Compact high voltage IGBT switch for pulsed power applications

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***Abstract* — This paper describes the development of a semiconductor based switch for use in pulsed power technology. Because of the more stable operating conditions, given by the semiconductor devices, this switch could be used to replace the up to now in pulsed power technology common used spark gaps.**

We defined a technical concept for a semiconductor based switch with a maximum voltage of 20 kV and a current capability in the order of 1 kA. This concept also should enable to generate pulses widths of a few µs. We found an IGBT with a maximum blocking voltage of 1700 V, a signal rise time of 100 ns, and a short circuit current rate of 650 A to be suited to realize our concept for the switch. Because of the defined maximum voltage of 20 kV it was necessary to use a series connection of the IGBTs. To ensure a synchronous switching of the in series connected devices, a trigger unit was built up which was inductively connected to the driver circuits of the single IGBTs.

Single devices where tested and separated for the series connection. With the handicap of a given 155 mm circuit board we designed a complete switch, basing on industrial standards, with 15 IGBTs and a finally maximum blocking voltage of 18 kV, and a current capability of 500 A. The design of this circuit also included the development of a protecting circuit (active clamp) to protect the single devices of an over voltage damage during the switching, and also to avoid an inhomogeneous split up of the voltage to the different devices.

Keywords – pulsed power; IGBTs; series connection;

I. INTRODUCTION

For different pulse power applications very fast switches with a high repetition rate at a high voltage and current capability are needed. Up to now the most used switches in this technology are spark gaps, because of their advantages concerning the power capability. But for several applications the disadvantages of this technology, e.g. the short lifetime, prevent to find a usable solution [1].

The development in semiconductor technology nowadays suggest to construct a switch for pulsed power applications by making use of the advantages of semiconductor technology, e.g. the long lifetime and stable operating conditions [2]. For a solution it is possible to use different devices. One of the usable devices for power applications are thyristors, with a high blocking voltage, a high current rate, but a small signal rise time [3, 4]. So they are not suitable to construct fast switches. Another possibility is to use MOSFETs. These are faster devices then the thyristors, but have a lower blocking capability for voltage and a low current capability. The third possibility is given by using an IGBT. Because these devices are an appropriate compromise between performance and fast switching we decided to use IGBTs to construct the switch [5, 6, and 7].

The idea was to use fast IGBTs in a series connection to develop a semiconductor switch with a high voltage and a high current capability. For that we had to identify a suitable device which has a blocking voltage and a current capacity as high as possible. For an exact simultaneous switching of these devices connected in series a trigger unit must be used which gives a simultaneous signal to all devices. Also the devices have to be protected against an inhomogeneous split up of the voltage to the single devices. This is possible to get by separating the devices out of one production line to have identical operating data. The same signal rise time of every single device means more safety of an overload at one point of the series connection. It is also possible to prevent an over voltage damage because of the inhomogeneous split up of the voltage by protecting the devices with a safety circuit. Here the devices will not be stressed by a voltage higher than the maximum blocking voltage of the single device.

II. DEVELOPMENT

A. *Single device tests*

After the decision was made to use IGBTs, several types were tested to find out which one was just the right one to realize this application. So the first tests are made to check the performance data of different single devices.

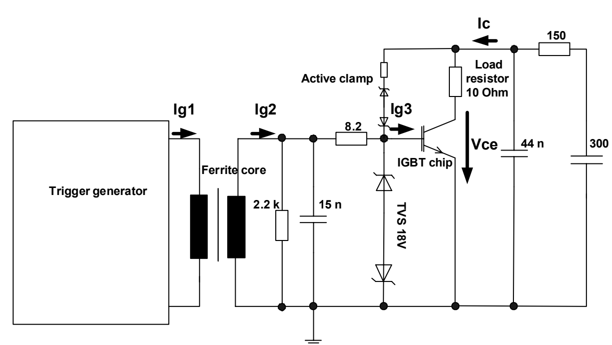

Figure 1. After the decision was made to realize the high voltage switch with IGTBs, different devices were tested. The figure shows the circuit schematics for the single device tests. A separated trigger generator was coupled with a ferrite core to the IGBT driver circuit.

