Adaptation of IGBT Switching Behaviour by Means of Active Gate Drive Control for Low and Medium Power

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Abstract

Active gate drive control methods for 1200V-IGBTs of low and medium power have been investigated. The control methods di/dt control, two step gate resisitor and du/dt-control have been investigated separately. For turn-on the di/dt control gives promising results. For turn-off one single method can't fulfil the needs for an optimal behaviour alone. However a combination of two step gate resistor control and di/dt control is favourable here. The selected methods enable full adaptation to the application and give significant lower turn-off delay time, losses and overvoltage.

1. Introduction

The standard solution for gate drives for IGBTs nowadays is mostly done with pure resistive control, see Figure 1. To turn-on, the gate on state voltage V_{GG} is switched to the IGBT gate via the turn-on gate pre-resistance R_{Gon} and in the analogous way for switching off. The switching speed can be controlled by these resistances. Gate-Emitter-Clamping (zener diodes ZD2 and ZD3), desaturation-monitoring (diode D_1) and overvoltage clamping (zenerdiode ZD_1) are usually integrated in the gate drive to keep the IGBT in its safe operating area under worst case conditions like short circuit or overvoltage in the dc link [1, 2].

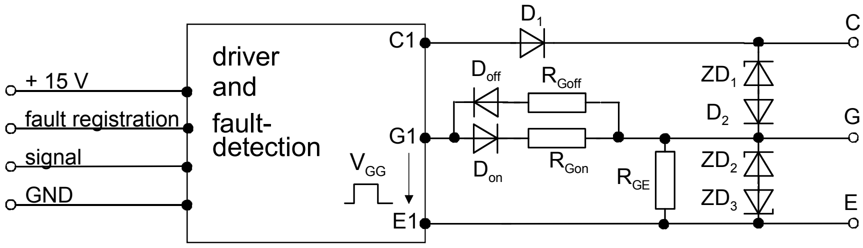


Fig. 1: Principle of a gate driver with resistive control and additional protective measures

There are some drawbacks of the resistive control. There is no separate influence on collector current and collector emitter voltage in the switching intervall. The switching losses increase relatively strong with higher R_G. Varying the gate resistance influences both the switching and delay times. Often it is not possible to control overvoltages at turn-off sufficiently and in case of series connection of IGBTs additional measures are to be taken. To avoid these drawbacks and to adapt and optimize the switching behaviour to the requirements, the gate drive can be controlled actively. A lot of work has been done and published in this field, mostly for IGBTs in series connection or for high power [3, 4]. There are only few investigations aimed at the power range below high power [5], where because of extreme sensitivity to costs only a limited number of additional electronic components are allowed.

In this paper investigations are presented on the optimization of the switching behaviour of single IGBT under the condition of use of relative few additional electronic components. Some basic concepts for active gate drive control are investigated and selected, adapted to the requirements at low and medium power, implemented and the behaviour is measured. The possible range of adaptation will be evaluated. The investigated IGBT module is of the planar type (BSM75GD120DN2, 1200 V/ 75 A) [6]. In chapter 5 some investigations are done for a new trench type module (FS450R12KE3, 1200 V/ 450 A) [7], too.

2. Active Gate Drive Control for Low and Medium Power IGBT

There are several concepts for active gate drive control. With the di_C/dt feedback control, shown in figure 2, the di_C/dt of the collector current i_C is sensed and fed back to the gate control path. In this way a control of the rise of the collector current is possible [8]. This is analogous possible for dv_{CE}/dt feedback control of the collector emitter voltage v_{CE} , see figure 3 [8].

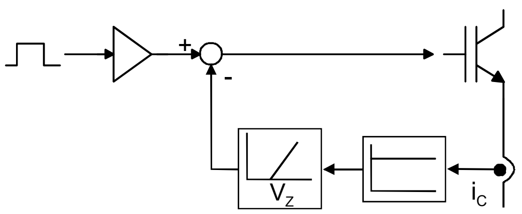


Fig. 2: di_C/dt feedback control, concept

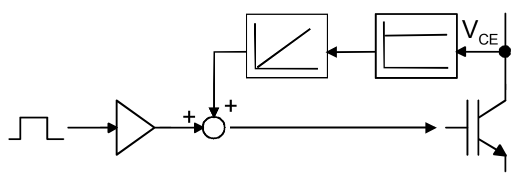


Fig. 3: dv_{CE}/dt feedback control, concept

The gate current can also be controlled by the multistep switching of gate pre-resistors, figure 4. In a two step version, for example, low resistances allow low delay time, soft di_C/dt is achieved by means of higher resistance values [9]. There is another method, that is to feed additional currents into the gate as shown in figure 5. In one application, for example, this is specifically used to increase the gate current i_G for accelerated loading of he gate capacitance when the miller plateau is reached and thus to reduce the losses [10].

