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Switching speed limitations of high power IGBT modules

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Abstract

In this paper the switching speed limits of high power IGBT modules are investigated. The limitation of turn-on and turn-off switching speeds of the IGBTs are experimentally detected in a pulse tester. Different dc-bus stray inductances are considered, as well as the worst case scenario for the blocking dc-link voltage. Switching losses are analyzed upon a considerable variation of resistor value from turn-on gate driver side. Short circuit operations are investigated along with safe operating area for entire module to validate electrical capabilities under extreme conditions.

Introduction

Switching losses in high power IGBT converters are usually dominant, with the conduction losses at just a fraction of the total power loss. Therefore, by design, it is critical that switching losses are reduced to a minimum by properly adjusting the gate driver. It is however not a straight forward process, and usually the relatively large safety margins make the switching of IGBT modules inefficient.

Switching energy loss at turn-on and turn-off transients depend on many factors, the most important being: blocking voltage, current to be switched, junction temperature, equivalent dc-bus stray inductance, turn-on and turn-off gate resistors [1] , [2]. For a given IGBT module and gate drive pair, for a maximum operating dc-link voltage and for a given dc-bus stray inductance, the turn-on and turn-off switching times should be reduced to a minimum [3]. In case of a gate drive with fixed resistors and fixed voltage levels, the reduction of the turn-on and turn-off resistors should be done. It is however critical to ensure that all devices in the IGBT power module will operate in the safe operating area (SOA) given by the manufacturer even in the worst case situations [4] , [5].

This paper experimentally investigates the switching limits of a 1700V, 1000A high power IGBT module. The switching speed turn-on and turn-off limits will be detected in the worst case conditions. A sweep of the stray inductance with few points will also be done to highlight the change in speed limits. For the experimental results and waveform interpretations is considered only the gate drive variation parameter, without adding the internal resistance of the module which is given in the datasheet as 1.5 ohm.

Turn-on speed limitation

It is critical to test the power devices in a half-bridge configuration, because the IGBT turn-on behavior and limitations are linked with the series connected diode in the bridge. In the presented work, the Infineon FF1000R17IE4 is considered [6]. The used gate driver is based on the Concept 2SC0435T driver core [7].

The power module is characterized in a pulse tester, measuring the collector-emitter voltage and collector current. The measurements are taken using a HRO 64Zi LeCroy oscilloscope. The turn-on transient of the IGBT is shown in Figure 1, switching from 1113V, 1914A at 125°C and gate driver $R_{ON} = 1.2\ \Omega$. The equivalent stray inductance detected at the low impedance collector emitter terminals can be calculated [8]:

$$L_S = \frac{\Delta V_{L_S}}{di/dt} \cong \frac{132.6V}{14.23kA/\mu s} = 9.32\,nH \qquad (1)$$

It can be seen that the peak turn-on IGBT current can reach significant values, even higher than the maximum current specified in the reverse blocking safe operating area (RBSOA). It is however not limited on how high can be the peak IGBT turn-on current. Therefore the focus at the IGBT turn-on transient must be placed on the reverse recovery of the diodes.

The peak reverse recovery current of the series connected diode with the switched IGBT is deduced with the switched IGBT:

$$i_{d,RR,pk} = i_{IGBT,peak} - i_{ON} = 1937A - 1157A = 780A \quad (2)$$

At the IGBT turn-on the series connected diode in the half-bridge has a limited turn-off power, specified by the manufacturer. The second pulse applies more stress on the diode due to parasitic capacitances of the system. Depending on the reverse voltage on the diode, the peak reverse recovery current should not exceed the current limitation, as seen in Figure 2. Therefore the speed limit at IGBT turn-on can only be limited by the RBSOA of the diode, by the maximum current that the gate drive can provide, and on the maximum electrical noise produced during this transient [9].

