Compact High Performance 13.5 kV Multi Wafer Discharge Thyristor for High di/dt Applications

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Abstract—**The design and performance of a compact multi wafer discharge thyristor for high di/dt applications are shown. Investigations under different application conditions show the results and limitations of this component. After tests with several prototype devices in glass fiber epoxy housings an industrial version in hermetically sealed ceramic housing is now available and compared with the prototypes. The device is 120 mm in diameter and 53 mm high, which results in a 50% height reduction and 40% weight reduction compared to discrete components and is therefore ideal for use in mobile applications like active armor in vehicles or deployable railguns. The 13.5kV multichip device is a joined development by ISL and ABB and now available as industrial designed component in hermetically sealed ceramic press pack housing.**

Index Terms—**Multichip Discharge Device, High di/dt Switching, Asymmetric Blocking, Reverse Conducting.**

I. INTRODUCTION

Based on original multichip Thyristors and Diodes with limited current rise rate capabilities of up to 1 kA/µs, ABB and ISL have jointly designed a novel high voltage high current and high di/dt thyristor. The main application areas are active protection launcher systems [1], electro-thermal ignition or electric armor. The device is containing a series connection of three switching wafers and one diode wafer each blocking 4.5kV resulting in a asymmetric device with Vdrm=13.5kV and Vrrm=4.5kV [2]. Due to the highly interdigitated gate structure (GTO-like structure) of the switching wafers, the current raise capability is very high and can reach up to 20 kA/µs. The current capability is up to 120 kA depending on pulse length. Intensive testing was done on several prototype devices before starting the supply as industrial product. This paper will show details about the design, production, testing and application of the new multichip thyristor which can be also supplied as reverse conducting version with monolithic integrated freewheeling diode.

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II. HISTORY

Multichip devices are very often used for discharge applications with low repetition rates and moderate di/dt switching. These products are based on standard 51 mm diode wafers and standard 51 mm thyristor wafers, resulting in limitations in di/dt capability. Such devices are in production and in use since the last 20 years. By using special designed 91 mm discharge thyristors with GTO-like gate structures the di/dt could be increased from max. 1 kA/µs to more than 20 kA/µs and because of larger wafers the current for single shot applications could be increased to > 120 kA. Fig. 1 is showing the different gate structures of both wafers.

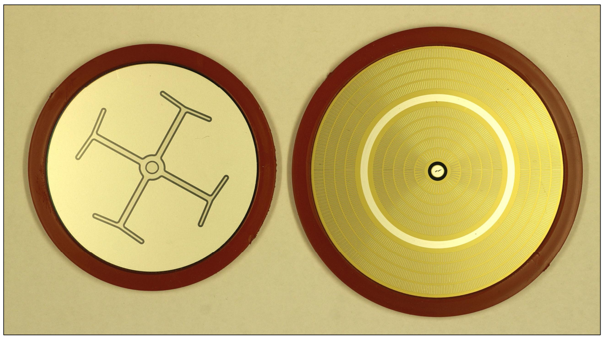


Fig.1: Wafer left with gate structure for ≤ 1 kA/µs, Wafer right with gate structure for > 20 kA/µs

III. TARGET SPECIFICATION

The target specification was based on the requirements for an active armor project with a 50 kJ discharge system. The data indicated is for this specific application but can very strongly for other systems. Table 1 shows the target data.

ABB Part Number:	**5SPB 36Z1350**
Forward Blocking Voltage:	**13.5 kV**
Reverse Blocking Voltage:	**4.5 kV**
Max. DC Charge Voltage:	**10.5 kV**
Peak Pulse Current:	**100 kA @ tp=50µs**
di/dt capability:	**>10 kA/µs @ 100 kA**
Max. Overall Dimensions:	**H=53 x Ø=120 mm**
Weight:	**2.6 kg**

