Fast switching behavior of IGBTs with high inductive and capacitive loads

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Abstract

Fast switching behavior of IGBTs is investigated at up to four times the nominal current with an inductive load connected using a 200 m motor cable. A power integrated module (PIM) with a blocking voltage of 1200 V was used for the measurements. In the module, fast IGBTs with increased channel width and reduced short-circuit withstand time were integrated as switches. The experimental waveforms manifest the expected reflection on the collector-emitter voltage and the collector current with considerable duration due to the long cable. It is shown that in spite of these significant parasitic effects, very fast short-circuit detection is still possible, which is required for fast switching IGBTs.

1. Introduction

1.1. High inductive and capacitive loads in power drive systems

In power drive systems, a common way to reduce the emission of electromagnetic interference (EMI) is to use shielded motor cables. Due to its shielding, the motor cable lowers radiated EMI but, on the other hand, adds parasitics, such as stray inductance and capacitance to the system. As the characteristic impedance of a shielded motor cable is relatively low, a significant additional charging current flows from the inverter into the cable when a switching operation takes place. The amplitude of this current increases with lower characteristic cable impedance, and its period is proportional to the cable length. As the charging current is superimposed on the load current, two major challenges are encountered:

1. *Protection circuit:*

   As the additional charging current increases the collector-emitter voltage (V_{CE}) at the end of the turn-on process of the IGBT, it becomes more and more difficult for the protection circuit to reliably make a differentiation between normal operating conditions and a short circuit. This is especially the case when fast switching IGBTs with a reduced short-circuit withstand time are being used.

2. *Thermal management:*

   For the thermal management of the inverter, and especially the semiconductor devices, the charging currents represent an additional load, which have to be considered in the design.

In this paper, the influence of a 200 m long, shielded cable on the switching behavior of IGBTs is investigated. The paper focuses on the influence of the charging current on the short-circuit detection. For evaluating this influence, the collector-emitter voltage is monitored. It is analyzed as to whether desaturation of the IGBT can be detected before the IGBT is thermally destroyed. Therefore, an IGBT with a very short short-circuit withstand time (t_{SC}) of only 5 µs is used.

1.2. Electrical chip performance and measurement setup

In order to minimize the losses of an IGBT in inverter applications, chip design must focus on achieving a low on-state voltage and small switching losses, i.e. a fast switching performance. However, optimizing these two parameters is typically associated with a reduced short-circuit withstand capability. Both the low on-state voltage and the fast switching performance can be realized by tailoring the design parameters of the IGBT, such as the width of the MOS channel or the chip thickness [1]. A low on-state voltage allows operation of the IGBT at very high collector currents (I_C), i.e. up to four times the nominal current without desaturation. Here, a 1200 V IGBT with a reduced on-state voltage and an increased dv/dt was used. The nominal current of the IGBT being examined was 25 A.

