THE SWITCHING BEHAVIOUR OF AN IGBT IN ZERO CURRENT SWITCH MODE

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Abstract. The IGBT is a useful device for resonant applications. Because of its bipolar conduction mode and its ability of blocking a reverse voltage it seems to be well suited to the zero current switching.
Measurements in a quasi resonant configuration which works in a full wave mode show, that the switching losses are dependent on the time between the begin of current oscillation and the moment the IGBT is turned off. These losses are at a minimum when the channel of the IGBT is opened as long as possible.
For the half wave mode it is shown that the stationary reverse blocking capability of a non-punch-through-IGBT can be improved by turning on the MOSFET-channel with a positive gate-source-voltage.

Keywords. IGBT, zero current switch, reverse blocking capability

INTRODUCTION

In some recent papers [1,2] the IGBT was proposed as an active switch in resonant applications where the switching frequency of the device can be increased up to 200 kHz.
An interesting application for a resonant switch is a Cuk-converter with additional resonant circuit. An investigation by Laska and Emsermann [3] shows that a SIRET-transistor can be used as active switch if the turn-off process starts 2µs before the zero-crossing of the current. Because this condition is hard to fulfill a lot of the SIRETs were distroyed during the operation of the converter.
By using an IGBT as active switch such problems did not occur, but there was still the question, if the time between turn-off of the IGBT and the zero crossing of the current has an influence on the switching behaviour of the IGBT.

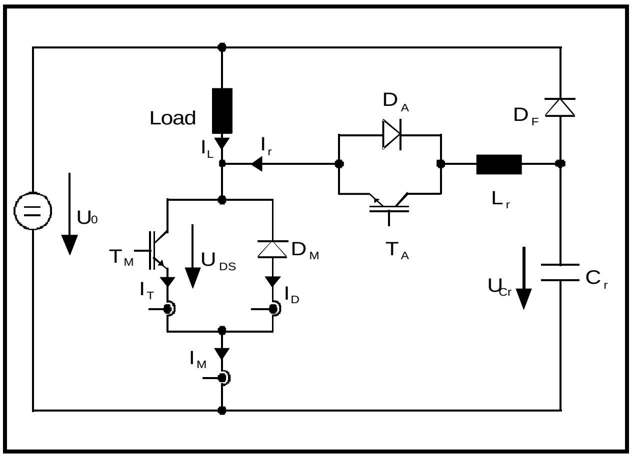

Figure 1: Test circuit

THE TEST CIRCUIT

Figure 1 shows the test circuit which was chosen because the operational conditions of the resonant switch are similar to those in a Cuk-converter. Another application of this configuration appears in three-phase-converters working with very high switching frequencies [4].
T_M is the main transistor whose switching behaviour is to be investigated. The resonant circuit consists of the auxiliary IGBT T_A, the inductor L_r and the capacitor C_r which provides the energy for the switching operation. Further the diodes D_M and D_A are needed to lead a negative switch-current I_M during the ring-around process. The diode D_F is working as a free-wheeling diode when both IGBT's are in the non-conducting state.
Before the turn-off is started by switching on the auxiliary IGBT T_A, the load current and also the current through the main IGBT T_M are assumed to be constant. The voltage across the resonant capacitor C_r is the same as the supply voltage U_0. After turning on T_A the current I_r in the resonant circuit begins to oscillate. A quarter of the oscillation period later I_r has reached its peak value and so the switch-current I_M decreases ($I_M = I_L + I_r$). After the zero crossing of I_M the negative current runs through the diode D_M. Then the IGBT is reverse biased by the small forward voltage of the diode D_M and should be turned off during the period of negative current I_M in order to block after the second zero crossing of the current I_M. From this moment I_r has the same value as I_L but a negative sign. This current feeds the capacitor C_r and the voltage across C_r increases linearly up to the value of U_0. Then the free-wheeling diode D_F becomes forward biased and begins

to lead the load current. The current and voltage waveforms and the switching losses during the turn-off will be described in detail by the next chapter.
Another advantage of the circuit explained above is that the resonant inductance L_r is working like a turn-on snubber limiting the rate of current rise after the main IGBT is turned-on.

