Analysis and Comparison of Planar- and Trench-IGBT-Modules under ZVS and ZCS Switching Conditions

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Abstract-For the qualification in resonant converters a Standard-IGBT-Module, a Fast-IGBT-Module, both with IGBT's of the 2nd generation and two new Trench-Gate-IGBT-Modules of the 3rd generation with different EMCON-Diodes are characterized and compared. A teststand was established, which works in the Zero Voltage or in the Zero Current mode. Investigations in the ZVS mode show that the Trench-IGBT-Module can be driven up to high frequencies in a low loss manner like the Fast-IGBT-Module which is optimized for this mode. In the ZCS mode the modules show comparable losses for low and medium frequencies. At very high frequencies the Fast-IGBT-Module and one of the tested Trench-IGBT-Modules show the best performance.

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 performance 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 as for example [4, 5, 6, 7] have dealt with this topic.

This paper presents an analysis and comparison of three IGBT-Modules (1200V, 75A) from one manufacturer in terms of their abilities for the application in resonant inverters which work in the Zero Voltage or in the Zero Current mode at high frequencies. This is at first a planar Standard-IGBT-Module, type BSM75GD120DN2. It consists of IGBTs of the 2nd generation and EPI-Diodes which are optimized for hard switching applications with low and medium switching frequencies. Second a planar Fast-IGBT-Module, type FS75R12KS4, with IGBTs of the 2nd generation and Fast-Diodes is tested. This module is specialized for high frequency applications. Third a new Trench-IGBT-Module of the 3rd generation, type FS75R12KE3, is measured which is composed of IGBTs with a trench gate structure and a field stop zone [8] as well as EMCON-HE-Diodes. This module is first of all provided for applications in hard switching converters with lower and medium frequencies. For the ZCS investigations the Trench-IGBT-Module was equipped with Fast-EMCON-Diodes also.

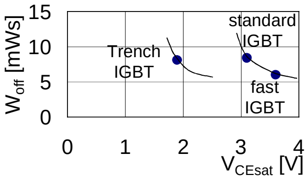

Fig.1. Trade off between saturation voltage V_{CEsat} and switch-off losses W_{off} for the investigated IGBTs at hard switching, cond.: I_C=75 A, V_{CC}=600V, T_J=125°C

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-Module is well suited for resonant applications with high frequencies, too, without special optimization.

II. RESONANT 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].

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. At frequencies lower than the resonant frequency the test circuit works in the Zero Current Switching mode. To guaranty the test at a defined chip temperature the test mode is limited to only 4 periods. By means of mounting on a temperature controlled heat plate a control of the chip temperature T_J is possible. All IGBT-Modules are tested under the same test conditions to ensure a good comparability.

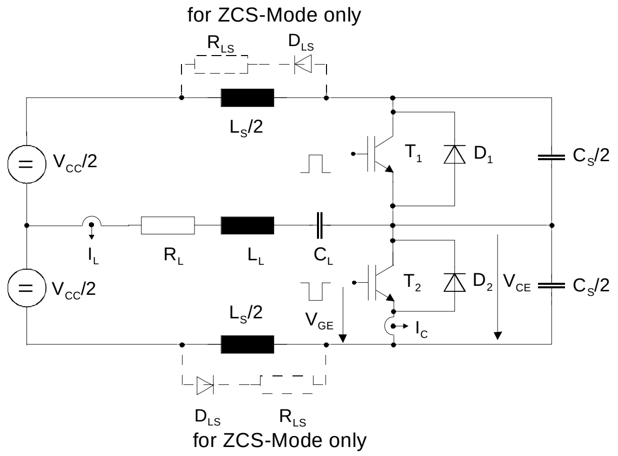

Fig. 2. Principle test circuit

III. ZERO VOLTAGE SWITCHING MODE

Figure 3 shows the typical behaviour of an IGBT and its anti-parallel diode in this mode.

