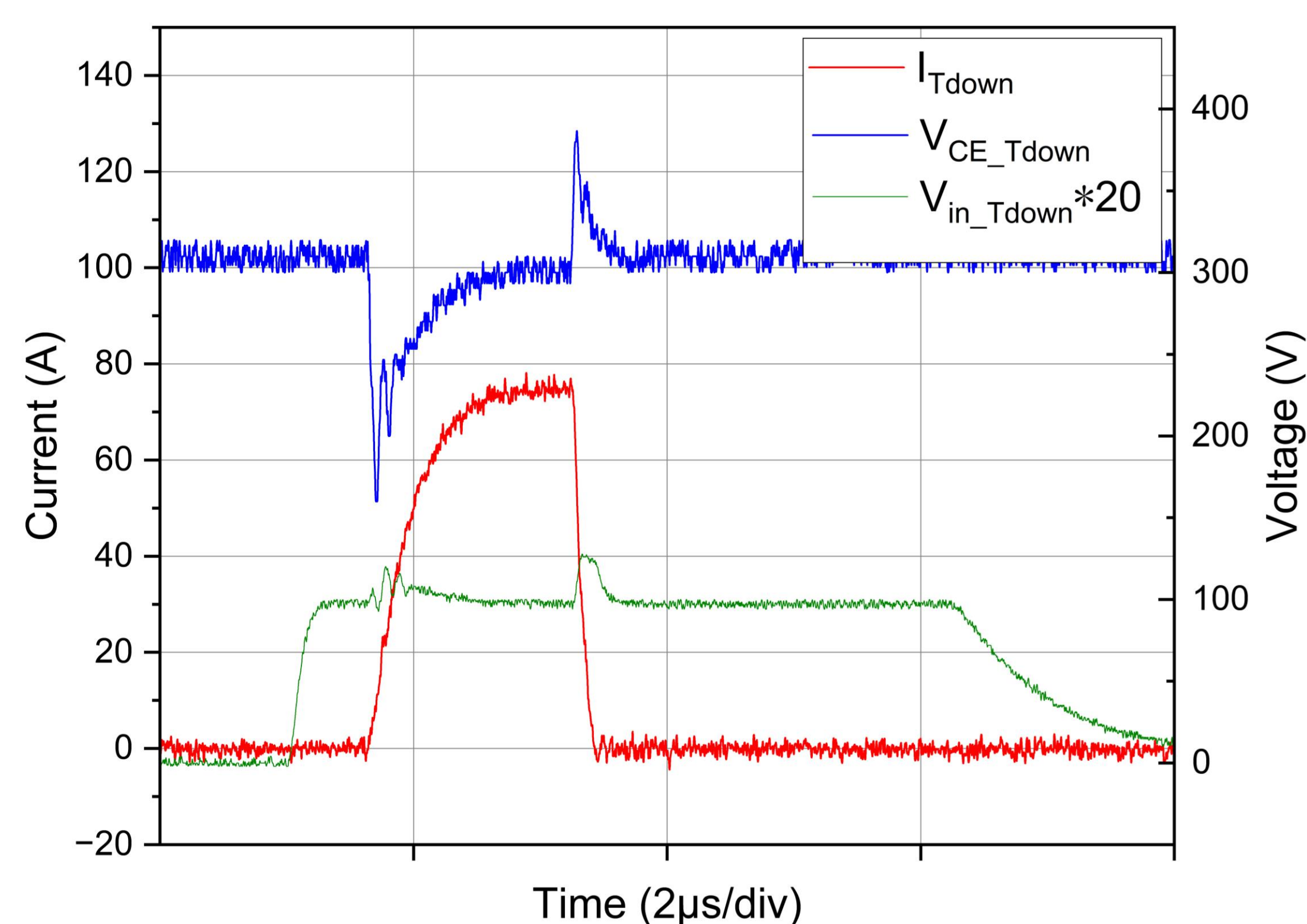


Fig. 2-a P-to Phase SC I waveform. The low-side IGBT is in the off-state when the SC occurs. Subsequently, the control system issues a normal PWM drive signal, and the device turns on while bearing the full DC bus voltage.