Fig. 1 shows the used test circuit schematics for the single device tests. It consists of a separated trigger generator which was coupled with a ferrite core to the IGBT driver circuit. The IGBT chips were fixed on a ceramic substrate with silicon gel. An active clamp circuit was used to protect the devices from damage due to over voltages. The tests were performed at two DC link voltages, 400 V and 1000 V, at room temperature. The following parameters were investigated:

- The collector current I_C.
- The collector emitter voltage drop V_{CE}.
- The gate current I_{G3}.
- The gate emitter voltage drop V_{GE}.
- The currents I_{G1} and I_{G2} in the primary and secondary winding linked to the ferrite core.

The tested devices are in the voltage classes of 1.7 kV, 3.3 kV, and 6.5 kV. The results showed that all of them could be controlled by the isolated trigger generator unit. During the tests it was also shown that it is possible to generate current pulses of 2 µs duration at 400 and 1000 V.

B. Series connection tests

To realize a switch as defined it is necessary to use the IGBTs in a series connection to get the high blocking voltage. Therefore the single devices now were tested concerning the possibility of a synchronous switching.

The tests were done at 70% of the maximum DC link voltage, with two devices connected in series. Fig. 2 shows the test circuit for two IGBTs in series connection, with the trigger generator linked with a ferrite core to the IGBT driver circuits.

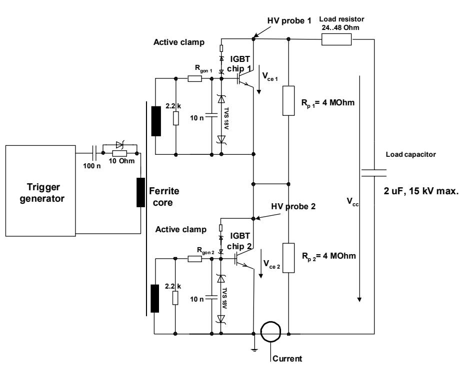

Figure 2. The same devices which were tested as single now were investigated in a series connection. Using the shown circuit the tests showed that it was possible to switch on and off the IGBTs with the trigger unit that was coupled with a ferrite core to all the driver circuits of the single IGBTs. The active clamp circuit was used for the 1.7 kV chip only.

For the three different IGBTs (1.7 kV, 3.3 kV, and 6.5 kV), which were tested as single devices before, now the following parameters were investigated in the series connection:

- The collector current I_C
- The collector emitter voltages V_{CE1} and V_{CE2} at the single devices
- The total collector emitter voltage $V_{CC} = V_{CE1} + V_{CE2}$
- The gate emitter voltage V_{GE}
- The voltage dV/dt and current slopes dI/dt
- The power and energy losses

For the 6.5 kV chips two devices were placed in parallel, however, all parameters were calculated down to one chip. Fig. 3 shows the test circuit which was used to do the measurements. It consists of a power supply unit and a gate driver unit which are combined to a trigger generator. Furthermore the ferrite core to connect this generator to the IGBT driver circuits and the two IGBT chips on a ceramic substrate, coated with silicon gel. The test circuit was completed by the active clamp circuits (used for 1700 V chips only), the load resistor (24 or 48 Ohms), and the load capacitor of 10 nF and 15 kV, in order to switch off the IGBT by a hard turn off. This results in a dynamic switching without loosing too much voltage in the capacitor. The test works therefore also with a 1 kHz cycle.

In the test we have to pay attention to the following problems:

The resistor load has to bear several hundreds of kilowatts during the 1 kHz cycle.