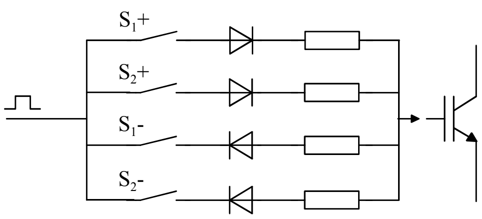


Fig. 4: Multi step gate resistor switching, concept

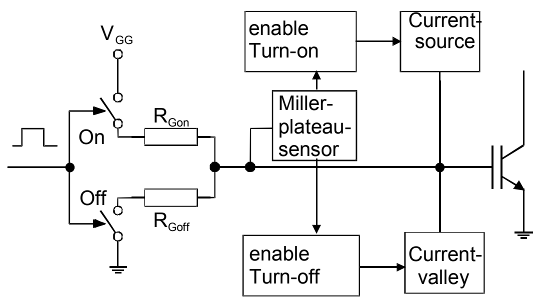


Fig. 5: Miller plateau controlled i_G control, concept

Several other variants of the basic methods have been investigated from other authors for high power or applications with series connection of IGBTs. Here, some of the active gate control methods have been selected and applied to IGBT modules of the 1200 V voltage class which are used in applications below the high power range. These are the two step gate resistance control for turn-off, the di/dt control and the dv/dt control for turn-on and turn-off.

3. Active Gate Control for Turn-on of a Planar IGBT

An easy realization of the dv/dt-control is possible by an external capacitance between the collector and the gate of the IGBT which differentiates the voltage rise. The current through this capacitance is proportional to the dv_{CE}/dt and fed back to the gate of the IGBT. Caused by the external capacitance the turn-on shows a slower fall of the collector emitter voltage. During the collector current rise this leads to a decrease of the di_C/dt and a lower reverse recovery current peak of the freewheeling diode. This causes a softer turn-off of the diode. On the other hand the slower drop of the collector emitter voltage leads to remarkable higher turn-on losses in the IGBT.

The practical realization of di/dt control used for the investigations is shown in figure 6. The internal inductance of the module between the control emitter and the main emitter is used as a sensor for the di_C/dt. The feedback circuit consists of a zener element with the zenervoltage V_Z and a resistor R_Z. Two variants of the zener element are tested. Variant b) has a better performance concerning the breakthrough behaviour and so it is used for the investigations. Table 1 gives an overview of the parameter of the test circuit.

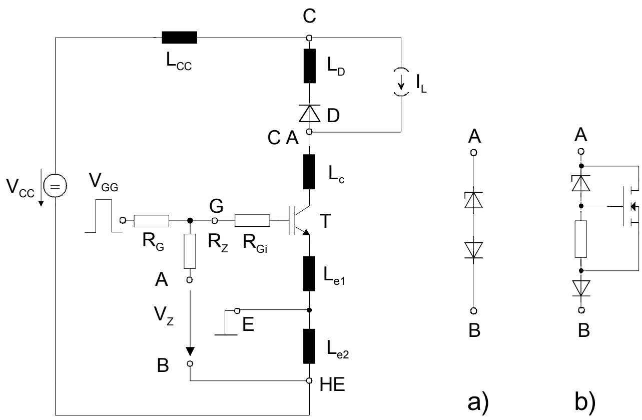


Fig. 6: Drive circuit with di/dt control

Table I: Overview on parameters

R_{Gi}	internal gate resistance of the module
L_{e1}	parasitic inductance between the emitter of the chip and the control terminal of the module
L_{e2}	parasitic inductance between the control terminal and the main terminal of the module
L_C	parasitic inductance between the collector of the chip and the main terminal of the module
L_{CC}	parasitic inductance of the busbar and the dc-link
L_D	parasitic inductance of the freewheeling diode

Analyzing the behaviour of this drive circuit, it is to be stated that the actual value of di_C/dt is given by the voltage drop v_{Le2}:

$$v_{Le2} = L_{e2}\frac{di_C}{dt}. \tag{1}$$

If the breakthrough voltage of the zener element is not exceeded, i.e. $V_Z > (v_{Le2} + v_{GE})$, the control loop is not active and the di_C/dt is given by the next equation [11]. The driver then acts in the resistor control mode.

$$\frac{di_C}{dt} = \frac{V_{GG} - V_{GE(th)}}{(R_G + R_{Gi})C_{GE}/g_{fs} + L_{e1}} \tag{2}$$