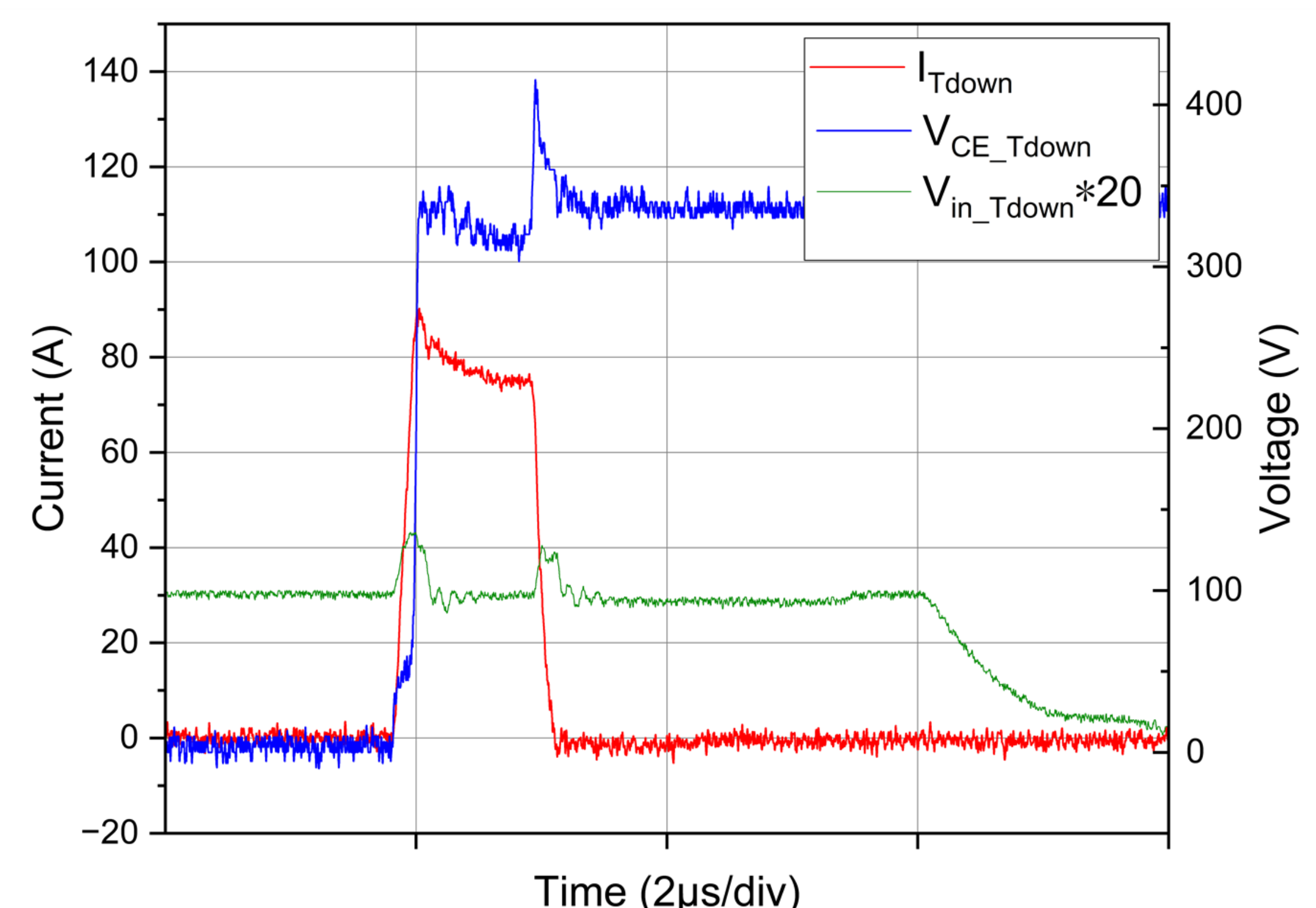


Fig. 2-b P-to-Phase SC II waveform. When the low-side IGBT is already in the on-state and carrying a normal inductive load current, the phase output terminal is suddenly shorted to the positive power supply. The high dV_{ce}/dt transient couples a massive displacement current (I_{CG}) through the internal collector-gate Miller capacitance (C_{CG}), which consequently causes an abnormal elevation of V_{GE} and large I_{sc} .