Considering the gate drive capabilities, from the datasheet parameters, the highest peak current provided is related to the voltage swing variation and can be subtracted as follows [10]:

$$\hat{I}_{\max(non-osc)} \cong 0.74 \cdot \frac{\Delta V_{Gate}}{R_{g,\min(non-osc)}} = 8{,}14A \qquad (3)$$

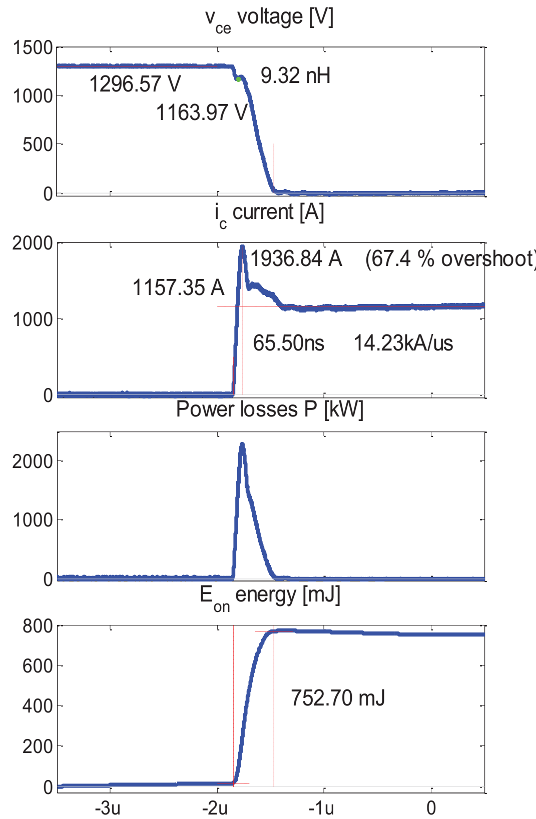

Figure 1: Turn-on transient IGBT T_j=125°C

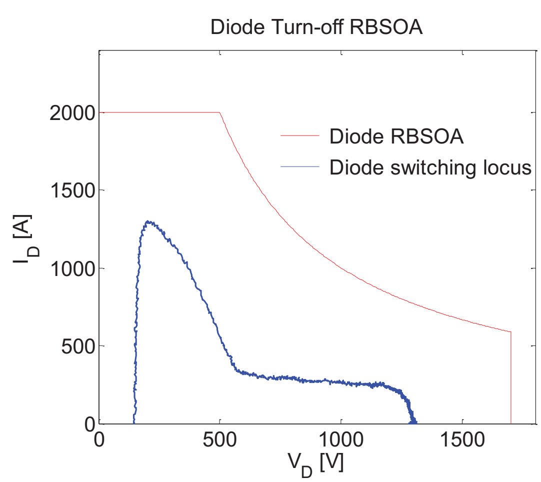

Figure 2: Diode Safe Operating Area T_j=25°C

Where, minimum gate resistance is a function of gate impedance and IGBT module input capacitance [10]:

$$R_{g,\min(non-osc)} = 2 \cdot \sqrt{\frac{L_g}{C_{gg}}} = 2{,}18\Omega \qquad (4)$$

The noise immunity level regarding dv/dt capabilities are as well given by the gate drive manufacturer. A smaller gate on resistance leads to decreases in switching losses through a smaller rise time of the current. Tests were performed by decreasing the on side resistance of the gate drive for two values of the stray inductance.

Figure 3 and 4 show a comparison between turn-on transient under different ramp values for collector-emitter voltage and current. Due to the stray inductance, the voltage waveform has a first peak affecting not only the fall time but also the amount of energy dissipated.

Table 1 presents a comparison between turn on switching losses for a gate drive on resistance of 0.47 ohm and a current of 1000A.

Table 1: Turn-on energy for a gate drive on resistance of 0.47 ohm

Temperature [°C]	Turn-on energy(Ls=8nH) [mJ]					Turn-on energy(Ls=12nH) [mJ]				
	900V	1000V	1100V	1200V	1300V	900V	1000V	1100V	1200V	1300V
25	430.2	502.7	577.1	652.1	731.4	392.6	420.7	478.2	540.3	608.9
50	460.1	538.4	617.2	698.4	784.2	420.7	448.8	510.8	576.8	650.3
75	493.1	575.2	664.3	748.2	841.8	425.3	502.7	581.4	654.2	741.2
100	529.2	618.3	708.1	803.8	919.2	458.5	548.2	620.9	698.8	804.7
125	561.4	658.2	756.8	859.6	967.3	492.9	591.2	663.4	756.5	840.4
150	591.5	678.4	776.6	885.7	1020.4	517.9	613.4	708.2	797.8	912.3

The gate drive resistance is decreased from nominal value (1.2 ohm) to 0.35 ohm lowering the dead time of transient. The most visible transition can be observed from 1 ohm to 0.7 ohm where at 10% of the nominal voltage, the time variation is approximately 0.1 µs.