Table 1: Target Specification of 5SPB 36Z1350

IV. MULTICHIP THYRISTOR DESIGN

To reach fast switching and high voltage the use of medium voltage wafers is preferred, but therefore series connection is needed. The selected wafers are asymmetric blocking forward 4500V but reversal only 17V. Therefore a series connection of three wafers is used to reach 13.5kV. To have enough reverse blocking capability a series 4500V diode wafer is used in the same package, resulting in a four wafer construction. The overall diameter of the switching and diode wafer is 91 mm. As gate structure a GTO-like lay-out is used to get a sufficient high di/dt capability. The diode wafer needs to be also in the position to handle also the very high current rise rates. The wafers used in the multichip thyristor are from the mass production line of IGCT components, but optimized for pulse power applications by using a different process and conditioning. Therefore these wafers are in the position to switch-on very fast and can handle very high di/dt, but are not in the position to switch-off any current. First prototypes were built with glass fiber epoxy housings to test the capabilities. Fig. 2 shows a cross section of the construction of the prototype device.

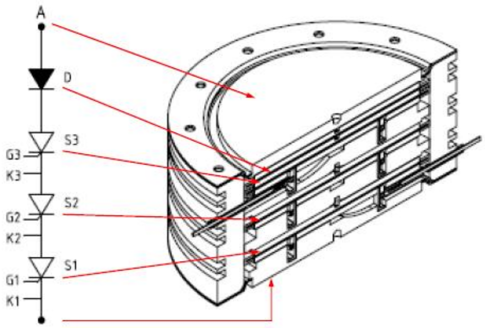


Fig. 2: Construction and Electrical Diagram of multichip thyristor prototype in epoxy housing.

As many single parts are used in the device it is important to have very high quality standards for flatness and parallelism. The next figure shows most of the single parts used except the diode wafer and 4 molybdenum discs.

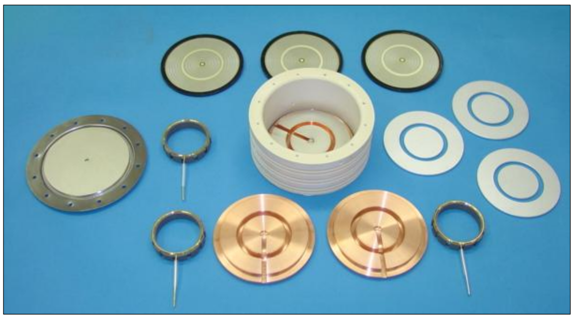


Fig.3: Parts used in the multichip thyristor.

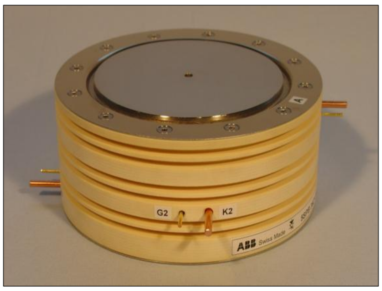
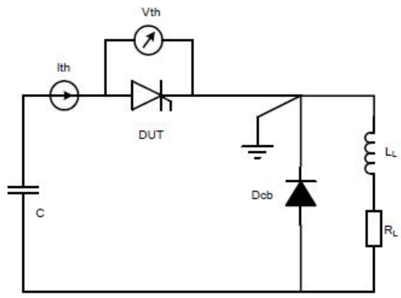


Fig. 4: Prototype multichip device 5SPB 36Z1350 (53 mm x Ø120 mm)

Compared to discrete devices with ring-gate connectors like IGCT, the multichip version has a pin-type connector which reduces slightly the di/dt capability. The gate drive units (one per wafer level) were manufactured by ISL. The multichip device is designed for single shot or low rep. rate applications because of limited cooling capability of the middle wafers.

V. TEST SETUP

Routine production test were done in ABB on the single wafers. After assembling the wafers in the housing the complete device was tested on full blocking voltage and leakage current. The final high current test under different load conditions was done at ISL [3]. The test circuit consists of a high power capacitor C, the switching module, composed of the new multichip thyristor Th (DUT) and a conventional multichip crowbar diode (Dcr) 5SDA 27Z1350, and the load (R_L and L_L).