If the breakthrough voltage is exceeded , i.e. $V_Z < (v_{Le2} + v_{GE})$, the di_C/dt-control is active and following equation is valid [12]:

$$\frac{di_C}{dt} = \frac{V_{GG}R_Z + V_Z R_G - v_{GE}(R_G + R_Z)}{\frac{C_{GE}}{g_{fs}}[R_G R_Z + R_{Gi}(R_G + R_Z)] + R_G(L_{e1} + L_{e2}) + R_Z L_{e1}} \tag{3}$$

The diode decouples the di/dt control loop at turn-off because of the inverse voltage drop over L_{e2}. With the resistor R_Z it is possible to tune the amplification of the di/dt control. The dimensioning of the control loop could be realized for a maximum di/dt or for the di/dt at the beginning of the reverse recovery respectively of the load current.

Figure 7 shows a turn-on with di/dt-control using a very small gate resistor R_G. Table II gives an overview about important parameters and measured data for turn-on with control via a gate resistor and with di/dt-control. A low value of R_G leads to a short delay time $t_{d(on)}$ and rise time t_r. A controlled rate of rise di_c/dt of the collector current with accordingly remarkable reduced reverse current peak I_{RRM} and softer reverse current drop of the freewheeling diode are achieved by the di/dt-control.

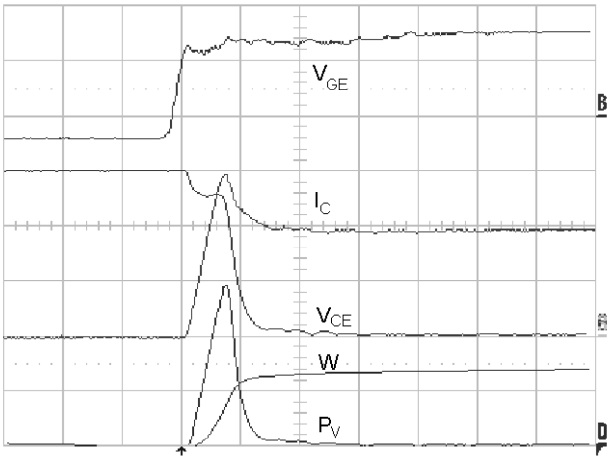


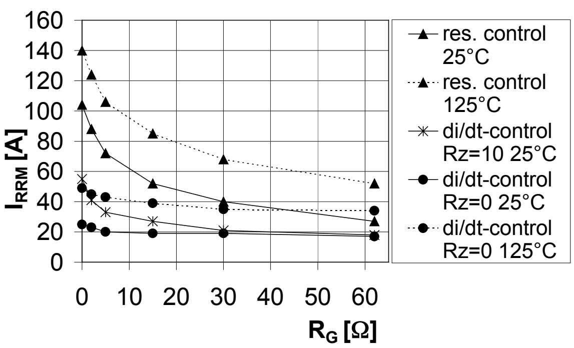
Fig. 7: Turn-on of a Planar-IGBT with di/dt control, R_G = 2Ω; R_Z = 10Ω; V_Z = 16V; t 0,2 µs/DIV; V_{GE} 10 V/DIV; V_{CE} 200 V/DIV; I_C 40 A/DIV; P_V 20 kW/DIV; W 5 mWs/DIV

Table II: Comparison between resistor control and di/dt control

cond.: V_{ZK}=600V; I_L=75A; T_J=25°C

parameter	resistor control		di/dt control
R_G [Ω] R_Z [Ω] V_Z [V]	15	2	2 10 16
$t_{d(on)}$ [ns] t_r [ns] di_c/dt_{max} [A/µs] I_{RRM} [A]	78 68 1250 52	55 36 2500 88	54 58 1100 41
W_{onT} [mWs] W_{offD} [mWs] W_{tot} [mWs]	7,8 0,78 8,6	4,3 0,89 5,2	6,7 0,83 7,5

The diagram in Figure 8 confirms this statement over a wide operating range for the reverse recovery current peak of the freewheeling diode. For a comparable di_C/dt the sum W_{tot} of the IGBT turn-on losses W_{onT} and the Diode turn-off losses W_{offD} are reduced compared to resistor control because of the use of a lower gate resistor (see table II). Figure 9 represents the losses at di/dt-control and at control via a gate resistor. In this way it is possible to meet the demands for an optimal turn-on with the di/dt-control.



