Edited by H. Ryssel, P. Pichler - September 1995

Preventing critical conditions in IGBT chopper circuits by a multi-step gate drive mode

W. Gerlach, U. Wiese

Inst. f. Werkstoffe der Elektrotechnik, TU Berlin, Sekr. J10
Jebensstr. 1, 10623 Berlin, GERMANY

Abstract

It will be shown, that critical conditions of the diode in a chopper circuit can be avoided using a multi-step gate drive mode. Moreover, it is demonstrated that the total losses of the chopper circuit can be reduced by an appropriate choice of the hight and length of the gate voltage steps.

INTRODUCTION

In chopper circuits and hard switching inverters, full use of the short switching times of IGBT's can only be made in combination with specially adjusted freewheeling diodes. These diodes are difficult to realize even with sophisticated technological processes and new design concepts [1, 2]. So diodes which can withstand all the stresses imposed by fast switching are scarcely available. Thus in practical circuits, the freewheeling diode may prove to be the weakest element. Especially for fast turn-on of the IGBT, the diode may be driven into an unstable state and can be destroyed [3]. To avoid this dangerous situation, it is common practice to reduce the switching speed of the IGBT current by increasing the rise time of the gate voltage via series resistors in the gate circuit. However, this increases the switching losses and may enhance the total losses appreciably at higher frequencies. In the paper it is shown, that with the multistep gate drive mode it is not only possible to prevent the dangerous situations but also to compensate the excess switching losses of the IGBT by lower on-losses.

PRINCIPLE OF THE MULTI-STEP GATE DRIVE MODE

When the IGBT is switched on fastly, a very high reverse current peak can occur in the freewheeling diode. The operating point in the IV-characteristics of the IGBT (Fig. 1) normally follows the dotted line from point A to point B. During this transition the diode takes over the full supply voltage and the excess reverse current tends to zero. But if the peak reverse current initiates the dynamic avalanche [4], the diode is no longer able to block the full supply voltage [3] and the trajectory of the operating point will end at point C. In this state the diode carries a large current at a high voltage. According to the enormous power losses it will be thermally de-

stroyed in a short time.
Reducing the gate voltage to V_{G1} offers a simple way to avoid this critical condition effectively. V_{G1} can be made as low as the gate voltage V_{GO} which is necessary to carry the load current I_L. At $V_{G1} = V_{GO}$ the IGBT would limit the recovery current of the diode to $I_R = I_L$. Since the drain voltage V_{CE} of the IGBT remains nearly at V_{DD} up to the moment where the stored carriers in the diode are removed, the fall-off of V_{CE} starts later for lower recovery currents. Thus it is to be expected that the turn-on losses of the IGBT for switching from the operation point A to B' are increased compared to switching from A to B. But if the gate voltage is raised from V_{G1} to V_{G2} after the transition to B', the current of the IGBT will remain at the load current I_L during the transient from B' to B. During this time the recovery current from the diode is zero. Therefore it is possible to raise the gate voltage to a value, which is higher than it is allowed by the normal driving mode owing to the dynamic avalanche. As a consequence the on-voltage of the IGBT can be driven lower, reducing the on losses. This can be utilized to compensate or even to over-compensate the excess switching losses. The extent can be controlled by the hight and time delay Δt of the gate voltage step and will depend on the lengths of the on-time of the IGBT.
This approach can also be extended to a multistep waveform of the gate voltage (Fig. 2). It offers additional flexibility to adapt the drive signal to varying load conditions.

CURRENT AND VOLTAGE TRANSIENTS

The detailed operation of the chopper circuit, shown in the inlet in Fig. 3, has been investigated by isothermal numerical simulation using the device simulator MEDICI. The calculations are performed for the temperature T = 300 K and for the supply voltage V_{DD} = 1600 V. The breakdown voltage of the diode is 1650 V and that of the IGBT 1800 V. The diode is a standard PIN-diode with a homogeneous carrier lifetime of $\tau = 0.5\ \mu s$ and a forward voltage $V_F = 0.95$ V at a current density of $j_F = 200\ A/cm^2$.

In Fig. 3, the current waveforms of the IGBT for different hights of a single gate voltage step are depicted. It can be recognized, that for a gate voltage of $V_G = 12$ V the dynamic avalanche in the diode will occur. Passing a sharp peak, the current steadily increases and tends to a value limited by the applied gate voltage. A similar behaviour is observed for gate voltages down to $V_{G,Cr} = 10$ V. Below this critical value, the current decays after passing a lower and broader peak to the stationary load current I_L. The quite abrupt fall off at t = 0.25 μs and t = 0.37 μs, respectively indicates a snap-off behaviour of the diode. According to the high dI/dt the voltage across the parasitic inductance L_σ drives the diode into breakdown for a short moment, as shown in Fig. 4. But carrier multiplication only produces a tail current, if the steep decay begins at a large current density, as represented by the waveform for V_G = 9V. For lower gate voltages, as for instance V_G = 8V, instead of a tail an oscillation appears in the current waveform. It is generated by the interaction of the parasitic inductance and the space charge capacitance of the diode.

From Fig. 4 it is seen, that for $U_G = 12$ V the diode cannot take over the full supply

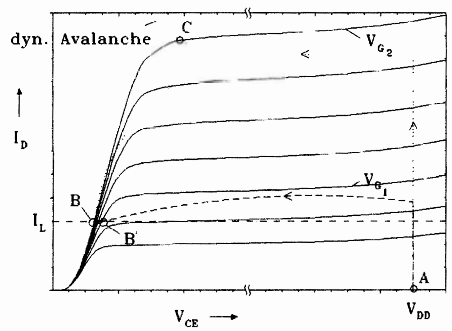

Fig. 1: Output characteristics of an IGBT and trajectories of the operating point for different gate voltages. I_L is the stationary load current.