From the current point of view the biggest overshoot appears at the smallest resistance value, 1894 A, as in the nominal situation the current being only up to 1594 A. The rise time is decreased also with the resistance, reducing the area of calculated power, from 10% of I_{CE} to 2% of V_{CE} [11].

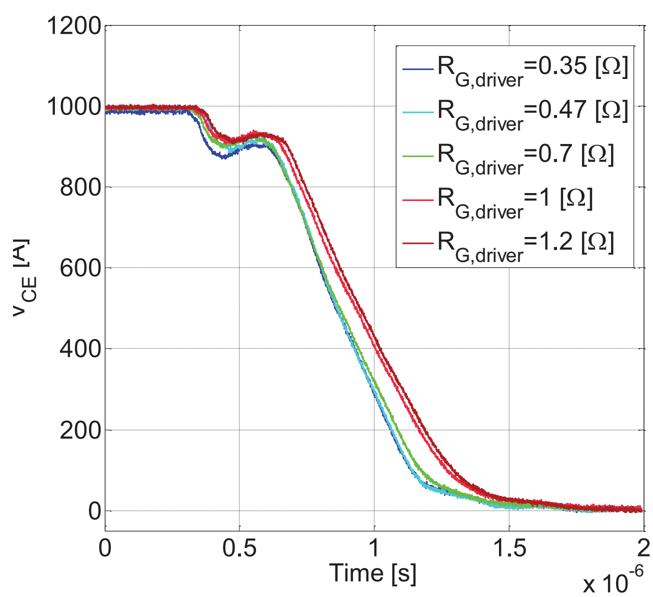

Figure 3: Turn-on collector emitter voltage at 125 °C

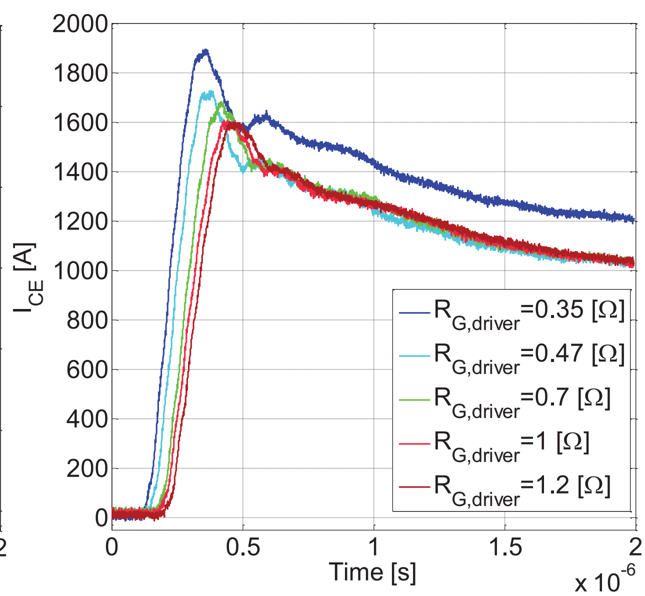

Figure 4: Turn-on collector emitter current at 125 °C

It can be observed in Figure 5 and 6 that decreasing the gate resistance slightly increases reverse recovery energy dissipated in diode.
For each test the temperature increases from 25°C to 150 °C in steps of 25 °C using a heat plate mounted below the module and a current sweep from 50 A to approximately 2500 A is applied. It is assumed that the junction temperature is equal to the temperature measured with a K-type thermocouple in the heat plate body.
Comparing the values of testing circuit stray inductance, the losses are higher with several mJ in case of 12 nH when the temperature is above 100 °C and smaller above this temperature. In table 2 are presented reverse recovery energy dissipated in diode for a current of 1000 A and a gate drive resistance of 0.47 ohm.

Table 2: Reverse recovery losses for gate drive on resistance of 0.47 ohm

Temperature [°C]	Reverse recovery energy(Ls=8nH) [mJ]					Reverse recovery energy(Ls=12nH) [mJ]				
	900V	1000V	1100V	1200V	1300V	900V	1000V	1100V	1200V	1300V
25	93.6	106.8	112.2	116.2	117.4	96.3	108.6	111.3	120.3	127.1
50	123.5	131.6	134.8	138.2	146.9	127.6	136.2	137.1	140.4	155.2
75	143.3	160.3	160.3	168.4	176.8	147.8	159.1	160.2	174.6	189.3
100	176.5	190.3	203.6	206.8	208.2	169.2	187.3	202.7	204.7	210
125	204.2	220.2	242.1	245.2	250.8	198.2	231.4	241	241.3	249.6
150	227.3	259.4	262.6	276.2	301.7	219.4	251.6	264.1	283.5	295.7

According to datasheet, the manufacturer does not provide information below 1.2 ohm gate resistance, but by linearizing can be observed a high increasing of reverse recovery losses which were not confirmed by tests [6].