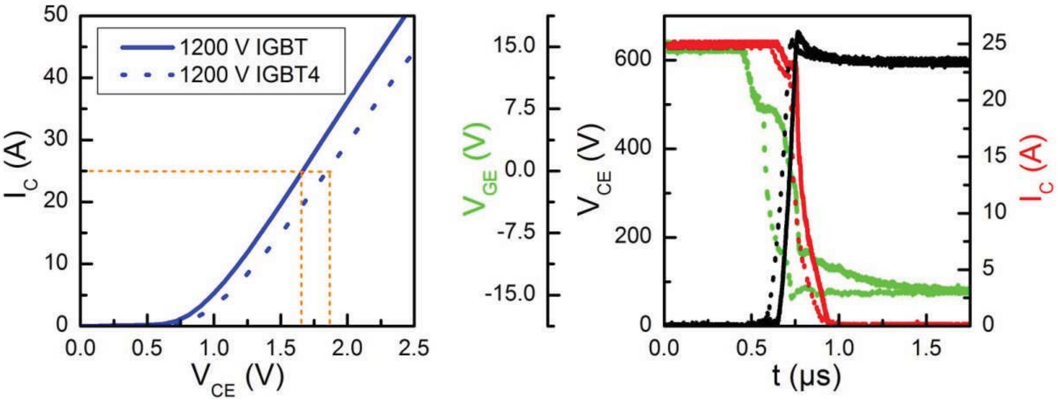

Fig. 1. Left-hand side: Comparison of the output characteristics of a 1200 V IGBT4 and the 1200 V IGBT. Right-hand side: Typical turn-off waveforms of the 1200 V IGBT (solid lines) and a 1200 V IGBT4 (dotted lines) with: V_{CE}: black, I_C: red, and V_{GE}: green.

The left-hand side of Fig. 1 shows a comparison of the static output characteristics of a 1200 V IGBT4 and the fast 1200 V IGBT being investigated. The measurement was performed with a gate-emitter voltage V_{GE} = 15 V and at a temperature T = 25 °C. It can be clearly seen that the collector-emitter saturation voltage ($V_{CE\,sat}$) of the 1200 V IGBT is lower than the $V_{CE\,sat}$ of the 1200 V IGBT4. For the 1200 V IGBT, $V_{CE\,sat}$ is 1.65 V, whereas the 1200 V IGBT4 provides a $V_{CE\,sat}$ of 1.85 V at the rated current.

The turn-off waveforms of the two IGBTs are shown on the right-hand side of Fig. 1. By comparing the turn-off characteristics of the IGBTs, the influence of the free-wheeling diode is avoided. For the dynamic measurements, the following parameters were used:

DC link voltage	V_{CC}	600 V
Collector current	I_C	25 A
Gate resistor	R_G	20 Ω
Temperature	T	25 °C
Gate-emitter voltage	V_{GE}	±15 V

The devices were operated with an identical test setup with a stray inductance L_σ of 35 nH. Both IGBTs manifest identical turn-off losses E_{OFF} of 2.0 mJ. The investigated 1200 V IGBT provides a dv/dt of 6.4 kV/µs, which is 40 % higher than for the 1200 V IGBT4. In addition, for the 1200 V IGBT, V_{CE} has a higher voltage peak, which indicates a steeper di/dt during turn-off.

In summary, the design parameters of the 1200 V IGBT allow both a low saturation voltage and a fast switching performance of the device to be achieved. Due to the fact that a reduced $V_{CE\,sat}$ usually leads to an increased E_{OFF}, the low E_{OFF} indicates that the fast 1200 V IGBT being investigated is optimized for fast switching and low conduction losses. Especially for the fast switching performance, an optimized charge distribution within the IGBT results in a faster clear out, which leads to low turn-off losses and high values of dv/dt and di/dt. As a result of the design parameters, the short-circuit withstand time is reduced to t_{SC} = 5 µs.

To analyze the influence of the cable parasitics on the fast switching behavior of the 1200 V IGBT, the IGBT was integrated in the standard layout of a power integrated module (PIM) in a standard housing (EasyPACK 2B). The device was operated with DC link voltages V_{CC} of 600 and 850 V, and the collector current I_C was increased up to 100 A, which is four times the rated chip current. All other circuit parameters were kept the same as the test above.