TURN-OFF BEHAVIOUR

Voltage- and Current-Waveforms

In figure 2 the essential current waveforms which occur at a non-punch-through-IGBT (npt-IGBT BUP 304) during the turn-off process are shown. In part a) there is the gate-source voltage U_{GS} which shows the moment of turning-off, the drain-source voltage U_{DS} and the switch current I_M. In part b) this current is shown enlarged and splitted into the diode current I_D and the IGBT current I_T. Additionally the voltage U_{DS} is figured in high resolution.

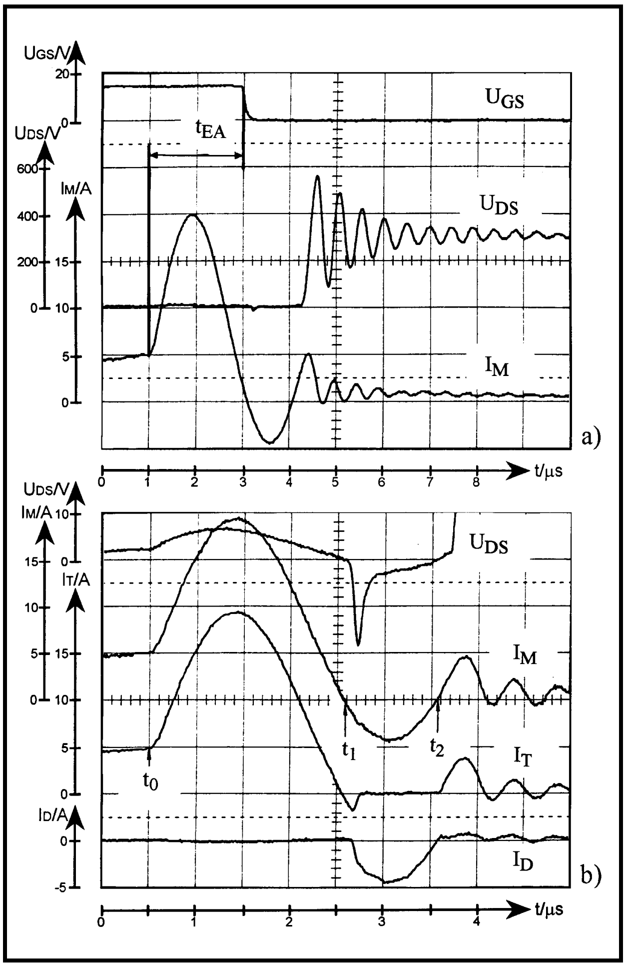

Figure 2: Current and voltage waveforms in a full wave application

By turning on the auxiliary IGBT T_A at the instant t_0 the turn-off process is started. After the first current-zero the main IGBT is still in a conducting state whereas the paralleled diode (Type BYT 30P-1000) is high resistance. Therefore the negative switch current first flows through the IGBT. This causes a removal of positive charge carriers in the drain sided pn-junction until the IGBT becomes reverse biased and the turn-on process of the diode begins.
The closing overvoltage of the diode can be seen in the voltage waveform of U_{DS}. This overvoltage is extraordinary high in a gold doped diode as it is used here. In a later chapter the influence of the turn-on behaviour of the diode on the turn-off behaviour of the IGBT will be described more detailed. When the diode is completely turned on its small forward voltage can drive a low negative current ($\approx$ 100mA) through the IGBT if its MOSFET-channel is still opened by a positive gate-source-voltage. After the second zero crossing (instant t_2) the positive switch current is caused by the stored charge in the semiconductor devices. The main part of the current I_M is running through the IGBT, where a current tail caused by charge carriers which are stored in the base near the drain sided pn-junction is recognizable. This current tail lasts until the charge is completely removed only by recombination of the carriers. Only if the time of negative switch current is long enough to remove all the charge the IGBT doesn't show current tail as stated by Rischmüller [2].
The drain-source capacitance and the resonant inductance L_r form a resonant circuit. Therefore the current-tail is added to superimposed oscillations whose frequency is not constant. The lower the charge of the inner space charge region the lower is the drain-source capacitance and, hence, the higher is the oscillation frequency. So the oscillation frequency is getting higher during the decaying of the tail.
Most of the turn-off losses result from the current-tail. They depend on the concentration of charge carriers in the base region at the instant t_2.