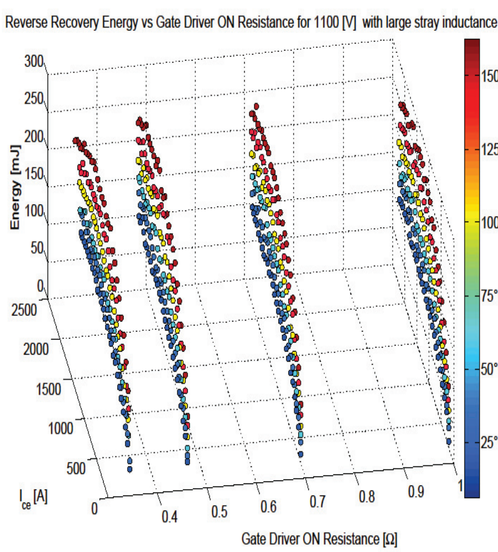

Figure 5: E_{rec} at 1100 V with L_s=12 nH

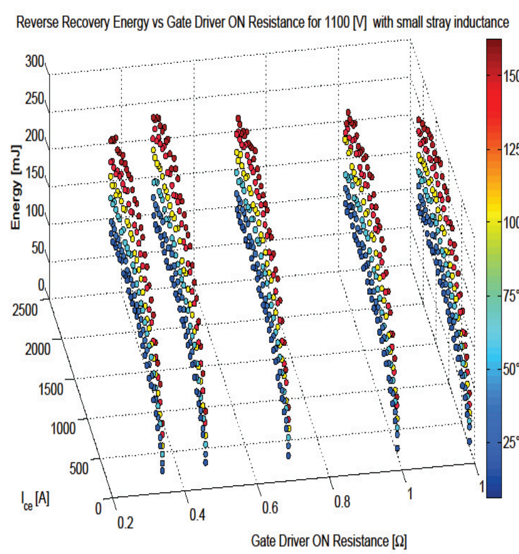

Figure 6: E_{rec} at 1100 V with L_s=8 nH

The turn-on losses of IGBT under different gate resistors are depicted in Figure 7 and 8 for 12 nH and 8 nH of the stray inductance parameter. The energy dissipated during on switching is predominant compared to reverse recovery as usually in case of high currents (> 500 A).
It can be seen that a large stray inductance means a smaller power dissipated during turn-on for all temperatures considered due to a smaller voltage variation, equation (1).