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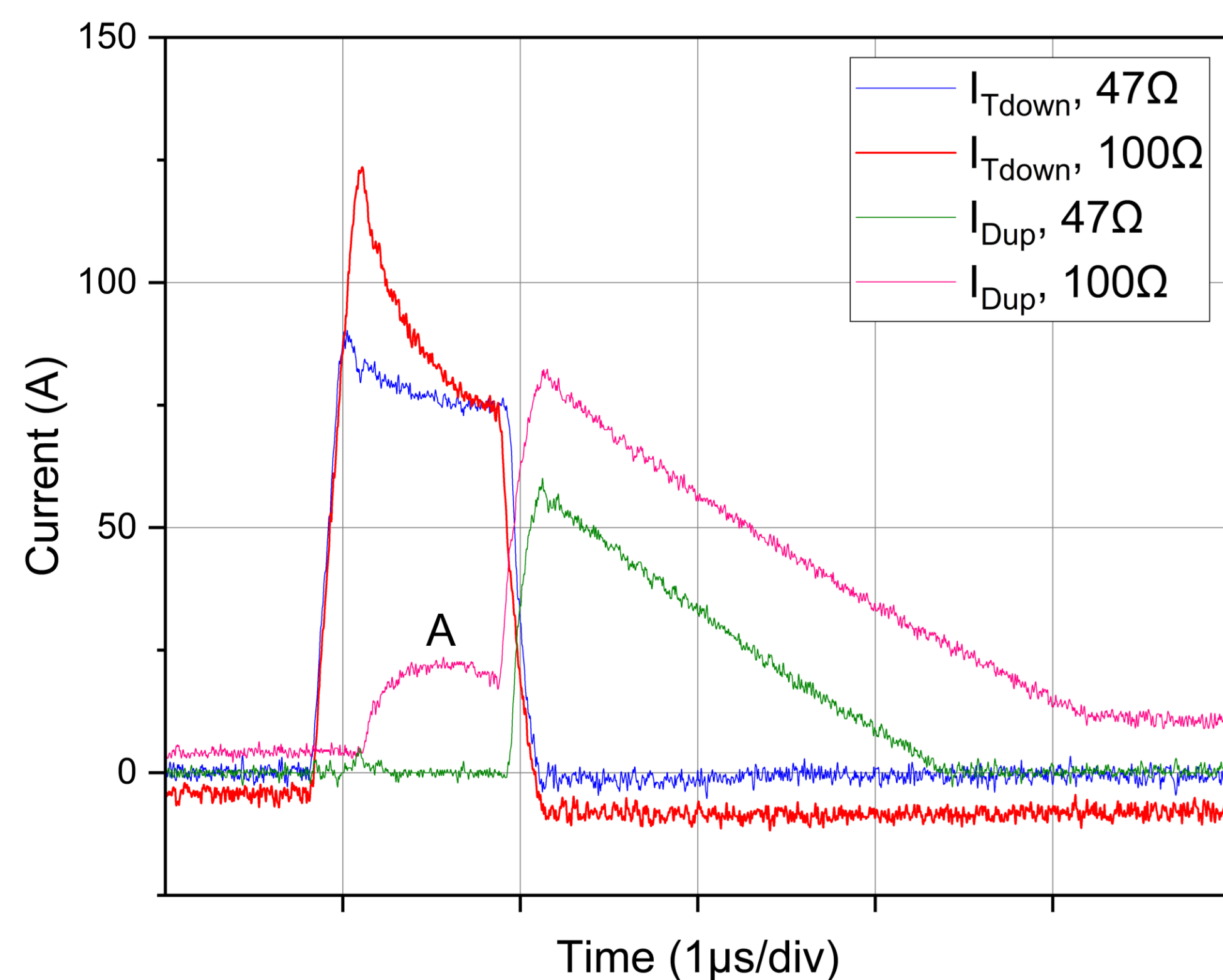


Fig. 3-a SCII waveform showing high side FRD and low side IGBT current under different R_g . When $R_g = 100 \Omega$, a significant current already flows through the high-side FRD while the low-side IGBT is still in the SC conduction state (point A in the figure).