The waveforms of I_C and V_{CE} show desaturation effects (V_{CE} > 10V) during turn off. There are two reasons for this effect. One reason is the high switching current which is close to the level of the desaturation current at V_{GE} = 15 V for the 3.3 kV and 6.5 kV chip. Another reason is the value of $V_{GE,}$ which is reduced to values lower than 15 V during turn off and therefore reduces the desaturation current level. Some tests have shown that the gate voltage waveform is also influenced by noise coupling. Higher energy losses are an important consequence of the desaturation effect.

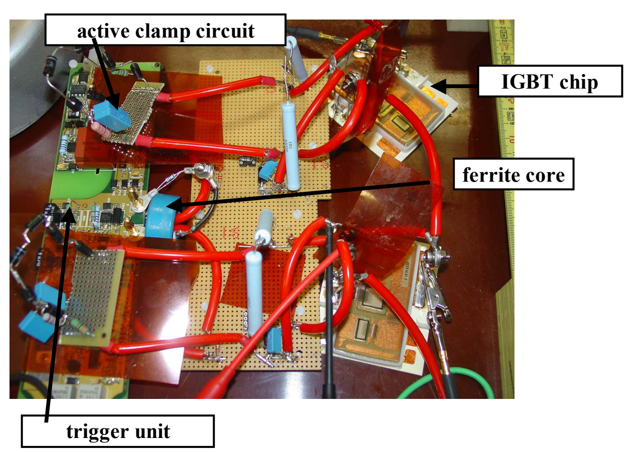

Figure 3. The tests with the in series connected IGBTs were done with a provisional test devices. The picture shows the test assembly for a test of two in series connected IGBTs. The IGBTs were fixed on a ceramic substrate with a silicon gel.

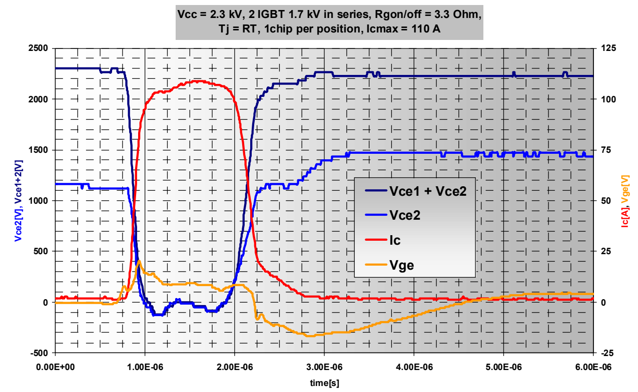

Figure 4. Measurement results by testing two in series connected 1.7 kV IGBTs. The dark blue curve show the total collector emitter voltage in the circuit. The light blue curve results from the measurement of the collector emitter voltage only of the second IGBT (measured at the point marked with "HV probe2" in figure 2).

The biggest problem is the voltage sharing between the chips after turn off. The voltage sharing during the first turn on is perfect due to the parallel resistors of 4 MΩ. However it exist a bad voltage sharing due to the tail current after turn off. We see a solution to this problem in an additional active clamp circuit. A first test with the 1.7 kV chip looks very promising, however, further tests with active clamp circuits adequate for higher DC voltages are needed.

Fig. 4 shows the waveforms for two 1700V chips at a total voltage V_{CC} of 2300 V. It shows that it is possible to turn on the IGBT chips in series with a short pulse of 100A and 1µs pulse width. However, the voltage distribution after turn off gets out of control when the tail currents of the chips become very small. This effect can be balanced by an active clamp circuit. Because the desaturation current is very high of this chip (about 650 A), the device can be turned on very fast and in a fully conduction condition (V_{CE} very low). This results in very low energy losses.

The higher blocking chip types show a larger effect regarding the inhomogenity of the voltage distribution after turn off. This effect is visible from the very early split up of the voltage V_{CE} after turn off in comparison with the 1700V chip. Here, an adequate active clamp circuit must be used which also demands further space on the circuit board.