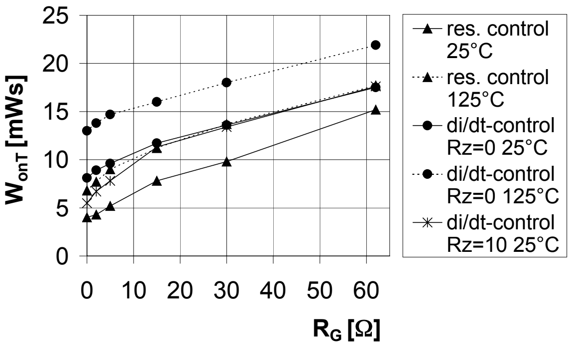


Fig. 8: Maximum reverse recovery current of the freewheeling diode at resistor control and at di/dt control, cond.: V_{ZK}=600V, I_L=75A, V_Z=16V

Fig. 9: IGBT turn-on losses at resistor control and at di/dt control, cond.: V_{ZK}=600V, I_L=75A, V_Z=16V

4. Active Gate Control for Turn-off of a Planar IGBT

First, methods for the adaptation of the turn-off are investigated separately. Some measurements under equal conditions are presented and analysed. It has to be stated, that the two step gate control, see figure 10, leads to a much higher reduced turn-off delay time $t_{d(off)}$. The rate of rise of collector current and collector emitter voltage can be reduced, the overvoltage can be reduced, too. Nevertheless, there are two drawbacks. Current and voltage cannot be affected independently during switching and when significantly reducing the overvoltage with higher gate resistance the losses increase remarkably.

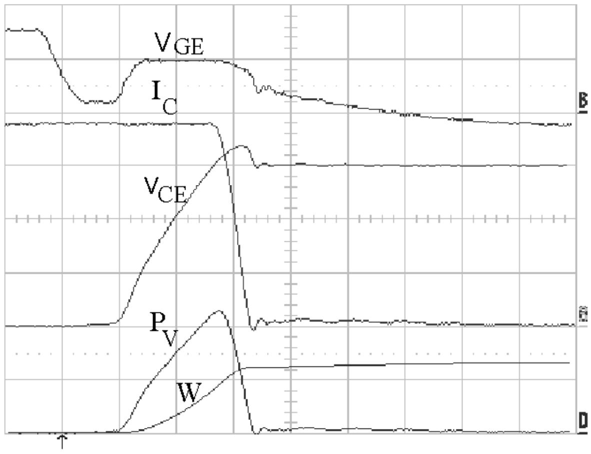


Fig. 10: Turn-off of a Planar-IGBT at two step gate resisitor control, cond. V_{ZK}=600V, I_L=75A, T_J=25°C, $R_{Goff\text{-}1}$=1Ω, R_{Goff}=200Ω, t 0,2µs/DIV, Ch. B: V_{GE} 10 V/DIV, Ch. A: V_{CE} 200 V/DIV, Ch. 3: I_C 20 A/DIV, Ch. C: P_V 20 kW/DIV, Ch. D: W 10mWs/DIV

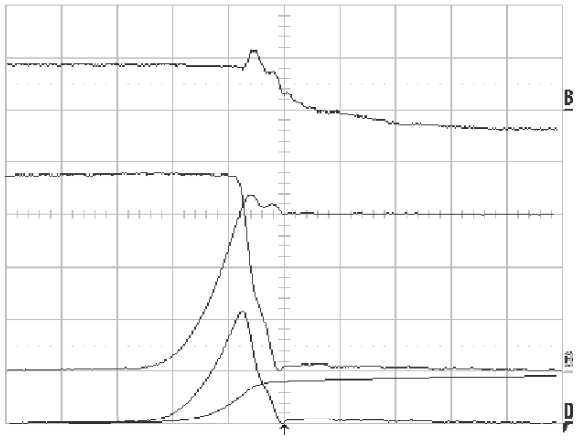


Fig. 11: Turn-off of a Planar-IGBT at di/dt-control, cond.: V_{ZK}=600V, I_L=75A, R_G=30Ω, R_Z=0Ω, T_J=25°C, t 0,2 µs/DIV; V_{GE} 10 V/DIV; V_{CE} 200 V/DIV; I_C 20 A/DIV; P_V 20 kW/DIV; W 10 mWs/DIV

Compared with that, di/dt control, see figure 11, makes it possible to control current and voltage independently over a wide range. With di/dt control first of all a reduced rate of fall of the collector current and lower overvoltage is obtained. Because of a lower speed of the turn-off only in the current fall time t_f the increase of the losses is rather low.

Switching off with du/dt control, the relevant figure is not shown here, leads to slower voltage rise, but in consequence to higher delay time. The fall time of the collector current is reduced, too. There is the disavantage of remarkable higher losses.

As a result of this investigation of applying the control methods separately for turn-off it is to be stated, that there is no single method that will meet all demands of an optimal turn-off alone. Only the combination of methods appears favourable to fulfill this.