Switching Losses Depending on the Turn-off Instant

In a resonant application as shown in figure 1 the moment the main IGBT is turned off is very important with regard to the switching losses in the device. In principle three different modes of operation are possible. The first mode is switching-off the IGBT before the first zero crossing (t_1) of the switch current I_M. This mode of operation is not critical but the switching losses are increased compared to the third mode discribed below.
Another possibility which should be avoided in any case is to turn off the IGBT after the second zero crossing. In this case the IGBT has to be turned-off against the reaction of the resonant inductance L_r which causes such high overvoltages that the device may be distroyed. Beside this the switching losses increase excessively with increasing time after the zero crossing (see figure 3).
The preferable turn-off instant lies in the time interval between the two current-zeros. Figure 3 shows the measured energy dissipation W_{off} in the switch in dependence on the switching time t_{EA}. This is the time

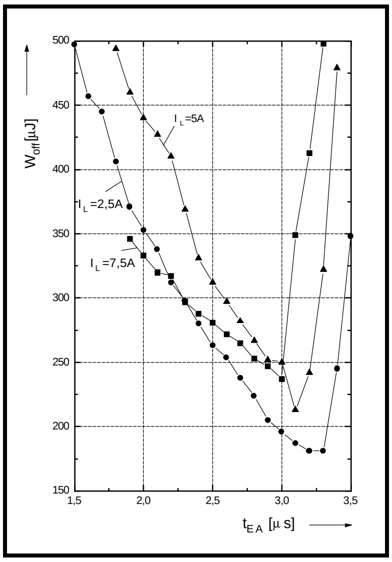

Figure 3: Energy dissipation W_{off} in dependence on the switching time t_{EA} for different load currents

between turn-on of the auxiliary IGBT and turn-off of the main IGBT (see figure 2a). To minimize the switching losses the IGBT should be kept in a conducting state as long as possible. So the optimal switching instant with a minimum of energy dissipation in the device is the instant t_2, the second zero crossing of the current. The reduction of switching losses with increasing time t_{EA} is caused by a small negative current running through the opened MOSFET-channel. This current removes, in addition to the recombination process, the charge carriers which are stored in the base region. During the time the current I_M is running through the diode, the charge and with it the current tail and hence the switching losses are the more reduced the longer the channel is opened.

Influence of the Load Current

The value of the load current has a great influence on the waveform of the switch current. The load current I_L represents the average value of the switch current I_M, which is superimposed to the oscillating resonant current I_r ($I_M = I_L + I_r$). So a variation of the load current value leads to different hold-off intervals in which the diode D_M is conducting. The higher the load current, the more charge is stored in the base region and the shorter is the hold-off interval in which the charge is removed by a negative drain current. The consequence is a rise of the switching losses (see fig. 5).

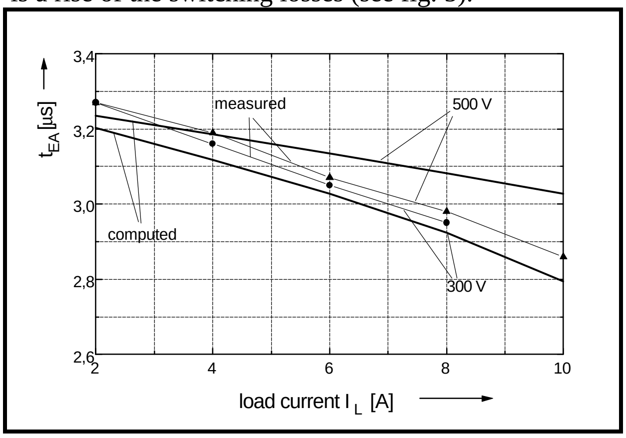

Figure 4: Optimal switching time t_{EA} as function of load current I_L and supply voltage U_0

Figure 4 shows the dependency of the optimal switch-off time t_{EA} on the load current. The measured curves represent those switch-off times t_{EA} where the switching losses are at a minimum. These minima can also be seen in figure 3.

