Robustness improvement of high-voltage IGBT by gate control

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Abstract

This paper considers the turn-off robustness (the maximal current being able to be turned off) of high power IGBTs under over current condition. The analysis of turn-off curves shows that the turn-off robustness of the investigated devices is not really limited by the rate of voltage rise on collector-emitter (dVCE / dt ). The main reason of the robustness limitation is found out to be the rate of the MOS channel turn-off and impact ionization rate. The control method of dynamic active clamping was developed to delay the MOS channel turn-off und thus to improve the turn-off robustness without elevating more turn-off energy compared to the standard turn-off.

1 Introduction

Turn-off robustness is always an important parameter for high-voltage IGBTs. Simulation studies show that a series of adverse processes such as dynamic avalanche, current localization and current filaments can be observed during high current turn-off. Together with the thermal effect such processes can lead to turn-off destruction. On the one hand the turn-off robustness can be improved by proper design of IGBT cells [1]. On the other hand it is reasonable to enhance the robustness by the use of appropriate gate control method.

The purpose of this paper is to find a gate control method to improve the turn-off robustness of high-voltage IGBTs. This gate control should be realizable in an easy and economic way. This will be discussed in following topics:

- Finding out the decisive factor by means of destruction curve analyise
- Target turn-off curve and the circuit to realize it
- Experiment at 6.5kV IGBT
- Simulation of the current commutation und electric field strength development during turn-off

2 Turn-off destruction under over current

Conventionally a gate resistor is used to adjust the slew rate of the collector emitter voltage (dVCE / dt). The reverse bias safe operation area (RBSOA) is also defined with respect to a certain gate resistor value. In order to analyze the inter-relationship between the turn-off robustness and dVCE / dt a series of turn-off curves under over current have been investigated. The destructions out of RBSOA show the commonness that the gate potential has been drawn below the threshold voltage before the current commutation is completed. In other words, at the moment of the gate pinch-off a good deal of current is still flowing. Fig. 1 shows a typical turn-off destruction of a 6.5kV IGBT. Almost the total load current is still flowing through the element by the time of pinch-off of MOS channel. The destruction occurs a little bit later (about 1µs), before the current commutation can be fully completed.

![Fig. 1 Turn-off destruction of a 6.5kV IGBT](image-url)
3 Idea to enhance the turn-off robustness and the circuit to realize it

The analysis of the experiments lead to the supposition that the early MOS pinch-off should be directly related to the cause of the destruction. If the MOS channel pinch-off could be delayed to the end of the current commutation, the turn-off robustness should be therefore improved. To keep the MOS channel open the internal gate potential should be kept above the threshold voltage until the end of the current commutation (Fig. 2).

In fact the current commutation is always accompanied by a $V_{CE}$ overvoltage. This property provides the opportunity to control the gate voltage and the current commutation by using the energy of the overvoltage. Active clamping has long been used to eliminate the overvoltage peak at turn-off. In the process a Z-diode is clamped between gate and collector. The clamping effect occurs when $V_{CE}$ exceeds the z-voltage. The gate potential is thereby shifted upwards. The z-voltage should be chosen above the DC-link voltage. Otherwise the IGBT can not be turned off. The experiments at 6,5kV IGBT show that such method can not improve the turn-off robustness seriously. The clamping effect indeed can reopen the gate channel a little bit at the end of the current commutation. But because of the stray inductivity it acts not fast enough to keep the gate open during the current commutation. In the dynamic active clamping a capacitor is connected in series to the z-diode as shown in Fig. 3. This allows the z-voltage to be selected below the DC-link voltage. The clamping effect can be thus shifted to the desired point of time by selection of the adapted z-diode. The action time of the clamping effect can be adjusted by the capacitor. And the desired turn-off curve could be approximately realized (Fig. 4).

![Fig. 2 Desired turn-off curve to enhance the turn-off robustness](image)

![Fig. 3 Circuit of dynamic active clamping](image)

![Fig. 4 Turn-off with dynamic active clamping](image)

$->$not destructed (out of specified RBSOA)

![Fig. 5 Turn-off without dynamic active clamping](image)

$->$destructed (out of specified RBSOA)
Fig. 4 and Fig. 5 show the turn-off curves of the same 6.5kV IGBT module and at the same d\(V_{CE}/dt\). By using the dynamic active clamping (Fig. 4) the gate potential can be kept above the threshold voltage until the end of the current commutation. The IGBT can still be turned off at 1700A. The measurement without dynamic active clamping shows that the IGBT was destructed at 1000A. The peak overvoltage in Fig. 4 is even lower than that in Fig. 5.

4 Simulation to clarify the functionality of dynamic active clamping

The functionality of the dynamic active clamping can be clarified by means of device simulation. The simulation result of current developing (Fig. 6) shows the difference between the turn-off processes with and without dynamic active clamping. The red curves demonstrate that without dynamic active clamping the electron-current disappears before the \(I_{CE}\) commutation starts. From that time on the total current must be carried by hole-current. The turn-off with dynamic active clamping, as shown by the green curves, however delivers electron current during the whole \(I_{CE}\) commutation. The plateau of the electric field strength curve in Fig. 7 shows the avalanche effect during IGBT turn-off. Larger current leads to stronger avalanche effect. Using dynamic active clamping the avalanche effect is strongly reduced compared to the turn-off without active clamping. Both the high density of hole-current and the strong avalanche effect could be the pre-stage of subsequent high-current effects. The high-current effect together with thermal feedback [1] can induce non-extinguishable filaments and finally the destruction of the element [2]. The improvement of the turn-off robustness by using of dynamic active clamping is thereby reasonable.

5 Conclusion

It was confirmed that the slew rate of collector-emitter voltage is not really responsible for the turn-off destruction of the investigated high-voltage IGBTs. For the same \(V_{CE}\) slew rate the turn-off current can be doubled by using dynamic active clamping. Induced overvoltages are suppressed. For the same turn-off robustness the dynamic active clamping allows the IGBT to be turned off with much higher \(dV_{CE}/dt\). Device simulations show that such control methods release the IGBT from high-density hole-current and strong avalanche effects.

6 Literature