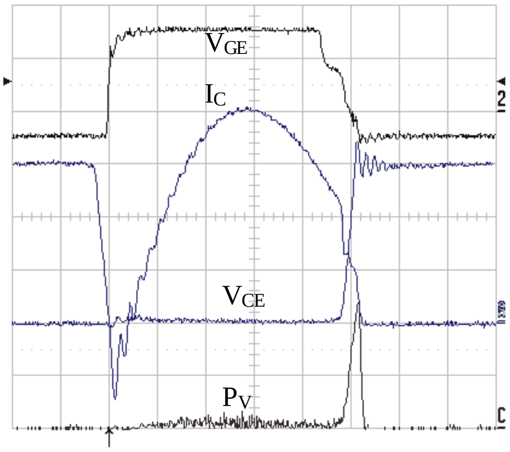

Fig. 3. Behaviour of an IGBT-Module in the ZVS-mode, 1µs/DIV, Ch. 2: V_{GE} 10 V/DIV, Ch. 3: I_{C}, I_{D} 40 A/DIV, Ch. A: V_{CE} = 200 V/DIV, Ch. C: P_{V} 10 kW/DIV

If for example the upper IGBT T_1 switches-off the diode D_2 takes over the load current for a short time. The IGBT T_2 passes over to a switch on standby mode at this time. At the zero crossing of the load current the IGBT T_2 switches on passively at nearly zero voltage and takes over the load current. Before the end of this half sinus wave the IGBT T_2 is soft switched-off. In practice the switch-off is performed usually at low load currents to limit the losses, moreover snubber capacitors C_S are used to reduce the switching losses.

A. IGBT 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.

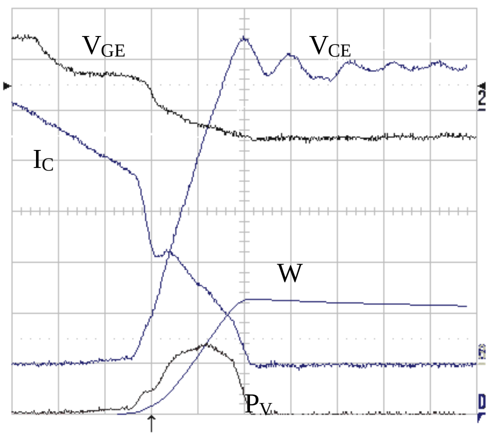

Fig. 4. Soft switch-off of a Trench-IGBT, cond.: V_{CC}=600V, C_S=13.6nF, T_J=25°C, 0.2µs/DIV, Ch. 2: V_{GE} 10 V/DIV, Ch. 3: I_C 20 A/DIV, Ch. A: V_{CE} 100 V/DIV, Ch. C: P_V 10 kW/DIV, Ch. D: W 2 mWs/DIV

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.

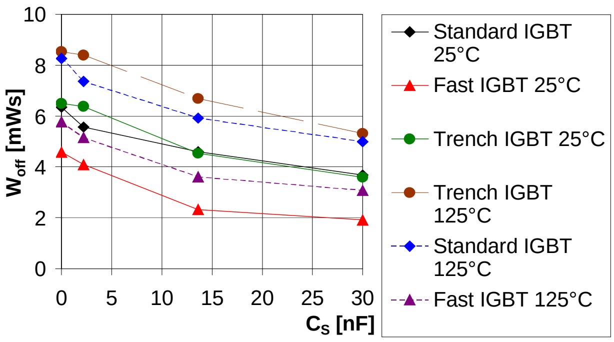

Fig. 5. Switch-off losses of the IGBTs via C_S at rated current, cond.: V_{CC}=600V, I_C=75A

With an increase of C_S (fig. 5) it is possible to decrease the switch-off losses. But the amount 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 modules at all measured C_S-values.