To prove that the best switching instant is at the second zero crossing these instants of zero crossing are exactly computed as a function of the load current by describing the current function as an addition of a sinusoidal oscillation, a constant value and a slope which is necessary because the load current increases until the instant t_2 (see fig. 2). Figure 4 shows that the computed results of the interval t_{EA} are similar to the measured results, where the switching instant (t_0 + t_{EA}) can be set in steps of 100 ns only.

This is a very interesting aspect for the design of trigger equipment. The ideal switching instants can first be calculated in dependency on the load current. The result can be approximated by a linear function which is easy to use in trigger equipments.

In figure 5 the dissipated energy during the described zero current switching turn-off process (soft switching) is represented and compared to that in a hard switching application. It shows that the switching losses can be reduced important by using the above described method of switching in the second current-zero, especially at high load currents.

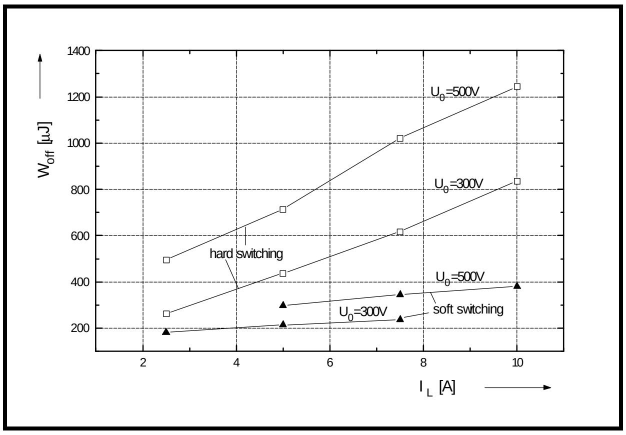

Figure 5: Dissipated energy W_{off} during the turn-off process in a zero current switching and a hard switching application

Influence of the paralleled diode on the turn-off behaviour

The turn-off behaviour of the anti-paralleled diode D_M has a great influence on the switching behaviour of the main IGBT T_M. A comparison between the waveform in figure 2b and figure 6 shows that the reverse current peak through the IGBT T_M is higher by using a gold doped diode (BYT 30P-1000) than by using a platinum doped (BYP 103). Also the diode's forward voltage peak which can be seen as a negative peak in the U_{DS}-waveform is much higher with the gold doped diode.

The closing overvoltage is caused mainly by the base resistance of the low doped middle region of the diode

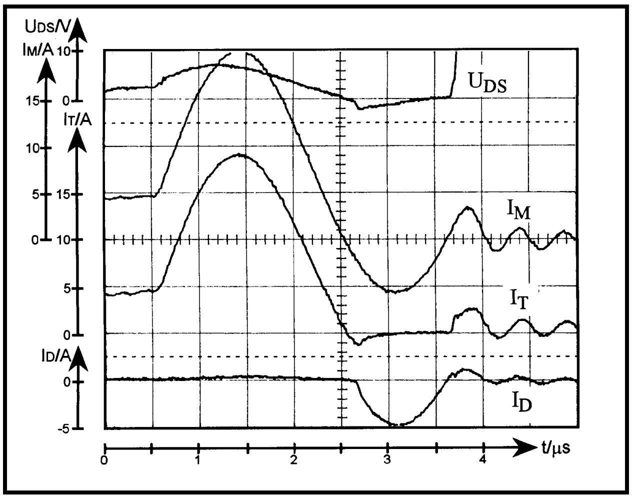

Figure 6: Current and voltage waveforms with a diode of type BYP 103 in anti-parallel to the main IGBT