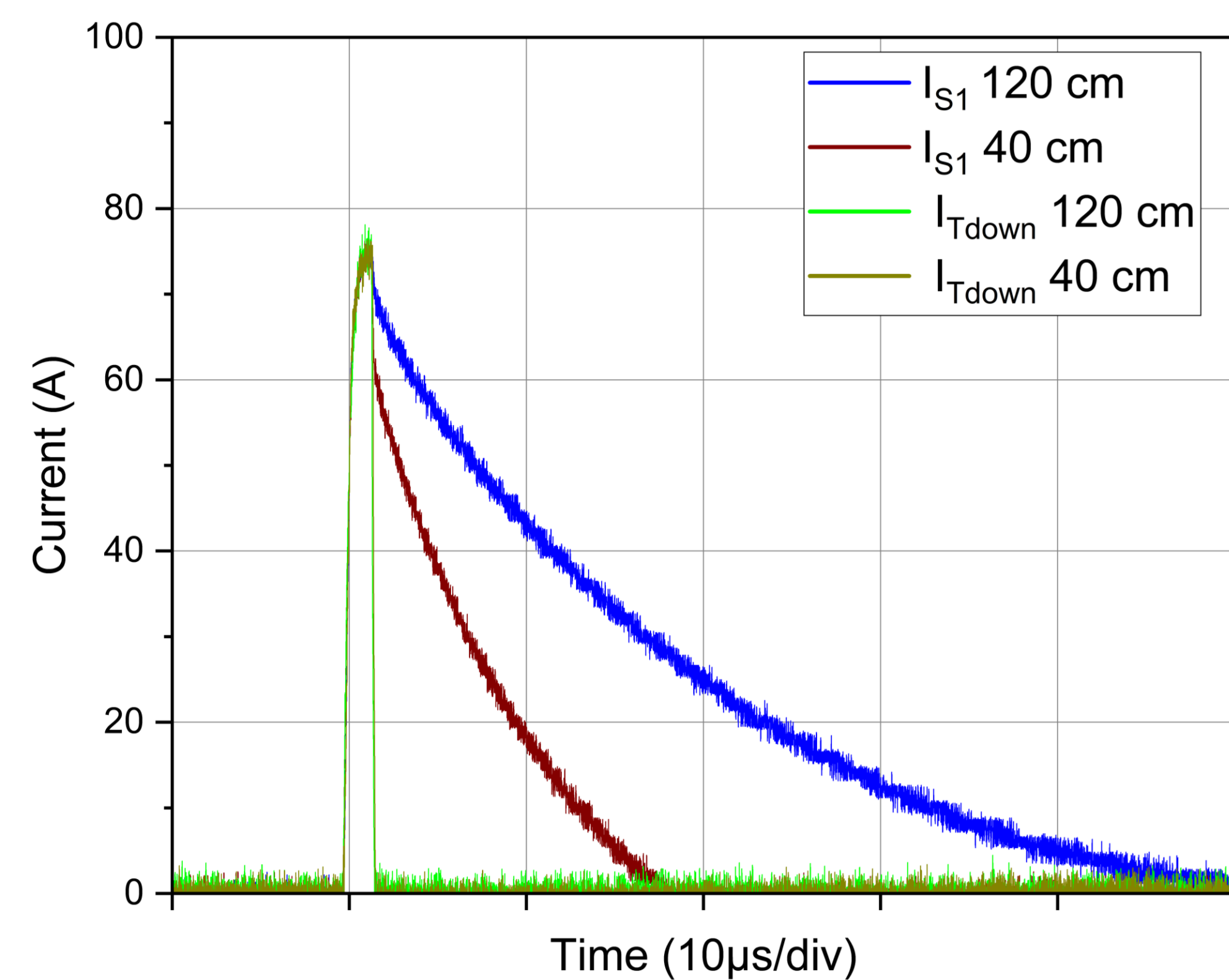


Fig. 3-b Comparison of SC current waveform under different SC line length. The experimental group with the longer wire exhibits a larger current and a longer conduction duration. During this process, the high-side diode endures immense current stress.