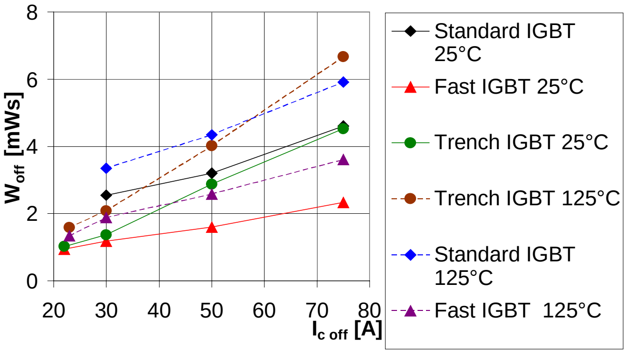

Fig. 6. Switch-off losses of the IGBTs via $I_{C\ off}$, cond.: V_{CC}=600V, C_S=13.6nF

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

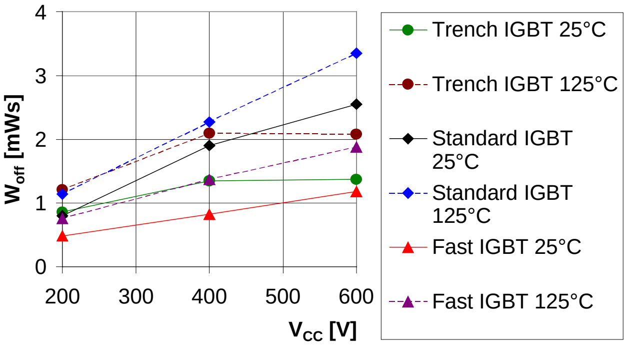

Fig. 7. Switch-off losses of the IGBTs via $V_{CC,}$ cond.: I_C=30A, C_S=13.6nF

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.

B. *Passive switch-on of the IGBT*

To test the passive switch-on in general a special circuit shown in figure 8 was used. The tested IGBT T_2 is in stand by mode every time at V_{GE} = 15V and switches passive on and off. The switch T_1 is used to switch actively the load current. According to the inductive load a certain di/dt will be forced into the switch T_2. Figure 9 and 10 show the passive switch on for the Fast-IGBT and the Trench IGBT. The voltage drop at the end of the current rise is due to over voltages caused by the stray inductance of the module.

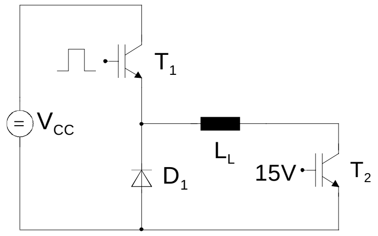

Fig. 8. Test circuit for passive switch-on

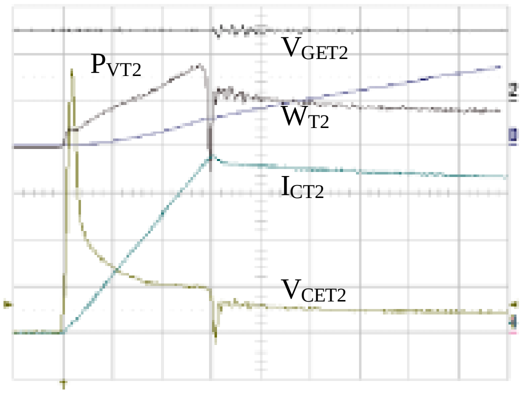

Fig. 9. Passive switch-on of a Trench-IGBT, cond.: T_J=125°C, di/dt=50 A/µs, V_{GE}=15V, 0.5µs/DIV, Ch. 2: V_{GE} 10 V/DIV, Ch. 4: I_C 20 A/DIV, Ch. 1: V_{CE} 5 V/DIV, Ch. C: P_V 200 W/DIV, Ch. D: W 0.5 mWs/DIV

The Trench-IGBT shows a high but very short voltage spike at passive switch-on and additional it reaches it's 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 lower voltage spikes at passive switch-on (see fig. 10 for the Fast-IGBT).