The combination of the two step resistor control and the di/dt control is most favourable and is presented here. The gate control circuit is shown in figure 12. Main elements are the via diodes separately, two step switched gate pre-resistances R_{Goff} and $R_{Goff\text{-}1}$. As long as the collector emitter voltage is lower than 15V the small resistor $R_{Goff\text{-}1}$ is active. If the collector emitter voltage exceeds 15 V, the transistor T_2 is switched off by a desaturation detection triggered by means of the diode D_{sat}. The turn-off now will be performed by the higher gate resistor R_{Goff}. The lower part shows the di_c/dt feedback circuit via the module internal stray inductance. Depending on the di_c/dt, this circuit feeds an additional current to the gate via transistor T_3 and three resistors, acting as a fast zener diode with tunable amplification.

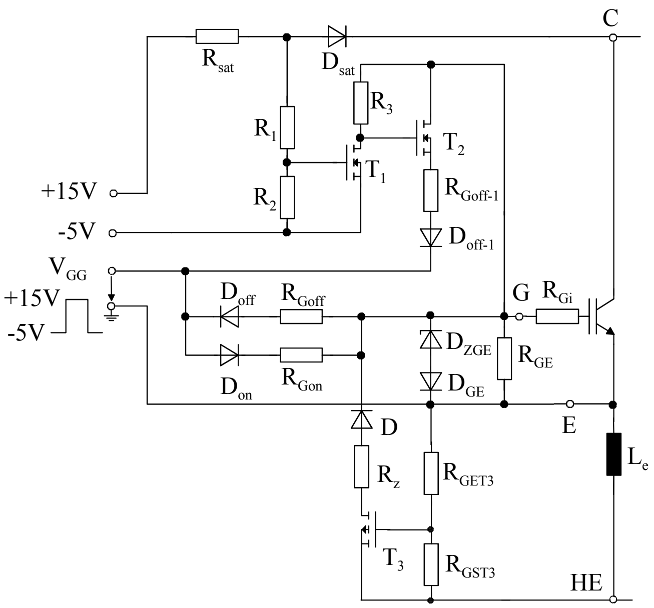


Fig. 12: Gate drive control circuit for combined two step resistor and di/dt control

The turn-off of a Planar-IGBT with the combined two step resistance and di/dt control for example is shown in figure 14 and compared with resistance control at the same value of R_{Goff} shown in figure 13. The low value of resistance R_{Goff-1} leads to a shortened turn-off delay time $t_{d(off)}$. Remind the different time scales of 0,2 µs and 0,5 µs respectively. By means of the higher value of resistance R_{Goff} the du_{CE}/dt can be controlled. Beginning at half of the load current the di_c/dt limiting starts to operate. The overvoltage is lower, the turn-off energy W_{off} is lower, too, compared with the turn-off at resistance control.

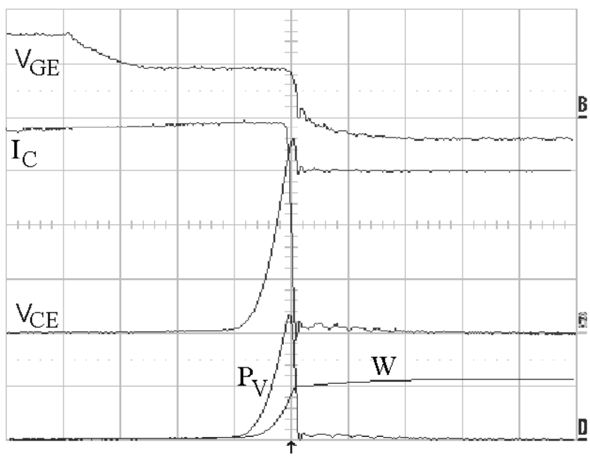


Fig. 13: Turn-off of a Planar-IGBT with resistance control, cond.: V_{ZK}=600V, I_L=75A, R_{Goff}=51Ω, T_J=25°C, t 0,5 µs/DIV; V_{GE} 10 V/DIV; V_{CE} 200 V/DIV; I_C 20 A/DIV; P_V 20 kW/DIV; W 10 mWs/DIV