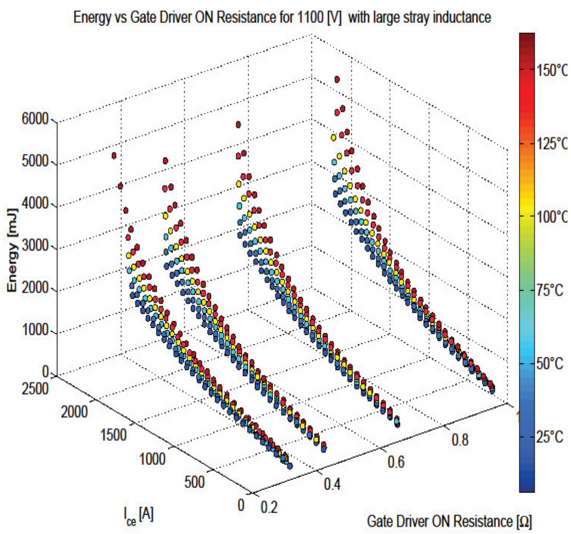

Figure 5: E_{on} at 1100 V with L_s=12 nH

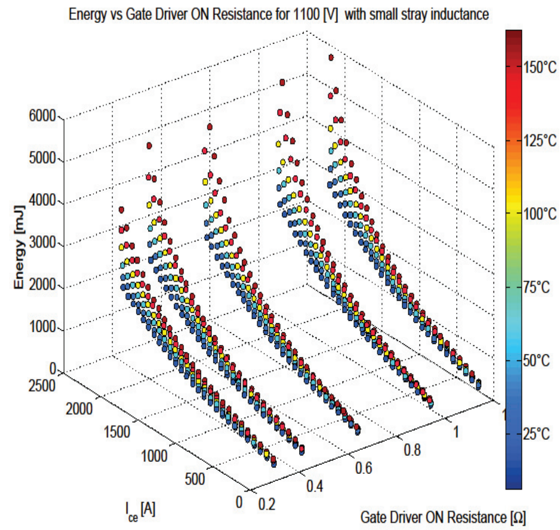

Figure 6: E_{on} at 1100 V with L_s=8 nH

Due to gate resistance decreasing, the switching delay time becomes smaller diminishing total losses on turn on transient of the module. In Figure 9 a sum of turn-on and reverse recovery energy is depicted, based on measurements for 1300 V at a temperature sweep between 25°C and 150°C. The total amount of energy dissipated is up to 8 Joules per turn-on, decreasing along with gate resistance value.