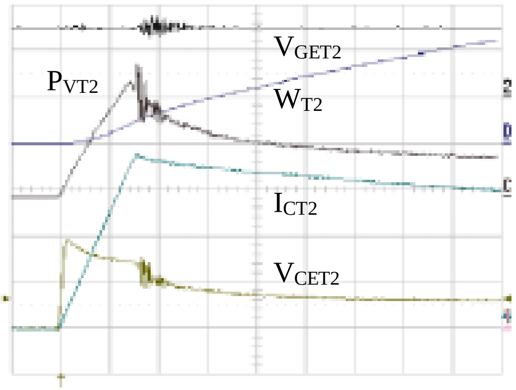

Fig. 10. Passive switch on of a Fast-IGBT, cond.: T_J=125°C, di/dt=50 A/µs, V_{GE}=15V, 1µs/DIV, Ch. 2: V_{GE} 10 V/DIV, Ch. 4: I_C 20 A/DIV, Ch. 1: V_{CE} 5 V/DIV, Ch. C: P_V 200 W/DIV, Ch. D: W 1 mWs/DIV

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.

For a load current of 75A and a di/dt = 50 A/µs which corresponds to a frequency of nearly 80 kHz an estimation of additional losses at passive switch on ($W_{on\ dyn}$) was performed. At low chip temperature (T_J=25°C) this losses are negligible for the tested IGBTs. At high temperature (T_J=125°C) this losses are for the Fast-IGBT 0.32 mWs and for the Standard-IGBT 0.44 mWs. With a value of $W_{on\ dyn}$ = 0.16 mWs the Trench-IGBT shows clearly the lowest losses at this test.

C. Calculation and comparison of total IGBT-Module losses

For an estimation of the whole losses of the tested IGBT-Modules in the ZVS-mode 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.

According to the results in chapter B. 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 both cases measured values of the IGBT switch-off energy and the switching times are used. For the calculations without the influence of the passive switch-on the conduction losses P_{condT} were calculated according to the static characteristics of the IGBT's at which the load current was assumed to be sinusoidal. At calculations with attention to the passive switch-on this event 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.

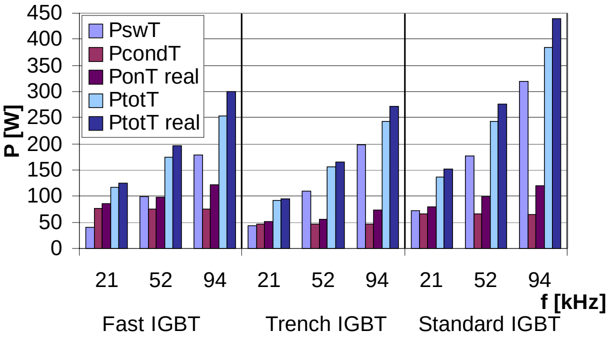

Fig. 11. Loss split of the IGBTs at different frequencies with and without a consideration of the additional losses at passive switch-on, cond.: I_{Lmax}=75A, I_{Coff}=30 A, V_{CC}=600V, T_J=125°C, C_S=13.6nF

Figure 11 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 ($P_{totT\ real}$) and without (P_{totT}) consideration of the passive switch-on. Measurements show that with increasing frequencies the IGBTs less and less reach their static working point in the conduction phase.

The Trench-IGBT shows at this load current the lowest total losses at all tested frequencies. Only for very high frequencies a remarkable influence of the passive switch-on on the total losses is to be noted. For the Fast- and especially the Standard-IGBT the total losses are higher and the passive switch-on is remarkable for frequencies of approx. 50 kHz and more. Only at relatively low frequencies the passive switch-on is negligible.

Further investigations of the behaviour of the tested IGBT-Modules under ZVS-conditions are performed [10]. They confirm the advantages of the Trench-IGBT at relatively low switch off currents. According to it's high conduction losses the Fast-IGBT has the lowest total losses at high switch-off currents and at high frequencies, only.