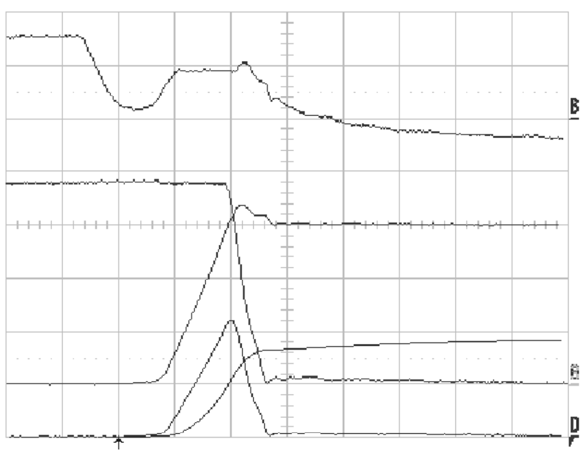


Fig. 14: Turn-off of a Planar-IGBT with two step and di/dt control, Cond.: V_{ZK}=600V, I_L=75A, R_{Goff}=51Ω, R_{Goff-1}=1Ω, R_Z=0Ω, T_J=25°C, t 0,2 µs/DIV; V_{GE} 10 V/DIV; V_{CE} 200 V/DIV; I_C 20 A/DIV; P_V 20 kW/DIV; W 5 mWs/DIV

The results of the combined two step and di/dt control method are summarized and compared to the others. The turn-off delay time for the chosen method in figure 15 is significant shorter as for separate resistor control or di/dt control and nearly the same as for applying only two step resistance control. Already the use of a little raised but relative small R_{Goff} leads to a remarkable reduction of the collector emitter overvoltage, see figure 16.

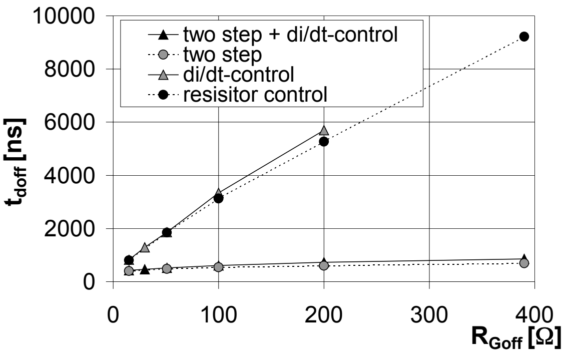


Fig. 15: Turn-off delay time at different control methods

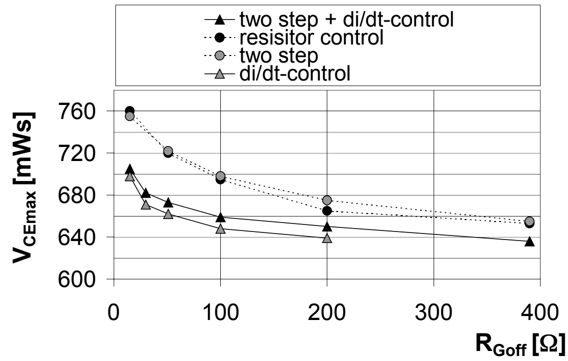


Fig. 16: Maximum collector emitter voltage at different control methods

A fundamental advantage of the proposed method is that for a certain tolerable overvoltage the lowest turn-off losses, see figure 17, are achieved compared to the other methods. A significant better performance for the combined two step resistor and di/dt control is obvious.

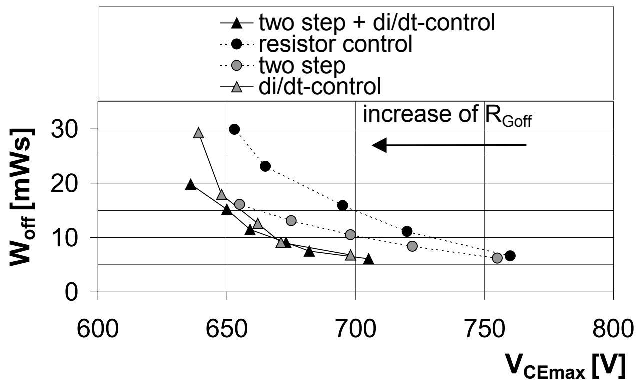


Fig. 17: Turn-off losses at different control methods, V_{ZK}=600 V; I_C=75 A; T_J= 25°C

5. Active Gate Control for a Medium Power Trench-IGBT

In the following part the investigations are expanded to a new 450 A/ 1200 V Trench-IGBT for medium power applications. Principally the same driver circuits are used as for the 75 A/ 1200 V Planar-IGBT. Because of it's fast switching behaviour the investigated Trench-IGBT puts high demands to the driver. Additionally to this, the significant higher current level compared to the Planar-IGBT investigated before leads to higher di_C/dt. That's why the problems with overvoltages for the Diode and the IGBT increase extraordinarily.

Figure 18 shows the turn-on of the Trench-IGBT with resistance control. The collector current rises with a high di_C/dt. This causes a high diode reverse recovery peak current I_{RRM} and following at the reverse current drop a high maximum diode voltage V_{Dmax}. The diode will be stressed strongly with this fast turn-on of the IGBT. With the di/dt-control it is possible to limit the di_C/dt, see figure 19. There is to be observed a lower di_C/dt which results in a lower reverse recovery peak current I_{RRM} and a very soft decrease of the reverse current of the diode. However the turn-on losses of the IGBT W_{onT} increase remarkably. Table III gives an overview about measured data for turn-on with resistance control and di/dt-control.