To decide which of the tested IGBT chips is suited to realize a switch for a high voltage pulse generator we compared the measurement results of all types. Table I gives an overview about the performance data of all tested IGBT chips. It turned out that the chip with the lowest blocking voltage is that with the best performance data. In addition with the measurement results these advantages also exist by investigating the values of the desaturation current, voltage sharing, switching losses, and switching time. For all the tested models of IGBTs the current rise time is not faster than 100 ns.

TABLE I. PERFORMANCE DATA OF THE INVESTIGATED IGBTS

Chip voltage class	1.7 kV	3.3 kV	6.5 kV
Short circuit current [A] (SC1, VGE = 15V, RT)	650.0	160.0	110.0
Peak power [kW] per chip, Turn on	22.0	62.0	90.0
Peak power [kW] per chip, Turn off	36.0	85.0	140.0
Energy losses [mJ] per chip	20.0	150.0	160.0
Voltage slope dv/dt[kV/us] per chip, Turn on	-10.0	-15.0	-30.0
Voltage slope dv/dt[kV/us] per chip, Turn off	6.0	20.0	31.0
Current slope di/dt[A/us] per chip, Turn on	800.0	800.0	600.0
Current slope di/dt[A/us] per chip , Turn off	-400.0	-100.0	-500.0
DC link voltage, Vcc [V]	2300.0	4700.0	9200.0
DC link voltage per chip, Vcc [V]	1150.0	2350.0	4600.0
Collector current Ic[A] per chip	110.0	105.0	105.0
Qtail [uC] integrated after change in di/dt	6.0	4.5	7.0
Rgon/off[Ohm]	3.3	3.3	3.3
All tests done with same GU conditions and at RT			

For the pulse current capability we could find that the 1.7 kV model could handle a current up to 500 A. Because of the lower desaturation current for the models with higher blocking voltage, their pulse current capability is very low at 100 A. Also for these types the voltage sharing is not as regular as for the 1.7 kV chip.

Using the 1.7 kV chip in a series or parallel connection there are 24 devices needed for a 20 kV and 1 kA switch. To realize such a switch with the 3.3 kV chip you have to use 7 devices in series and 7 in parallel. So these are finally 49 devices. And for the 6.5 kV chips the number of needed devices is 40. So as a result it follows that the minimum number of needed devices to realize the defined switch is given for the 1.7 kV chip. So in summary it may be said that the only advantage for the 3.3 kV and 6.5 kV chips is the higher blocking voltage.

As a result from the previous investigations we find that the 1.7 kV chip is the suitable one for the realization of a switch for pulse power applications with a voltage of 20 kV and a current of 1 kA. In order to investigate the serial configuration, the next step was to build up a switch for a blocking voltage of 10 kV, basing on the 1.7 kV chip.

C. *Series connection tests on test board*

The aim of these measurements was to determine the possibility of series connection of 1700 V IGBT chips with simple gate drive. The dynamic voltage sharing was provided by use of a voltage clamp in gate drive. Individual IGBT chips have individual switching times that result in voltage redistributions during turn-off. The fastest IGBT has to block the whole voltage, because the other IGBT do not block yet. The voltage clamp provides feedback in a gate of the IGBT whose voltage exceeded the clamp voltage. The gate voltage goes above threshold, thus keeping the fast IGBT from blocking stage until the slow IGBT will start to block.

For these investigations we realized a test board with ten 1.7 kV IGBTs in series connection. The devices are fixed on ceramic with silicon gel as in the tests before. The board was used to test the series connection and the quality of the trigger unit for a synchronous switching.