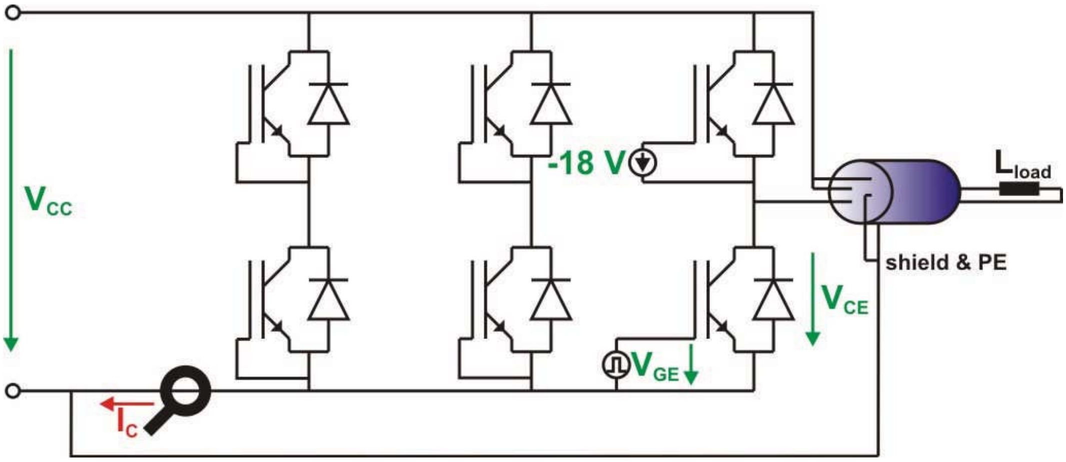

Fig. 2. Schematic view of the experimental setup together with the applied and determined voltages.

A 4-core cable was used to connect an inductive load between the positive DC link rail and one AC output terminal of the PIM. Fig. 2 shows the electric setup schematically, where only the inverter of the PIM is shown. V_{CE} and V_{GE} of one lower system were measured directly, and I_C was measured using a current probe that was integrated in the measurement setup.

2. Experimental results and interpretation

The main aspect of the measurement is to investigate the charging current (I_{Osc}) as a result of the cable parasitics. Due to the position of the current probe and the load inductance in the measurement setup, the charging current can only be clearly measured when the device is turned-on. The charging current I_{Osc} is superimposed on the common turn-on waveform of the IGBT.

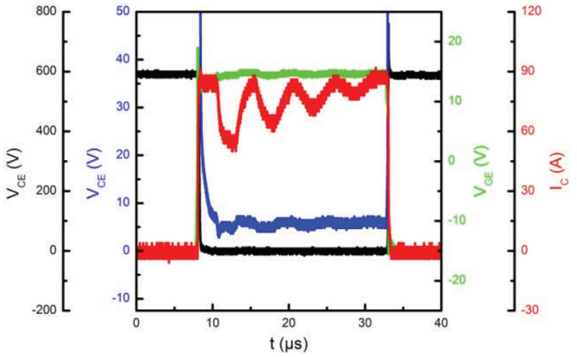

Fig. 3. Turn-on characteristics of the 1200 V IGBT, i.e. the lower system in the setup. The measurement parameters were: V_{CC} = 600 V, T = 25 °C, I_C = 45 A, and an on-state time t_{ON} = 25 µs. The curves shown are: V_{CE}: black, I_C: red, and V_{GE}: green. In addition, a higher resolution measurement of V_{CE} for voltages below 50 V is displayed in blue.

The device was operated in the double-pulse mode, and the turn-on characteristics were investigated. A measurement for the device is shown in Fig. 3. Here, the DC link voltage V_{CC} was 600 V, the time between the two pulses was 50 µs, and I_C = 45 A, which corresponds to approximately twice the nominal current.

V_{CE} decreases rapidly when the IGBT is turned-on. In the on-state, reflections in the range of a few volts occur on V_{CE}, which decay with time. Reflections with an amplitude of more than 15 A occur in the collector current, and are superimposed on the well-known diode-recovery peak current (I_{rec}). These oscillations decay over time.

The period of the oscillations is proportional to the cable length, and the oscillations themselves are attributed to the propagation time of the signal and its associated reflections along the cable. Amplitude and decay time are determined by the characteristic impedance and resistive damping of the cable. V_{CE} and I_C differ significantly from ideal waveforms and may limit the short-circuit detection of the IGBT.