which is not yet overflowed by charge carriers. In gold doped diodes this resistance is much higher than in platinum doped [5]. The different values of resistance are the reason for the different waveforms of the IGBT reverse current. The time integral of the reverse current is proportional to the charge carriers removed from the drain sided pn-junction during the interval of negative current. The higher the base resistance of the diode the greater is the reverse current peak and the more charge carriers are removed. Hence the turn-off losses of the switch must be higher by using a platinum doped diode because they are mainly caused by the current tail. This fact is shown in figure 7 where the measured energy dissipation W_{off} during switch-off is figured in dependence on the switching time t_{EA} and the type of diode. At the optimal switching instant (t_{EA}≈3,1µs) the dissipated energy of the switch with the gold doped diode (solid triangles) is less than half of the dissipated energy of that with the platinum doped diode.

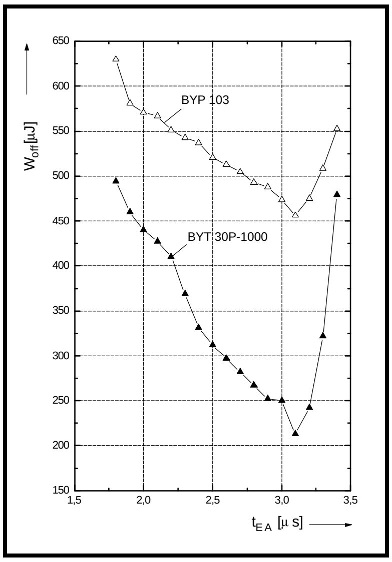

Figure 7: Energy dissipation W_{off} for two diodes of different type at load current I_L=5A

REVERSE BLOCKING CAPABILITY OF A NPT-IGBT

A resonant switch working in the half wave mode demands a device which is able to block a large reverse voltage. In principle a npt-IGBT has this capability because of its pn^--junction between drain and base as it is shown in figure 8.

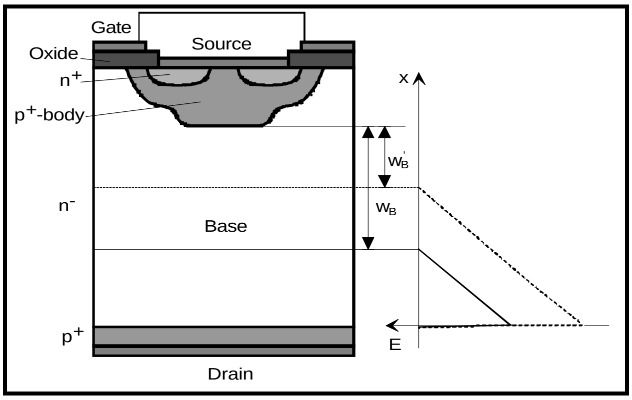

Figure 8: Structure of an IGBT-cell and electrical field distribution in the case of reverse bias voltage

Figure 9 shows the stationary reverse blocking characteristics of an IGBT of the type BUP 304 (15A / 1000V) for different values of the gate-source-voltage.

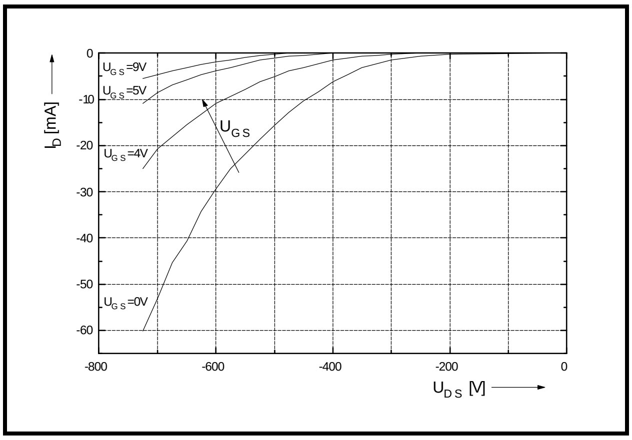

Figure 9: Reverse blocking characteristics of an IGBT for different values of the gate-source-voltage

Although the breakdown voltage is not yet reached the leakage current I_D of the device is much greater than the leakage current I_{DB0} of the drain sided pn-junction. The current I_D increases with increased reverse voltage.