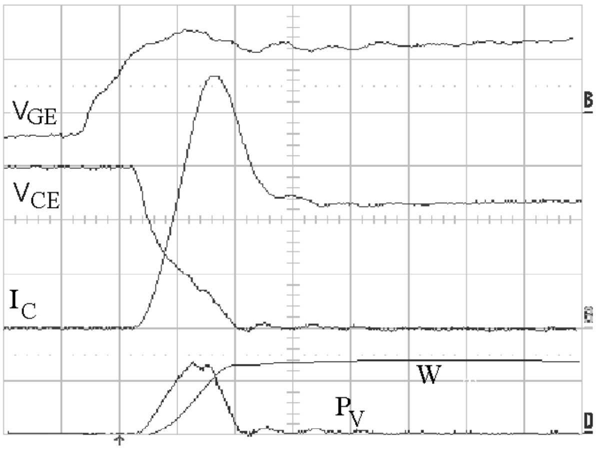


Fig. 18: Turn-on of the Trench-IGBT with resistor control, cond.: V_{ZK}=600V, I_L=450A, T_J=125°C, R_{Gon}=1,6Ω, t 0,2µs/DIV, Ch. B: V_{GE} 10 V/DIV, Ch. A: V_{CE} 200 V/DIV, Ch. 3: I_C 200 A/DIV, Ch. C: P_V 100 kW/DIV, Ch. D: W 20mWs/DIV

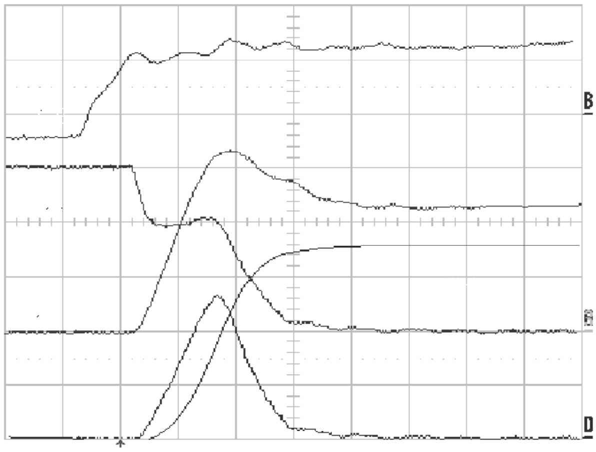


Fig. 19: Turn-on of the Trench-IGBT with di/dt control, cond.: V_{ZK}=600V, I_L=450A, T_J=125°C, R_{Gon}=1,6Ω, R_Z=10Ω, V_Z=16V, t 0,2µs/DIV, Ch. B: V_{GE} 10 V/DIV, Ch. A: U_{CE} 200 V/DIV, Ch. 3: I_C 200 A/DIV, Ch. C: P_V 100 kW/DIV, Ch. D: W 20mWs/DIV

Table III: Comparison of measured data at turn-on with resistance control and di/dt-control

cond.: V_{ZK}=600V, I_L=450A, R_{Gon}=1,6Ω, T_J=125°C, for di/dt-control: R_Z=10Ω, V_Z=16V

conditions	t_{don} [ns]	t_r [ns]	W_{onT} [mWs]	I_{RRM} [A]	V_{Dmax} [V]	W_{offD} [mWs]
resistor control	180	98	27,6	488	816	42,1
di/dt-control,	176	131	70,7	210	600	22,7

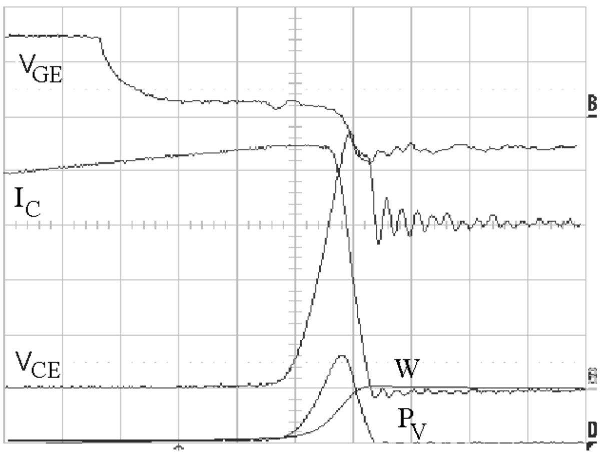


Fig. 20: Turn-off of the Trench-IGBT at resistor control, cond.: V_{ZK}=600V, I_L=450A, T_J=25°C, R_{Goff}=1,6Ω, t 0,2µs/DIV, Ch. B: V_{GE} 10 V/DIV, Ch. A: V_{CE} 200 V/DIV, Ch. 3: I_C 100 A/DIV, Ch. C: P_V 200 kW/DIV, Ch. D: W 50mWs/DIV