Phase-to-Phase SC Behavior

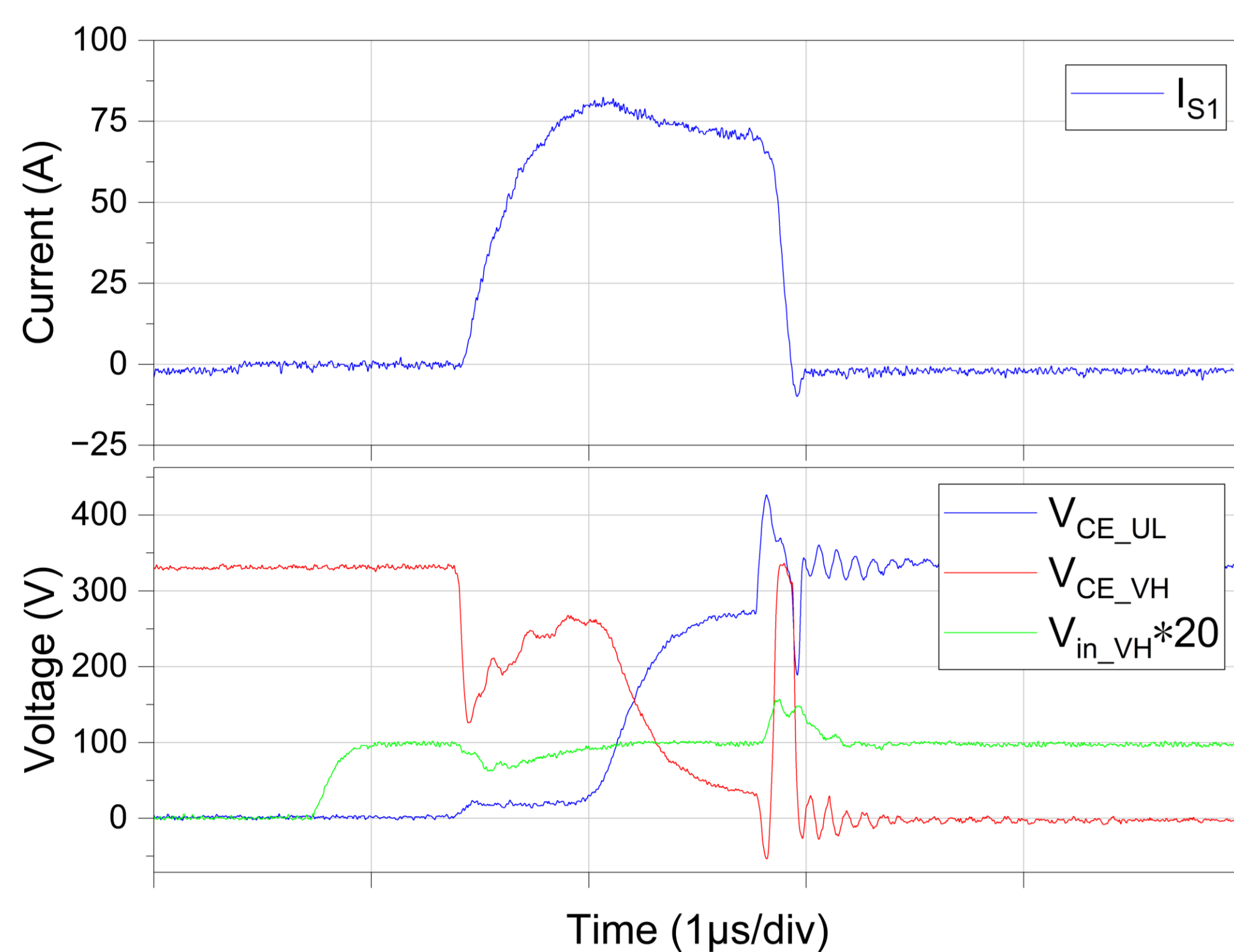


Fig. 4-a High-side IGBT SC I in phase to phase SC. the voltages across the high- and low-side devices alternate during the SC process.