IV. ZERO CURRENT SWITCHING MODE

Figure 12 shows as an example the behaviour of an IGBT-Module in this mode. Refering to fig. 2 for example the upper IGBT T_1 switches actively on at first and takes over the load current from Diode D_2. This IGBT leads the load current up to it's zero crossing. Then the IGBT T_1 is passive switched-off. It's antiparallel Diode D_1 leads the load current after the zero crossing up to the time when the bottom IGBT T_2 is actively switched-on. Diode D_1 is switched-off at this moment.

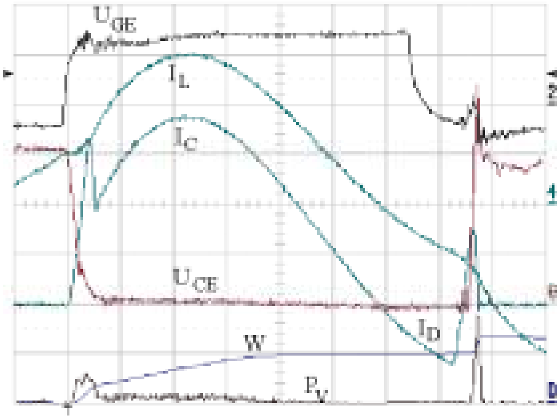

Fig. 12. Behaviour of an IGBT-Module in the ZCS-mode, V_{CC}=600V, L_S=2µH, T_J=25°C, 1µs/DIV Ch. 2: V_{GE} 10 V/DIV, Ch. 3: I_C or I_D 40 A/DIV, Ch. 4: I_L 50 A/DIV,

In terms of dynamic demands and switching losses the behaviour of an IGBT-Module is dominated in the ZCS-mode by the active switch on of the IGBT and the switch off of the corresponding freewheeling diode. That's why the switch on is performed usually at low load currents to limit the losses. In opposite to the hard switching additional snubber inductances L_S (Fig. 2) are used to reduce the switching losses. Stress and losses at the passive switch-off of the IGBT and the corresponding switch-on of the freewheeling diode are negligible. The measurement results which are shown in the following chapters are obtained at T_J=25°C. Measurements at 125°C confirm the statements given here.

A. *IGBT switch-on*

Figure 13 shows the switch-on of an Trench-IGBT in this mode. The snubber inductance L_S leads to a fast collector emitter voltage drop on the IGBT before the collector current rises remarkably.

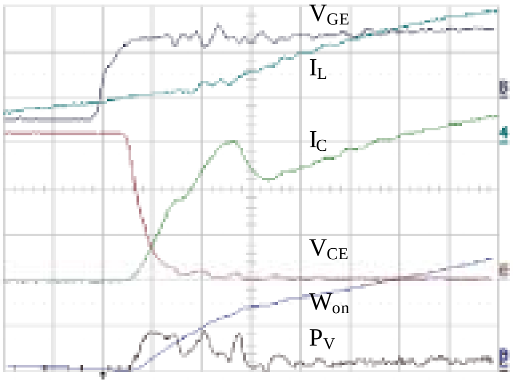

Fig. 13. Switch-on of a Trench-IGBT in the ZCS-Mode, V_{CC}=600V, L_S=2µH, T_J=25°C, 0.2µs /DIV, Ch. 2: V_{GE} 10 V/DIV, Ch. 3: I_C 40 A/DIV, Ch. 4: I_L 50 A/DIV, Ch. A: V_{CE} 200 V/DIV, Ch. C: P_V 5 kW/DIV, Ch. D: W 1 mWs/DIV

From figure 14 it can be seen that for all tested IGBT-Modules an increase of the snubber inductivity leads to a decrease of the switch-on losses. Especially for the Trench-IGBT-Modules, which passes very fast into the saturation, the loss reduction is rather high.