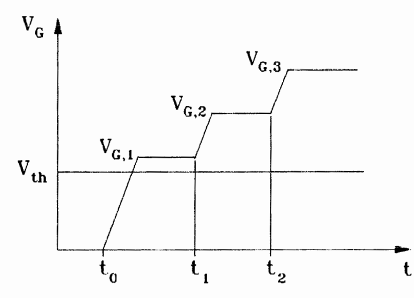

Fig. 2: Typical waveform of the multi-step drive mode

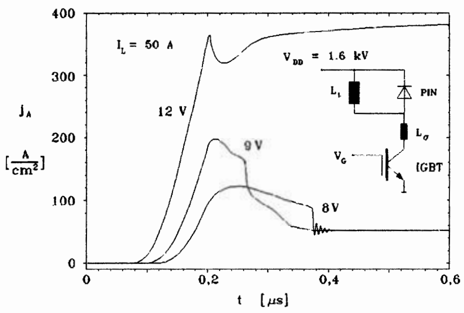

Fig. 3: Current waveforms of the IGBT for different single-stepped gate voltages (L_σ = 50 nH)

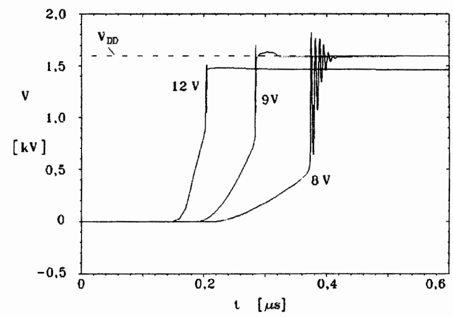

Fig. 4: Voltage transients of the PIN - diode for different gate voltages

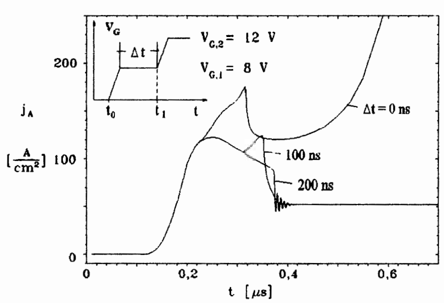

Fig. 5: Typical waveforms of the anode current in the case of a dual-step gate voltage for different time delays Δt_1 of the second step (L_σ = 50 nH)

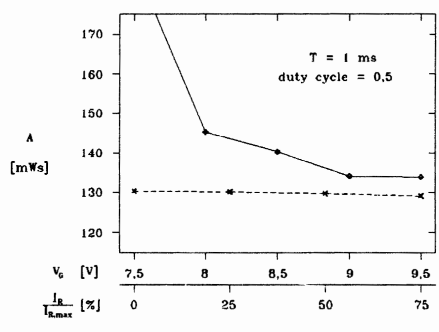

Fig. 6: Total losses of the chopper circuit
♦ : single-step drive mode
x : dual-step drive mode

voltage of 1600 V. Its blocking voltage is reduced to 1470 V so that a voltage of 130 V remains across the IGBT.

In Fig. 5 typical waveforms of the IGBT current are shown for a dual-step gate voltage. The gate voltage is ramped in the first step from 0 V to 8 V and in the second one from 8 V to 12 V within 200 ns in each case. The time delay Δt is varied from $\Delta t = 0$ to $\Delta t = 200$ ns. The case, where the second step starts after the end of the recovery process of the diode, is represented by the waveform marked by $\Delta t = 200$ ns. It is the same curve as obtained for a single-step gate voltage of 8V. Its peak current remains well below the value initiating the dynamic avalanche (peak for $\Delta t = 0$). On the other hand it could be easily lowered by a smaller V_{G1}. Moreover, if the second step starts before the recovery process is completely finished ($\Delta t = 100$ ns), the induced excess current also does not grow to a dangerous value. This demonstrates the stability of the drive mode against slight fluctuations of the recovery time.

POWER LOSSES

The total losses of the chopper circuit are calculated for a frequency of $f_o = 1$ KHz and a duty-cycle of 0.5. The results are shown in Fig. 6. For the dual-step gate drive mode V_{G1} is 8 V and $V_{G2} = 12$ V. The corresponding losses are presented for different time delays in the lower curve. Instead of expressing Δt in nanoseconds, the start, t_2, of the second step is marked by $I_R(t_2) / I_{R,max}$, where I_R is the recovery current of the diode. The total losses remain unchanged whether the second step starts after the decay of the recovery current (0 %) or about 150 ns before (75 %). This is attributed to the on losses of the IGBT, which dominate the switching losses at the frequency f_o. Although V_{G2} exceeds the critical gate voltage $V_{G,cr} = 10$ V by only 2 V, the total losses are less than those for the single-step gate drive at the maximum allowable gate voltage ($V_G = 9.5$ V).

CONCLUSION

The multi-step gate drive mode has been studied by means of two-dimensional device and circuit simulation. It is shown, that the stresses imposed on the freewheeling diode in a fast switched IGBT chopper circuit can be drastically reduced. Further, it is demonstrated that this mode can be utilized to minimize the total losses.

ACKNOWLEDGMENTS

This work has been financially supported by Siemens. We thank Dr. M. Braun, Dr. H. Mitlehner and A. Porst for helpful discussions.

REFERENCES

/ 1/	H. Schlangenotto, et.al.	IEEE Electr. Dev. Let. 10, pp. 322-324, 1989
/ 2/	M. Mehrotra, B.J. Baliga	Proc. ISPSD, pp. 190-204, 1993
/ 3/	A. Porst	Proc. ISPSD, pp. 163-170, 1994
/ 4/	H. Schlangenotto, H. Neubrand	Arch. Elektrotech. 72, pp. 113-123, 1989