Abstract:

For the qualification in resonant converters in the Zero Voltage Mode at high frequencies a Standard-IGBT-Module, a Fast-IGBT-Module, both with IGBT’s of the 2. generation with a planar gate structure and a new Trench-Gate-IGBT-Module of the 3. generation are characterized and compared. Investigations show that the Trench-IGBT-Module can be driven at high frequencies in a low loss manner like the Fast-IGBT-Module which is optimized this mode. Indeed for the Trench-IGBT these advantage exists at a mode at high voltages and relatively low switch off currents. At high switch off currents and high frequencies the Fast-IGBT-module has the best performance. At lower and medium frequencies the new Trench-IGBT works with the lowest losses.

I. Introduction

In resonant applications like microwave, arc welding or battery chargers IGBT-modules are increasingly used according to their good static and dynamic performance [1,2,]. The IGBT-modules work in these applications usually at frequencies higher than 20 kHz. Maximum frequencies between 100 kHz and 200 kHz are possible [3] in soft switching topologies. In this operation besides a good static ability especially the switching behaviour of the IGBT-modules is very important. To evaluate the properties of IGBT-modules for soft switching applications the datasheets give not enough information. Thus numerous publications [4, 5, 6, 7] have dealt with this topic.
This is at first a planar Standard-IGBT-Module, type BSM75GD120DN2, of the 2. generation, optimized for hard switching applications with low and medium switching frequencies. Second a planar Fast-IGBT-Module of the 2. generation, type FS75R12KS4, specialized for high frequency applications is tested. Third a new Trench-IGBT-Module of the 3. generation, type FS75R12KE3, with a trench gate structure and a field stop zone [8] is measured. This IGBT is first of all provided for applications in hard switching converters with lower and medium frequencies.

Figure 1 shows in which manner the necessary trade off between saturation voltages and the switching losses is realized for the modules at hard switching. The general advantage of the Trench-IGBT is clearly to be observed here. An important question of this investigation is to find out if the Trench-IGBT is well suited for ZVS applications with high frequencies also without special optimization.

II. ZVS test circuit

For the investigations a test circuit, see figure 2, has been built which operates under application specific conditions. It has the topology of a voltage source series loaded resonant dc-to-ac converter [9].

Figure 2: Principle test circuit

To realize the zero voltage switching mode of the IGBT-modules the resonant circuit must be driven at frequencies higher than the resonant frequency of the load. Figure 3 shows the typical behaviour of the IGBT S2 and its anti-parallel diode D2 in this mode.

Figure 3: Behaviour of an Trench IGBT Module in the ZVS-Mode, 1µs/DIV, Ch. 2: VGE 10 V/DIV, Ch. 3: IC, ID 40 A/DIV, Ch. A: VCE = 200 V/DIV, Ch. C: PV 10 kW/DIV

If the upper IGBT S1 switches off the diode D2 takes over the load current for a short time. The IGBT S2 goes in a switch on standby to this time. At the zero crossing of the load current the IGBT S2 switches on passively at nearly zero voltage and takes over the load current. Before the end of this half sinus wave the IGBT S2 is soft switched off. In practice the switch off is performed usually at low load currents to limit the losses, moreover snubber capacities Cs are used to reduce the switching losses.

To guaranty the test at a defined chip temperature the test mode is limited to only 4 periods. By means of mounting on a controlled heat plate a control of the chip temperature TJ is possible. All IGBT-modules are tested under the same test conditions to ensure a good comparability.

III. ZVS switch off

In the ZVS-mode the switch off of the IGBT has a superior importance. Figure 4 shows the active switch off of the Trench-IGBT in this mode.
In opposite to the hard switching at inductive load the collector emitter voltage \( V_{CE} \) starts rising at the beginning of the collector current fall. This is caused by the snubber capacitors \( C_S \). According to the size of \( C_S \) the rise of \( V_{CE} \) is limited. It is very important to remark that at soft switch off the tail current dominates the losses. In addition the switch off behaviour of the IGBTs depends on different parameters especially temperature, supply voltage and switch off current.

Figure 4: Soft switch off of a Trench-IGBT

\[ \text{cond.: } V_{CC}=600\text{V}, \quad C_S=13.6\text{nF}, \quad T_J = 25^\circ\text{C}, \quad 0.2\mu\text{s/DIV} \text{ Ch. 2: } V_{GE} 10 \text{ V/DIV}, \text{ Ch. 3: } I_C 20 \text{ A/DIV}, \text{ Ch. A: } V_{CE} 100 \text{ V/DIV}, \text{ Ch. C: } P_L 10 \text{ KW/DIV}, \text{ Ch. D: } W 2 \text{ mWs/DIV} \]

With an increase of \( C_S \) (fig. 5) it is possible to decrease the switch off losses. But the size of this decrease is not very high compared to hard switching. This is caused by the high influence of the tail current. The Fast-IGBT shows the best performance at switch off at rated current of the module at all measured \( C_S \)-values.

Figure 5: Switch off losses of the IGBTs via \( C_S \) at rated current

Figure 6: Switch off losses of the IGBTs via \( I_{C_{off}} \)

At reduced current at switch off it can be seen that at \( V_{CC}=600\text{V} \) the losses of the Trench-IGBT converge to that of the Fast-IGBT.