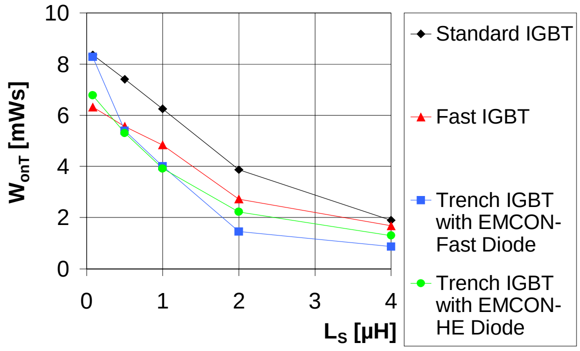

Fig. 14. Switch-on losses of the IGBTs via the inductivity L_S, cond.: V_{CC}=600V, I_{Con}=50A, T_J=25°C

B. *Diode switch-off*

Figure 15 shows a Diode switch-off in the ZCS-mode. Depending on the switching conditions e.g. V_{CC}, I_L, T_J, di_C/dt and L_S the dynamic demands on the Diode could be very high in this mode. Especially the diode over voltage can be relatively high in this mode. This can be seen as an example in figure 15. Only very high snubber inductance values can decrease this effect.

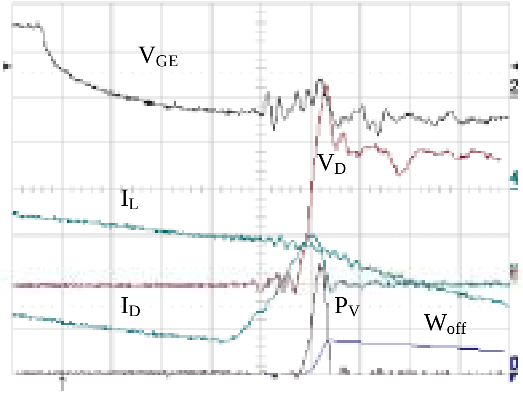

Fig. 15. Switch-off of a Fast-Diode (Fast IGBT Module) in the ZCS-mode, V_{CC}=600V, L_S=2µH, T_J=25°C, 0.2µs/DIV, Ch. 2: V_{GE} 10 V/DIV, Ch. 3: I_D 40 A/DIV, Ch. 4: I_L 50 A/DIV, Ch. A: V_D 200 V/DIV, Ch. C: P_V 10 kW/DIV, Ch. D: W 2 mWs/DIV

Figure 16 presents the switch-off losses of the tested Diodes via the snubber inductance. It is to be seen that the Fast-Diode has the lowest switch-off losses in the investigated working points. The losses of the EMCON-Diodes drops for relatively high snubber inductances, only.

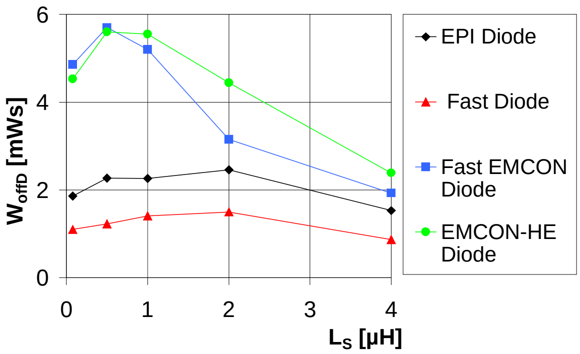

Fig. 16. Switch-off losses of the Diodes via L_S, cond.: V_{CC}=600V, I_{Doff}=50A, T_J=25°C

C. *Calculation and comparison of total IGBT-Module losses*

For an estimation and a comparison of the whole losses of the IGBT-Modules in the ZCS-mode a calculation was performed, too. Measured values of the IGBT's switch-on and the Diodes switch-off energies as well as the switching times are used. The calculations of the conduction losses were performed according to the static characteristics of the IGBT's whereas the load current was assumed to be sinusoidal.