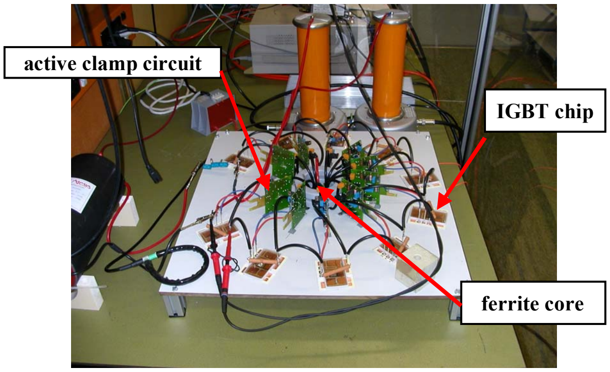

Figure 5. The second step in testing the in series connected IGBTs was to use ten devices. The were also switched with the ferrite core connected triger unit. The picture shows the used test board with 10 in series connected 1.7 kV IGBTs.

The tests were done with a collector voltage V_{CC} from 200 V to 12000 V. The load resistor R_{load} was 20 to 30 Ohm, so that the switched current I_C was in the range from 60 A to 600 A. Fig. 5 show the test assembly which was used to do the switching tests as pulses. The IGBT turn on and off characteristics was measured at RT.

Fig. 6 shows the measurement result of a switching test at V_{CC} = 12000 V. The current I_{Ce} was 450 A. So the series connection works, and it is possible to switch on and off the IGBTs. The blue curve shows the collector – emitter voltage at one single IGBT. It was in the range of 1200 V, which means the exact sharing of the complete voltage V_{CC} of 12000 V for the 10 used devices. It could also be seen that there is no significant over voltage in the moment of turn-on. The blue curve also shows the behavior of the IGBTs protected by the active clamp circuit during the turn-off. The protection circuit slows down the time of turn-off, so that there is no risk that one single device has to block the complete voltage. This could be seen in the figure at the point marked with (*).

After turn-off the voltage V_{CC} does not reach the start value of 12 kV at once. This is because the energy losses of the used capacitor.

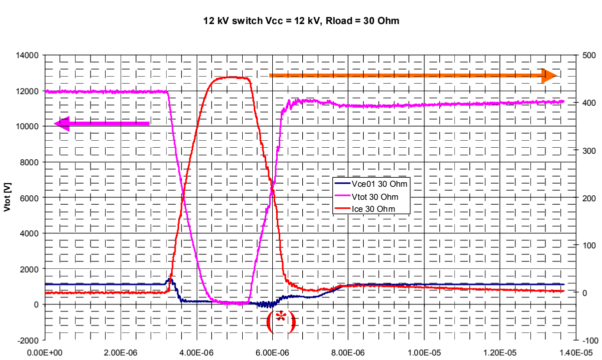

Figure 6. Measurement results by using the test board in figure 5. The maximum blocking voltage for the 10 1.7 kV IGBTs was V_{CC} = 12 kV, because of the limit at 70% of the maximum DC link voltage. The results show a collector voltage V_{CC} of 12 kV and acollector emitter current of 450 A, limited by the used load resistor.

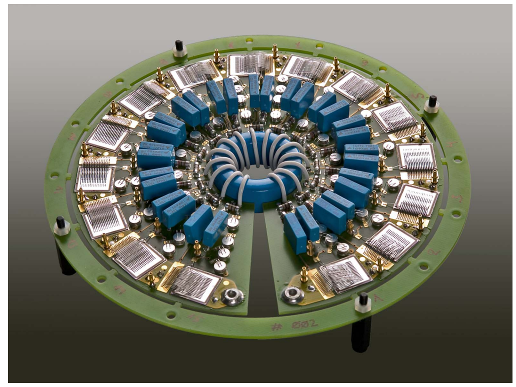

Figure 7. The predefined size for the board and the because of that limited number of the chosen IGBTs that could be used, finally results in the design of a semiconductor switch board with 15 1.7 kV IGBTs for a maximum blocking voltage of 18 kV and a curent of 500 A.

For 10 in series connected 1700 V chips the applied voltage V_{CC} of 12 kV is a limit. Due to the variation in clamp parameters and dynamic over voltage during turn off, the maximal collector voltage could be exceeded which will lead to IGBT failure in open circuit and consequent circuit disconnection. For higher voltages more devices are required. As it could be seen by the results the voltage does not drop to the value of the conduction drop, it means that IGBT is in desaturation phase, (I_{CE} > 600 A) and combination of high current and high remaining voltage across device leads to high losses.