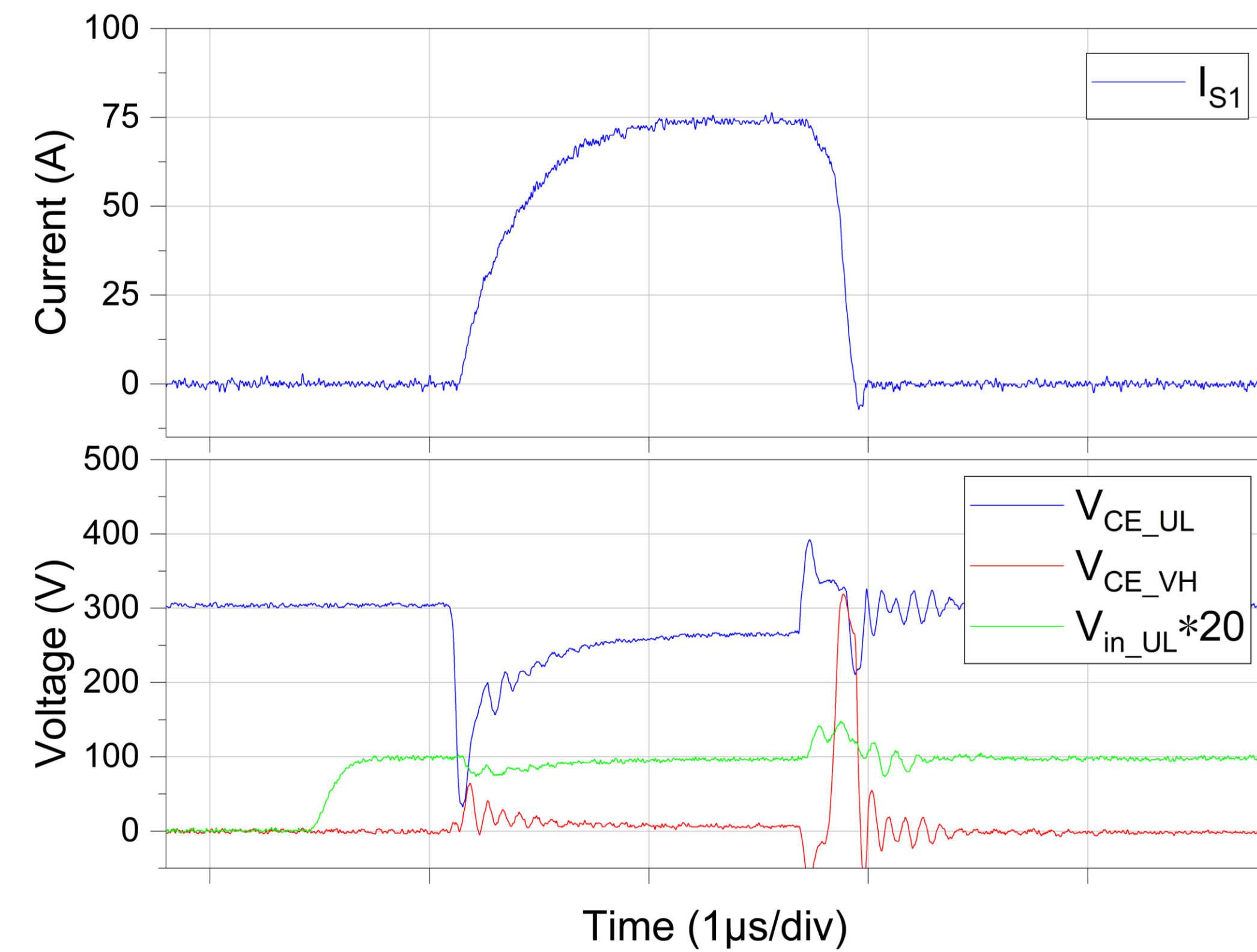


Fig. 4-b low-side IGBT SC I in phase to phase SC. The low-side continuously sustains a high volt-age