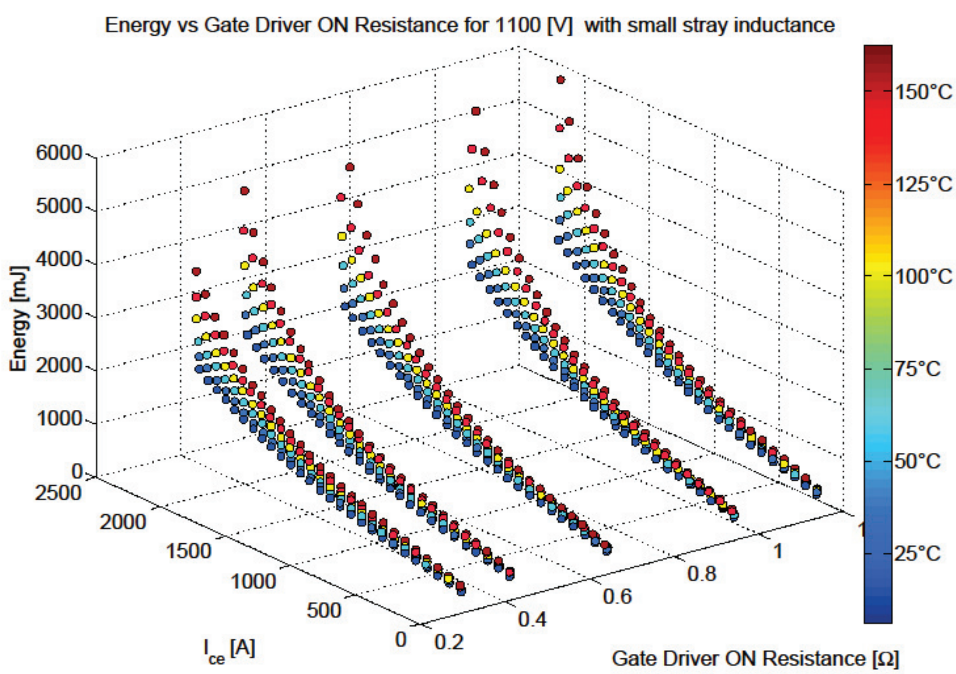

Figure 7: Total on switching and reverse recovery energy at 1100 V

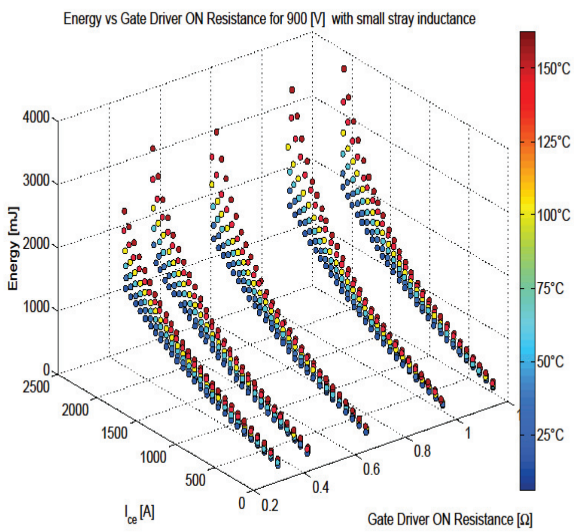

Figure 8: Total on switching and reverse recovery energy at 900 V

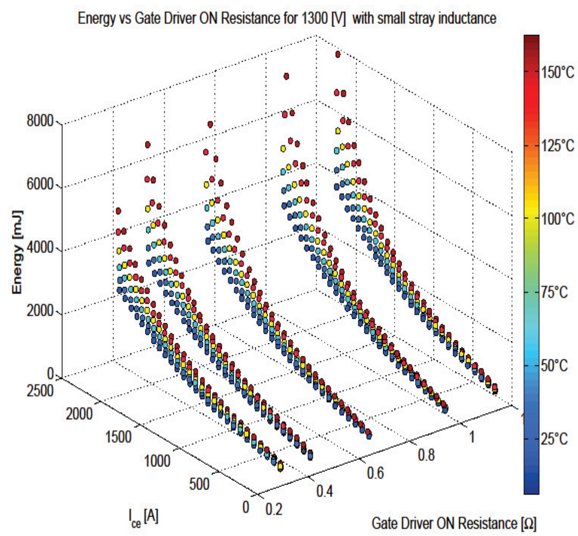

Figure 9: Total on switching and reverse recovery energy at 1300 V

In Figure 10 and 11 are depicted total on transient losses, adding reverse recovery losses to turn-on switching losses for 900 V and 1300 V. It can be observed that the amount of total energy dissipated during turn-on transient is approximately double in case of 1300 V as for 900 V. Considering the same gate driver on resistance variation, losses decreases from 1.2 Ω to 0.35 Ω. This difference is above 1 Joule at 900 V and almost 3 Joules for a voltage of 1300 V.

At a gate on resistance of 0.25 ohm and a stray inductance of 12 nH, a failure appeared affecting both the gate drive and the high power IGBT module. The high EMI level during the switching produced oscillations in the gate current along with the current limit crossing, over 2000 A pulses damaged both lower side transistor and upper side diode.

Turn-off speed limitation

The turn-off transient of the IGBT is shown in Figure 9, switching to 1153V, 2008A at 125°C and gate driver $R_{OFF} = 1.8\,\Omega$. The dc-bus stray inductance at this operating point will create a 25% voltage overshoot and the active clamping circuit in the gate driver is not active.

An example of the RBSOA for the used power module is shown in Figure 10, for a 1996 A turn-off current, switching to 1256 V at 125°C and gate driver $R_{OFF} = 1.8\,\Omega$. The nominal recommended parameters from datasheet were exceeded due to high currents pulses with a good overall behavior until the gate resistance limit was reached.

Depending on the transistor technology, it is usually feasible to switch a higher turn-off voltage by using an active clamping circuit [7], however at

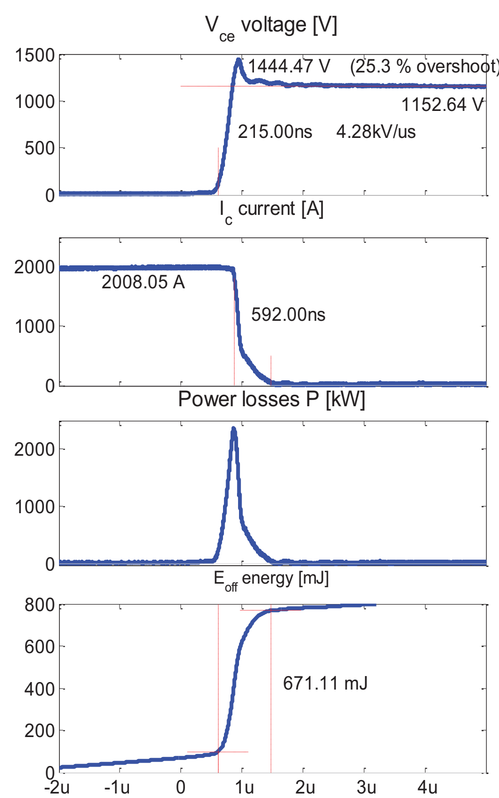

Figure 12: Turn-off transient IGBT, T_j=125°C

the price of increased switching losses.
The critical turn-off is in the situation when a very high current is turned-off, such as in the case of short circuit.
An example of a short circuit test is shown in Figure 11, where a low impedance (L_S≈5nH) short circuit is realized to the 1300 V pre-charged dc-link, before the IGBT is turned ON. The same gate drive setup is used. The red line is the collector-emitter voltage, magenta and blue lines are the collector currents in the two IGBT terminals, the green line shows the gate voltage and the black line shows the total collector current in the IGBT as the sum of collector currents. The di/dt is determined by the driver dynamics and the transfer characteristic of the IGBT. The peak current is around 7.4 kA and the gate driver desaturation detection time is around 6.5 μs.