This behaviour is caused by the internal pnp-transistor of the IGBT whose base current is zero (base open-circuited) if the MOSFET-channel is closed (U_{GS} = 0). The collector of this transistor is identical to the drain of the IGBT and the emitter is identical to the p^+-body. In this configuration the leakage current is amplified by a factor which includes the static common-base current gain α:

$$I_D = \frac{I_{DB0}}{1-\alpha} \quad (1)$$

The current gain α itself is a function of the base width w_B [6]:

$$\alpha \approx 1 - A \cdot w_B - B \cdot w_B^2 \quad (2)$$

The constants A and B depend on the doping concentration, the diffusion coefficient and the diffusion length of base and emitter.

Like shown in figure 8 the base width w_B decreases with increasing blocking voltage (area below field distribution), because the space charge zone is extended into the n^--base region of the pnp-transistor. The current gain α is the closer to unity the smaller the base width w_B. So the leakage current I_D in (1) increases with decreasing base width which explaines the reverse blocking characteristic for closed MOSFET-channel ($U_{GS} = 0$) shown in figure 9.

If the MOSFET-channel is opened by a positive gate-source-voltage U_{GS} the junction between base and emitter is paralleled by the channel-resistance. So the emitter efficiency and with it the current gain α are reduced. The current gain decreases with increasing gate-source-voltage and is nearly zero if the MOSFET-channel is completely opened ($U_{GS} \approx 15V$). In this case the leakage current I_D is equal to the leakage current I_{DB0} of the drain sided pn-junction.

The stationary reverse blocking characteristics in figure 9 show that if the condition of positive gate-source-voltage is fulfilled the npt-IGBT can be used in applications which demand the reverse blocking capability of the semiconductor device.

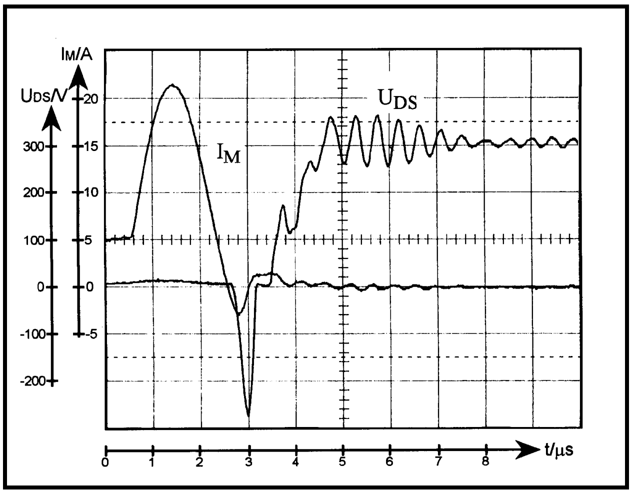

Figure 10: Current and voltage waveforms during the turn-off process in a half wave mode application

This is demonstrated in figure 10 where the current and voltage waveforms during the turn-off process in a half wave mode application are figured. For the measurement of these waveforms the test circuit shown in figure 1 was operated without the diode D_M. The operating conditions are similar to those published by Heumann et. al. [1] but the resulting waveforms are different because the MOSFET-channel is opened during the whole interval of negative IGBT voltage. So the reverse recovery of the IGBT is similar to that of a p^+n^--diode where the negative current removes charge carriers from the base region. If the whole charge is removed no current tail occurs when the IGBT is blocking a positive voltage. Beside this the on-state voltage drop is lower than in [1] because the series diode is not necessary.

These are some new aspects in conjunction with the half wave mode operation of a npt-IGBT. In principle it can be used in applications demanding the reverse blocking capability. But there is to do some more investigation to give a final statement if the application in current source inverters and in cycloconverters may be possible.

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