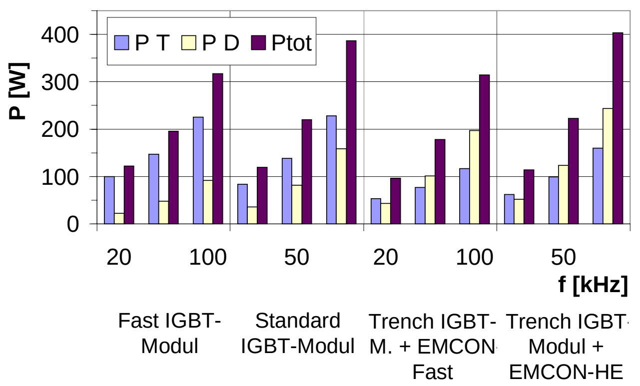

Fig. 17. Loss split of the IGBTs at different frequencies, cond.: I_{Lmax}=75A, I_{Doff}=50 A, V_{CC}=600V, T_J=25°C, L_S=4µH

From figure 17 it can be seen that for low and medium frequencies the losses of the modules are comparable. At high frequencies the Fast-IGBT-Module and the Trench-IGBT-Module with a EMCON-Fast-Diode show the lowest total losses P_{tot}.

V. CONCLUSION

IGBT-Modules from one manufacturer are tested in terms of their properties for applications in resonant inverters which are working in the Zero Voltage mode or the Zero Current-mode up to high frequencies. These are a planar Standard-IGBT-Module of the 2nd generation, a planar Fast-IGBT-Module of the 2nd generation specialized for resonant applications and two new Trench-IGBT-Modules of the 3rd generation with different EMCON-Diodes. For the investigation goals a resonant test stand was established.

The conduction and especially the switch-off losses of the IGBT are the most important parts of the total losses in the ZVS mode. The passive switch-on losses are to be noted especially for the planar IGBTs. 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.

In the ZCS-mode beside the conduction and switch-on losses of the IGBT especially the switch-off losses of the diode are important. The losses of the tested modules are comparable for low and medium frequencies. At high frequencies the Fast-IGBT-Module and the Trench-IGBT-Module with a Fast-EMCON-Diode have the lowest losses.

REFERENCES

[1] H. Mecke, W. Fischer, F. Werther: “Soft switching inverter power source for ARC welding”, EPE 1997, pp. 4.333-4.337

[2] U. Kirchenberger, K. Fischer, D. Schröder: “Analysis of a constant frequency series-parallel multiresonant converter”, EPE 1993, pp. 76-82

[3] C. Keller, “Einsatzkriterien schneller abschaltbarer Leistungshalbleiter in Quasiresonanz-Umrichtern”, German Diss., Technical University Berlin, 1991

[4] A. Claudio, J. Aguayo, M. Cotorogea, “Characterization of different IGBT’s in ZVS commutation including parameter variation”, PESC 2001

[5] T.Reimann, “Verhalten abschaltbarer Leistungshalbleiterbauelemente im ZVS-Mode”, German Diss., Technical University Ilmenau, 1994

[6] S. Pendharkar, K. Shenai, “Zero voltage switching behaviour of punchthrough and nonpunchthrough IGBT’s!”, IEEE Transactions on Electron Devices, Vol. 45, No. 8, 1998, pp. 1826-1835

[7] A. Claudio, J. Aguayo, M. Cotorogea, “Special test circuit for the analysis of IGBT behaviour in ZCS Commutation”, EPE-Journal, Vol. 11, No. 1, February 2001, pp. 25-32

[8] L. Lorenz, “IGBT’s for next decade’s motor drive systems”, PCIM-Europe, January/February 2001, pp. 20-22

[9] N. Mohan, T. Undeland, W. Robbins: “Power Electronics”, 2. edition, John Wiley & Sons, New York, 1995, ISBN 0-471-58408-8

[10] M. Helsper, F. W. Fuchs, M. Münzer, “Comparison of Planar and Trench IGBT Modules for resonant applications”, PCIM Europe 2002, Nuremberg, in press