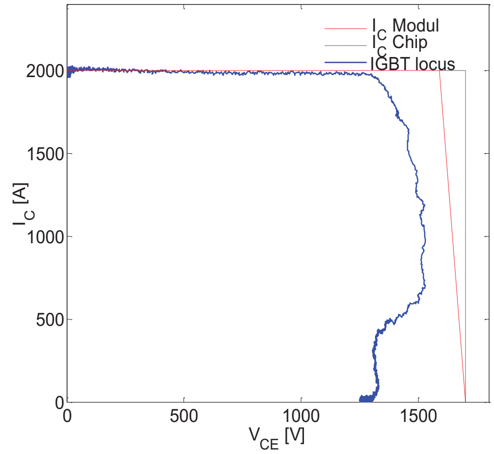

Figure 10: IGBT safe operating area at T_j=125 °C

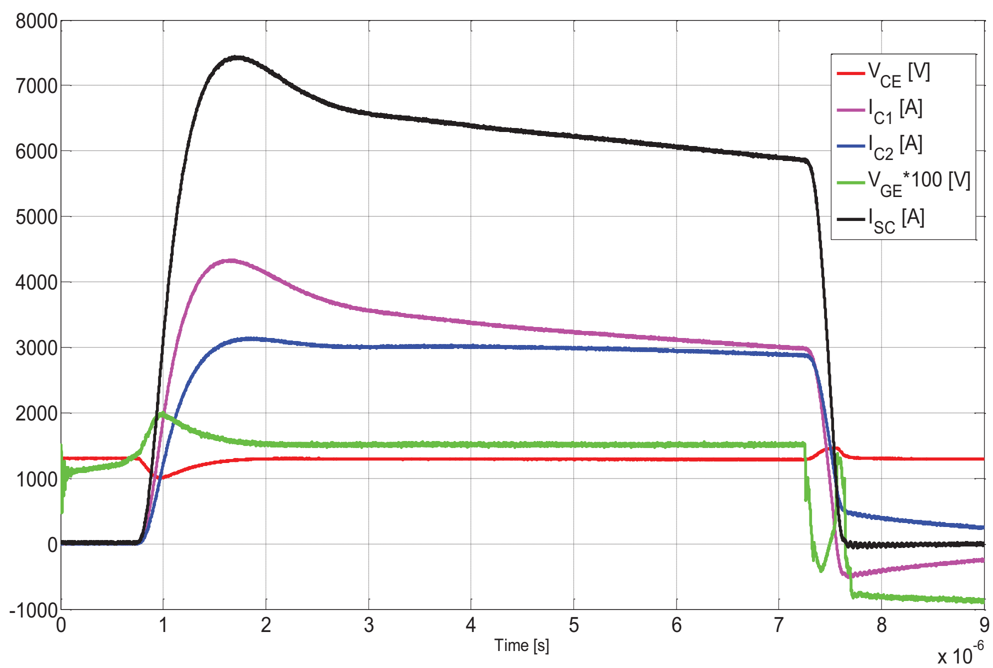

Figure 14: Short circuit test of IGBT at T_j=25°C

Conclusion

The optimization of switching losses is very important. The conversion efficiency or increased power density can be achieved by doing so. The switching speed limitations of a high power IGBT module are analyzed in this paper. An 8 and 12 nH stray inductance of the dc-bus is considered, as well as critical operating voltage and current points.
The switching losses are measured and analyzed based on a temperature up to 150°C and a speed variation for the transient. The turn-on side resistor limit value of the gate drive where the IGBT module presented a good behavior is 0.35 ohm. Further tests were performed with no success for the device under test. The turn-on losses analysis shows an improvement due to the resistor decreasing in both cases of dc-bus stray inductances values. The safe operating area of IGBT and diode is investigated emphasizing datasheet limit parameters crossing for currents above 2000A. A short circuit test is successfully performed, exhibiting great capabilities to withstand extreme conditions.

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