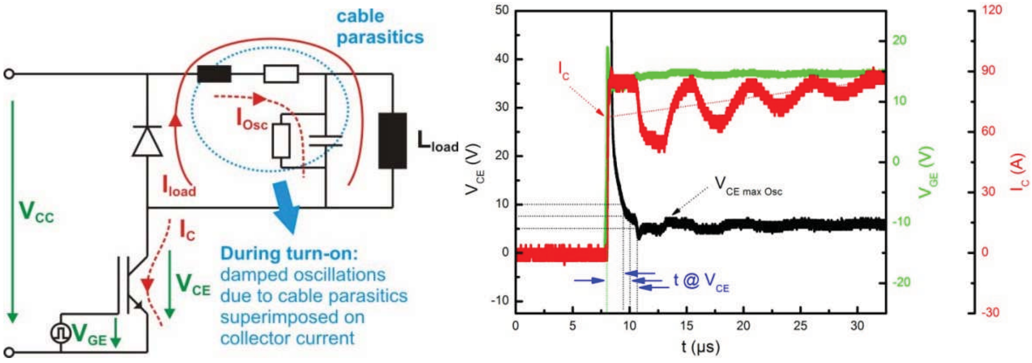

Fig. 4. Left-hand side: Schematic drawing of a simplified equivalent circuit diagram of the measurement setup. Right-hand side: Detailed view on the turn-on characteristic of the 1200 V IGBT.

The left-hand side of Fig. 4 shows a schematic drawing of a simplified equivalent circuit diagram of the measurement setup. The cable parasitics form a characteristic impedance in parallel to the load inductance and the free-wheeling path. This means that when the voltage drop across the load inductance L_{load} changes rapidly, as is the case when switching, the charging current in the characteristic impedance can be observed, followed by reflections after twice the propagation time. Therefore, the collector current through the IGBT is given by: $I_C = I_{load} + I_{Osc} + I_{rec}$, with load current I_{load}. As I_{rec} is significantly lower than I_{Osc}, it can be neglected.

The right-hand side of Fig. 4 shows a detailed view of the turn-on characteristics of the 1200 V IGBT. To extract the collector current, a linear fit is used to separate the charging current from the load current. In addition to this, it is important to evaluate the influence of the cable on short-circuit detection. With an assumed propagation speed of 150 m/μs, a period of 2.67 μs is expected for a 200 m cable. This value correlates very well to the current waveform at the right-hand side of Fig. 4.

As fast short-circuit detection is to be realized with a V_{CE}-desaturation-detection circuit, the decay of V_{CE} is monitored and the reaction time of the system is extracted. To determine this reaction time, the time interval is measured between the turn-on pulse at the gate terminal, i.e. $V_{GE} = 0$, and the instant in time that V_{CE} drops below a certain value, e.g., $V_{CE} \leq 10$ V. A desaturation-detection circuit can be realized if this reaction time is well below the short-circuit withstand time of the IGBT, which is 5 μs for the chip being investigated. At high currents, this reaction time is expected to be longer, as the fall time of V_{CE} increases.