Fig. 6 show that with a smaller current I_{CE} of 450 A the device switches to a low voltage drop and the current graph has a more trapezoidal than triangular shape. That means that, for the low loss operation, a load resistor should be chosen so that I_{CE} remains below 550 A.

D. Circuit board

Because of the up to now given results the values for the pulse power switch as fixed in the beginning now got redefined. The limit in size given by a circle of 140 mm diameter and the chosen 1.7 kV IGBT leads to a series connection of 15 IGBTs. There is no device in parallel so that the limit in current is now 500 A. We have also to consider the 70 % limit for the maximum blocking voltage, so that we finally have a pulse power switch of 18 kV and 500 A.

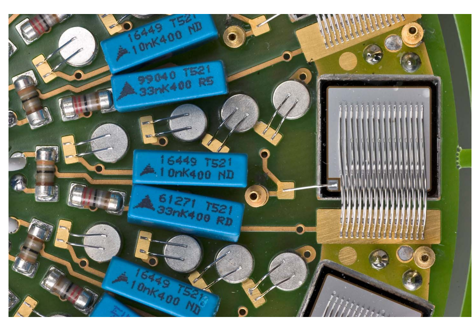

Figure 8. This picture shows some details of the bonding of an IGBT on the board. The components in the left are from the IGBT driver and the active clamp circuits.

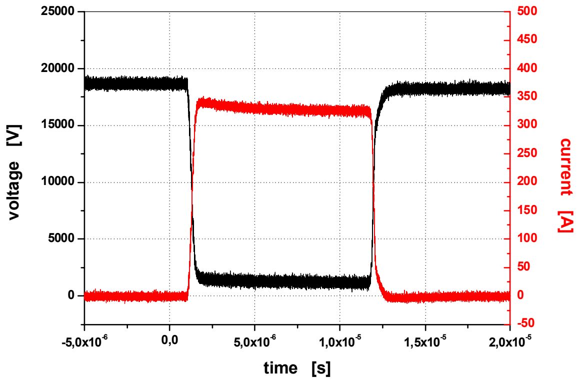

Figure 9. Results from the measurements done with a switch realized with the final design. The collector emitter voltage V_{CC} was 18 kV @ 350 A. The current was limited by the given load resistor. The signal rise time for the current was 110 ns.

Fig. 7 shows the final layout of the realized switch. In the middle of the board the ferrite core can be seen with the secondary windings for each IGBT. Fig. 8 shows some details of the board. There the bonding wires which connected the IGBTs to the board can be seen. At least three of these boards are produced and measured to check the final performance.

The boards were tested in an isolation liquid, here Galden™, to protect the circuit from damage by flashover. The tests were done with a load resistor of 50 Ohms. So it is ensured that the 500A limit will not be toped. Fig. 8 shows the measurement result at 18000V and 350A. It can be seen that the trigger unit works, the switch could be turned on and off, released by a trigger pulse. The current rise time for the pulse is 110 ns.

III. SUMMARY

In this report we presented the development of an 18 kV, 500 A pulse power switch, based on semiconductor devices. Starting with a predefinition of a 20 kV, 1 kA switch we tested different models of IGBTs concerning their usability for such a switch.

We find an IGBT with a maximum blocking voltage of 1.7 kV and a short circuit current of 600 A in maximum as suitable. We defined a trigger unit to switch several IGBTs connected in series simultaneously. The trigger unit was linked to the IGBT driver units by a ferrite core. Also we constructed a protecting circuit (active clamping) to protect the single devices from an over voltage caused by a inhomogeneous voltage distribution.

Finally we developed three pulse power switches with 15 IGBTs connected in series. The maximum voltage amounts at 18 kV, the maximum current at 500 A. We got a signal rise time of 110 ns.

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