Figure 7: Switch off losses of the IGBTs via \( V_{CC} \)

Figure 7 shows that for the standard and the fast IGBT’s the losses linearly increase with the voltage \( V_{CC} \). The Trench-IGBT losses show for voltages more than 400V only a small increase. This is caused by the field stop layer in this IGBT [8]. For high voltages and low switch off currents the Trench-IGBT can switch off with low-loss nearly like the Fast-IGBT specialized for this aim.

III. Passive switch on

To test the passive switch on in general a special circuit shown in figure 8 was used. The tested IGBT \( S_2 \) is in stand by every time at \( V_{GE} = 15\text{V} \) and switches passive on and off. The switch \( S_1 \) is used to switch actively the load current.
According the inductive load a certain di/dt will be pressed into the switch S2. Figure 9 and 10 show the passive switch on for the Fast-IGBT and the Trench IGBT. The voltage drop at the finish of the current rise is due to over voltages caused by the stray inductance of the module.

The Trench-IGBT shows a high but very short voltage spike at passive switch on and additional it reaches its low saturation voltage very fast. The process of conductivity modulation which is responsible for this behaviour is finished in this IGBT very fast. Both IGBT’s of the second generation show similar lower voltage spikes at passive switch on (see fig. 10 for the fast IGBT).

On the other hand they need nearly double the time to come into saturation. Further measurements show for all IGBT’s a rise of the overvoltage at increasing di/dt.

Table 1 specifies the additional losses caused through the passive switch on for a di/dt = 50 A/µs which corresponds to a frequency of nearly 80 kHz. At low chip temperature this losses are negligible. At high temperatures the losses for the IGBTs of the second generation could be important.

For an estimation of the whole losses of an IGBT and a diode of the modules a calculation was
performed using the program Mathcad. Measurements show that under the test conditions the switching losses of the diode are negligible in the investigated frequency range.

The evaluation was performed first for 25°C. Here the passive switch on losses of the IGBT are neglected (see table 1). Measured values of the IGBT switch off energy and the switching times are used. The conduction losses were calculated according the static characteristics of the IGBTs and Diodes whereas the load current was assumed to be sinusoidal. The diagram in figure 11 shows the calculated loss split of the modules at f=50 kHz under this conditions.

The Fast-IGBT shows the lowest switching losses but the conduction losses are relatively high. The Trench-IGBT has very low conduction losses and at low switch off currents nearly the same low switching losses like the Fast-IGBT. This leads in this range to the lowest total losses. Additional calculations at 100 kHz show that at this frequency the conduction losses dominate. The Trench-IGBT has here the lowest losses. The IGBTs of the Fast- and the Standard-IGBT-Modules have nearly the same losses.

According to the results in table 1 the influence of the passive switch on of the IGBTs at a temperature of T_J=125°C is considered and compared to a calculation without the influence of the passive switch on.

For this aim the passive switch on and the conduction phase were measured directly in the resonant converter for some few working points and regarded together as P_{onT real}. Further more the influence of the voltage drop at the stray inductance caused through the nearly sinusoidal load current was noted at this calculations. The calculations without the passive switch on were performed in the same manner as for T_J=25°C.

The Trench-IGBT shows only for very high frequencies a remarkable influence of the passive switch on to the total losses. For the Fast- and the especially the Standard-IGBT the passive switch on is remarkable for frequencies of approx. 50 kHz and more. At relatively low frequencies the passive switch on is negligible for T_J=125°C also.

Figure 12 shows that at T_J=125°C a rise of the frequency leads for all investigated IGBTs to an increase of the difference between the calculated losses with and without a consideration of the passive switch on. Measurements show that with increasing frequencies the IGBTs ever less reach their static working point at the conduction phase.

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Figure 13: Loss split of the IGBT-Modules at different switch off currents, cond.: I_{Lmax}=75A, f=52kHz, V_CC=600V, T_J=125°C, C_S=13.6nF

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The losses of the investigated IGBTs at \( T_J = 125^\circ C \) and \( f = 52\text{kHz} \) are presented in Figure 13 for different load currents. Expectedly the losses are higher than those at \( T_J = 25^\circ C \) for all modules. Also at \( T_J = 125^\circ C \) the Trench-IGBT has an advantage against the Fast-IGBT especially at low switch off currents.

V. Conclusion

Three IGBT-Modules are tested in terms of their properties for applications in resonant inverters which are working in the Zero Voltage Mode up to high frequencies. These are a planar Standard-IGBT-Module of the 2. generation, a planar Fast-IGBT-Module of the 2. generation specialized for resonant applications and a new Trench-IGBT-Module of the 3. generation. To meet the investigation goals a test stand was established which works in the ZVS-mode. The conduction and especially the switch off losses of the IGBT are the most important parts of the total losses in this mode. The passive switch on losses are to note especially at the Standard- and the Fast-IGBT. For the Trench-IGBT these losses are negligible up to high frequencies. The results show that it is possible to drive the Trench-IGBT without special optimization up to high frequencies on a low loss level like the Fast-IGBT specialized for this application. Indeed for the Trench-IGBT these advantages exists at a mode at high voltages and relatively low switch off currents.

References