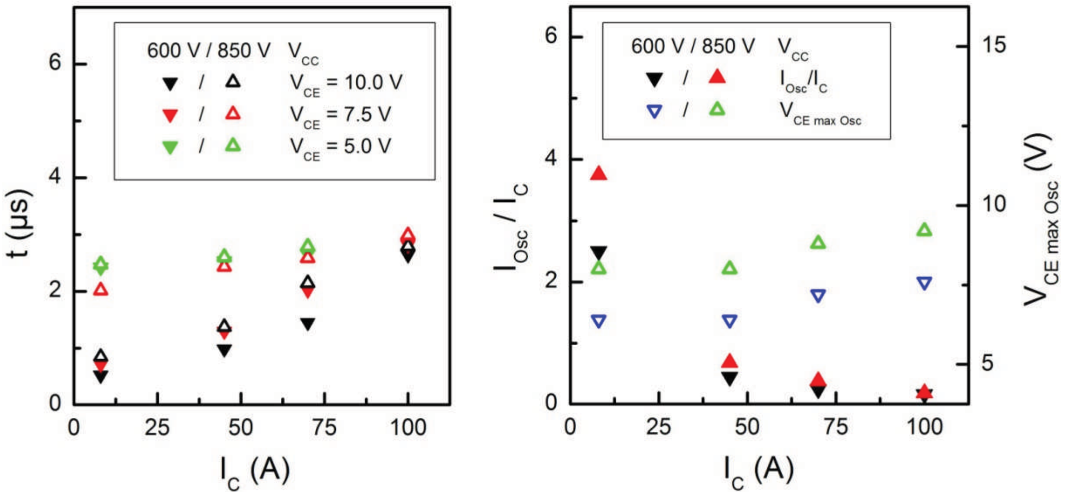

Fig. 5. Left-hand side: Reaction time of the system versus the collector current at different V_{CE}-desaturation-detection levels and for V_{CC} = 600 and 850 V. Right-hand side: The maximum amplitude of I_{Osc} in relation to I_C and maximum V_{CE} after the turn-on of the 1200 V IGBT for V_{CC} = 600 and 850 V.

On the left-hand side of Fig. 5, the reaction time of the system versus the collector current is shown for V_{CC} = 600 and 850 V. For a desaturation-detection level of V_{CE} = 7.5 and 10.0 V, the reaction time of the system increases from 0.8 μs at a low collector current to 2.6 μs at a high collector current with V_{CC} = 600 V. At V_{CC} = 850 V and for V_{CE} = 10.0 V, the same behavior is observed, however the reaction time is less than 0.3 μs longer. In contrast to this, the reaction time is always longer than 2 μs for V_{CE} = 7.5 V at V_{CC} = 850 V.

Independent of the DC link voltage, a desaturation-detection level of V_{CE} = 5.0 V always provides reaction times longer than 2.5 μs, and for four times the nominal current, V_{CE} did not decay below 5.0 V at all. Therefore, V_{CE} = 5.0 V does not allow a reliable distinction to be made between normal operating conditions and short circuit.

The right-hand side of Fig. 5 shows the maximum value of the collector-emitter voltage ($V_{CE\ max\ Osc}$) after the turn-on process of the 1200 V IGBT has finished. For V_{CC} = 600 V, $V_{CE\ max\ Osc}$ is in the range of 6.0 V for low collector currents, and reaches a value of 7.5 V at four times the nominal current. At V_{CC} = 850 V, $V_{CE\ max\ Osc}$ is consistently above 7.5 V; however, even for I_C = 100 A, it still remains below 10.0 V.

These results show that even for very high collector currents, a reaction time of less than 3 μs can be achieved. Together with the typical propagation delay of a protection circuit, even at twice the rated IGBT current, it is possible to turn-off the IGBT in time before the critical short-circuit withstand time of 5 μs is reached. To implement reliable short-circuit protection at V_{CC} = 600 V, the desaturation-detection level for the desaturation detection should be at least 7.5 V. At V_{CC} = 850 V, reliable short-circuit protection requires a desaturation-detection level above 10.0 V.

The right-hand side of Fig. 5 also shows the maximum amplitude of I_{Osc} in relation to I_C. It can be seen that for low collector currents, the charging current is at least twice the load current. With increasing collector current, the ratio between I_{Osc} and I_C decreases and the charging current becomes less dominant.

These results illustrate that the charging current leads to a massive additional load for the IGBT. Especially for low collector currents, the losses of the IGBT increase significantly. As a consequence the thermal management of the inverter and the IGBT has to consider these additional losses.

3. Conclusion

The protection of fast switching IGBTs is influenced significantly by cable parasitics, which are typical for, e.g. motor cables. Especially for very long cables, a significant charging current is added to the load current, which is also observed in the collector-emitter voltage. These effects can significantly limit the efficiency of protection measures, such as short-circuit or over-current detection. Based on the experimental results, it is concluded that the short-circuit detection for fast switching IGBTs with a reduced short-circuit withstand time of 5 µs is theoretically possible.

4. Literature

[1] A. Ciliox, P. Kanschat, O. Hellmund: „Degrees of freedom for optimisation of IGBTs for 400 V AC-line applications“, PCIM 2009, Nuremberg, Germany