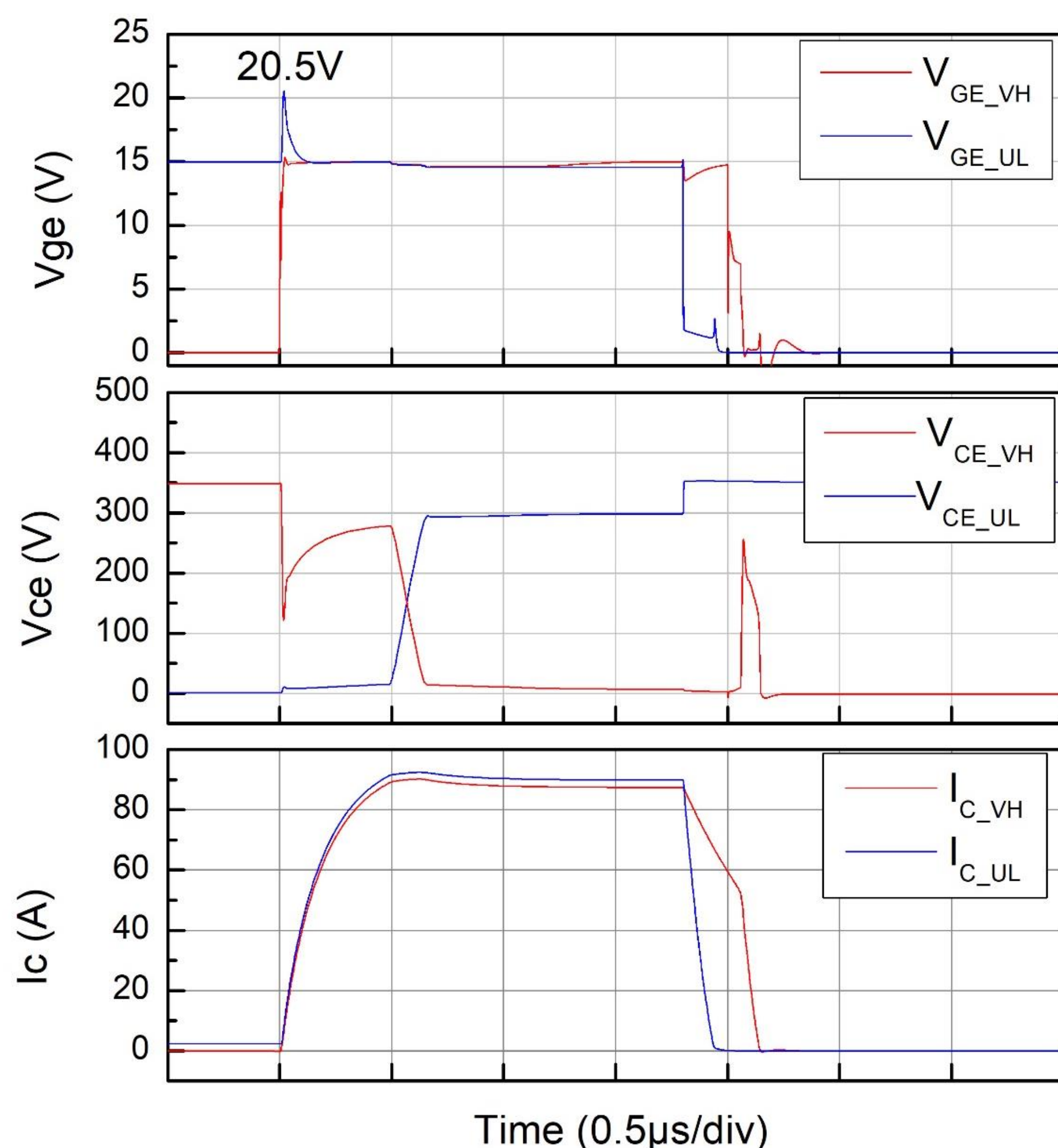


Fig. 5-a Phase to phase high-side SC I simulation. The V_{GE_UL} elevation is suppressed by L_{SS} , leading to V_{CE} alternation during the SC process.