Table IV: Parameters of the Trench-IGBT at resistance control

cond.: V_{ZK}=600V, I_L=450A, R_{Goff}=1,6Ω, T_J=25°C

R_{Goff}.	t_{doff} [ns]	t_f [ns]	W_{off} [mWs]	V_{CEmax} [V]
1,6	813	98	51,5	948
5,1	1440	88	61	1103
10	2190	104	78,4	939
15	2970	136	93,4	848

The turn-off of a Trench-IGBT with resistor control is shown in figure 20. There is to be seen the very fast fall of the collector current I_C which causes a high maximum collector emitter voltage V_{CEmax}. Table IV verifies that increasing the gate resistance R_G is not the optimal way to reduce the stress for the IGBT. Only very high values of R_G can limit V_{CEmax} significantly. But the turn-off delay time t_{doff} then rises up to no practicable values. A better way is to use more intelligent control methods. Especially the combination of the two step resistance and the di/dt control is well suited and presented here.

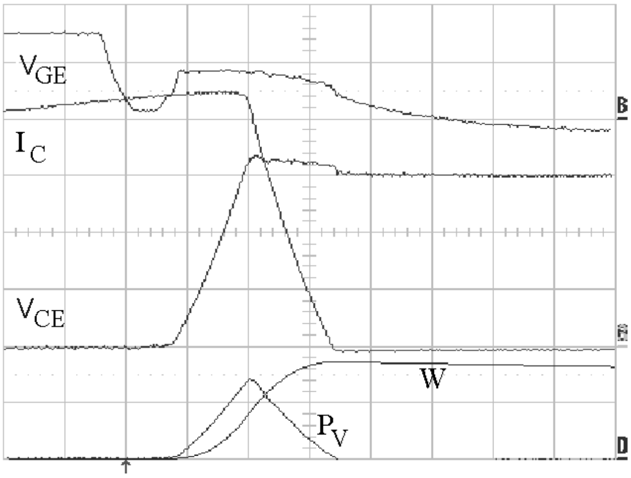


Fig. 21: Turn-off of the Trench-IGBT at two step resistance and di/dt control, Bed.: V_{ZK}=600V, I_L=450A, T_J=25°C, R_{Goff}=51Ω, R_{Goff-1}=0,4Ω, R_Z=0Ω, V_Z=16V, t 0,5µs/DIV, Ch. B: V_{GE} 10 V/DIV, Ch. A: V_{CE} 200 V/DIV, Ch. 3: I_C 100 A/DIV, Ch. C: P_V 200 kW/DIV, Ch. D: W 100mWs/DIV

Table V: Important parameters at the turn-off of the Trench-IGBT with the combination of the di/dt-control and the two step resistance control

cond.: V_{ZK}=600V, I_L=450A, T_J=25°, R_Z=0Ω, V_Z=16V, R_{Goff-1} = 0,4Ω

R_{Goff} [Ω]	t_{doff} [ns]	t_f [ns]	W_{off} [mWs]	V_{CEmax} [V]
5,1	930	475	98	795
15	1017	512	111	748
51	1217	552	171	675
100	1372	580	210	656

Figure 21 shows the turn-off with this control method. The low gate resistance at the start of the turn-off causes a short delay time. The gradient of the collector current is significantly reduced against the resistive control. This leads to a low overvoltage. Table V verifies that thus the switching speed of the Trench-IGBT is controllable in a wide range with the two step resistance and di/dt control. The increase of the losses hereby is moderate compared to the strong reduction of the overvoltage.

6. Conclusion

Methods for active gate control of IGBT modules for the low and medium power range and the adaptation of the switching behaviour to the requirements have been investigated. A limited number of additional electronic elements has been used. Basic methods have been analyzed and selected, implemented and the behaviour has been measured. The di/dt control for turn-on is an optimal method to realize a fast, stressless and low loss switching. The combination of two step resistor control and di/dt control is a very favourable way for the turn-off. This method leads to a reduced turn-off delay time, a lower gradient of the collector current and thus to a low overvoltage. The increase of the losses is moderate. Thus, adaptation to the application is reasonable with these methods in the low and medium power range for Planar-IGBT and also for new Trench-IGBT.

7. References

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