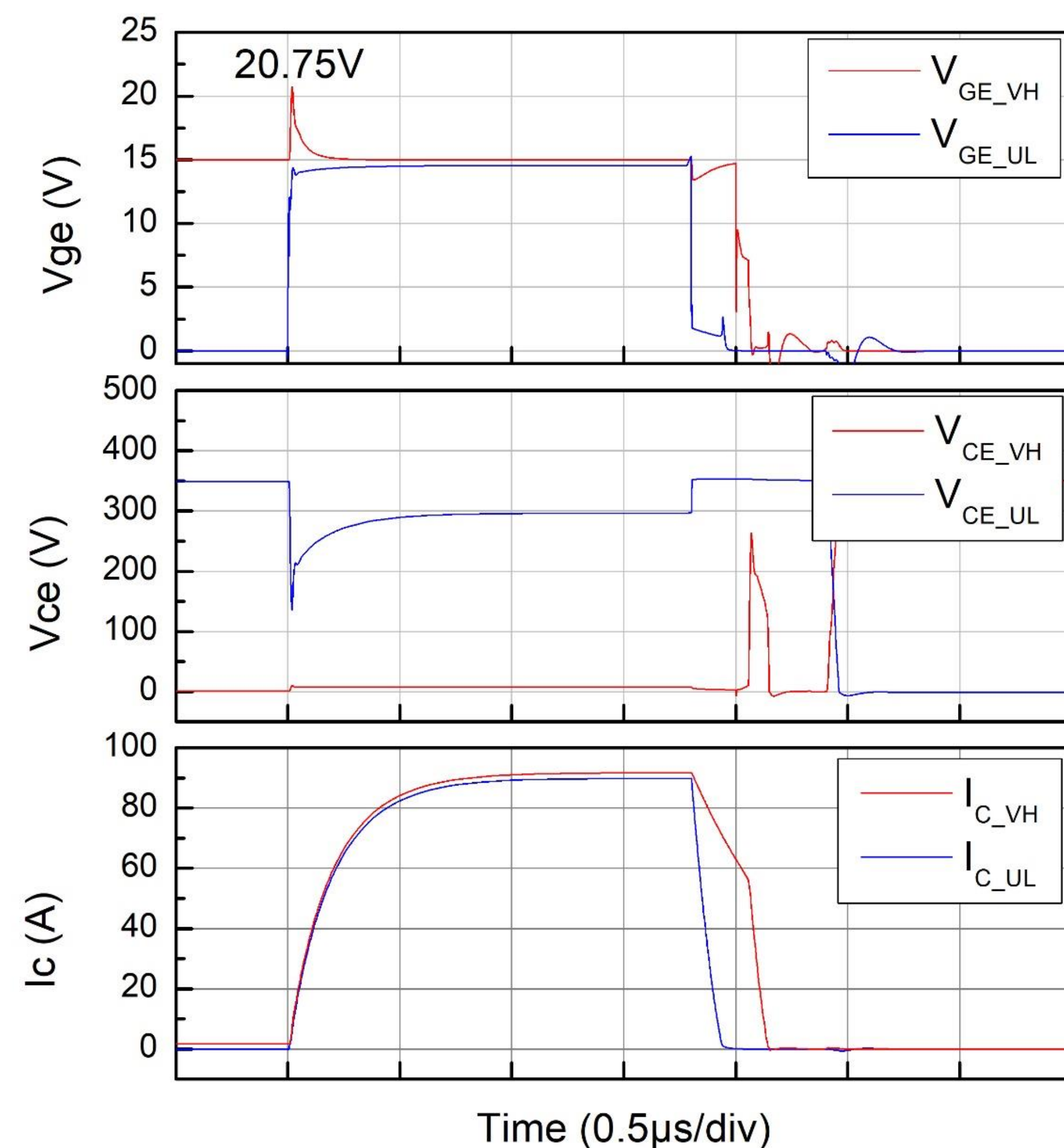


Fig. 5-b Phase to phase low-side SC I simulation. During the whole SC process, UL IGBT has smaller desaturation current due to low V_{GE} caused by L_{SS} .