Capacitor Switching module Load

Fig. 5: Test circuitry

The capacitor (C) is 50kJ / 850µF. Since the attention was focused on the determination of the maximum possible di/dt of the device under different pulse load conditions, the passive elements were adequate adjusted. In all cases the gate pulse had a peak current of 840A and a di_{gate}/dt of 400A. Table 2 lists the three conditions under consideration and its corresponding characteristics as well as the results attained. Initially (condition 1) the device was stressed with 35µs half sine pulse, having a peak current of 100 kA maximum. Next condition (condition 2) the di/dt was raised by reducing the capacitance to 250 µF and finally (condition 3) the elements were adjusted to attain a very high di/dt at reduced peak current level.

VI. TEST RESULTS

A. Prototype device

Figure 6 resumes 4 shots under condition 1. Under this condition the device did not fail. The upper graph shows the current pulse which comes close to a half sine wave with a periodic time of 70 µs. For a capacitor charging voltage of 1,6 kV, the peak current attained 100 kA, which is about the limit of the device. In this case, the maximum di/dt amounted to 9 kA/µs. We did not notice any unusual behavior, as can be deduced from the lower graph of Figure 6, showing the cathode-anode voltage drop of the thyristor. The voltage drop was measured using a voltage dividing method [4]. With the aim of determining the on-state power loss of a high power semiconductor device during switching, this method allows a higher voltage resolution as compared to conventional high voltage probes. This is achieved to the detriment of the maximum voltage which is, in case of the shown curves, limited to 300 V. Additionally, the zero passage of the voltage is slightly shifted, which is to be explained by a parasitic inductance of the measuring loop. Under condition 2 the periodic time of the half sine wave was reduced to 40 µs (20 µs pulse width). This allowed increasing the di/dt at reduced peak current levels (as compared to condition 1). Figure 8 depicts a shot where the di/dt amounts to 12.5 kA/µs at a peak current level of 80 kA. In a subsequent test (not shown) the peak current attained 100 kA and the di/dt even reached 14 kA/µs, but in this case the device failed.

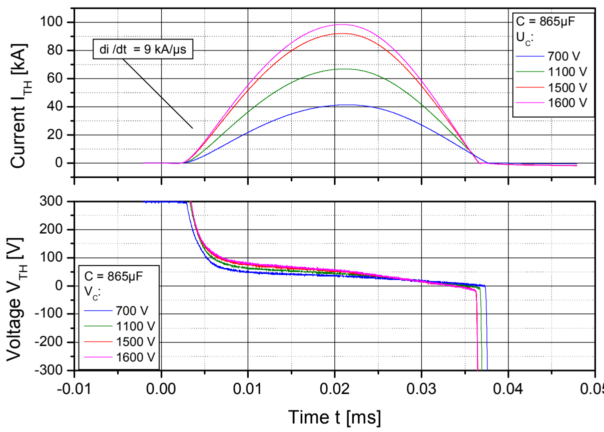


Fig. 6: Condition 1 – Half sine current pulse (upper graph) with a peak current of up to 100 kA and a current rise rate of up to 9 kA/µs. No unusual behaviour of the thyristor voltage drop (lower graph).

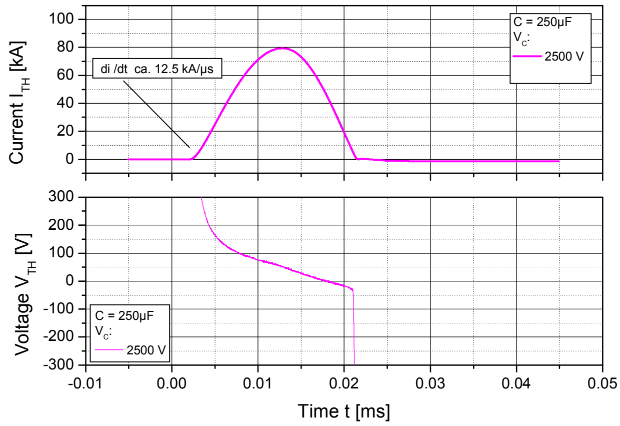


Fig. 7: Condition 2 – Current pulse (upper graph) with a peak current of 80 kA and a current rise rate of 12.5 kA/µs. No unusual behaviour of the thyristor voltage drop (lower graph).

Tests under condition 3 aimed at a further di/dt increase at lower current levels. As can be seen in Figure 8, the peak current amounted to only 9 kA, but the di/dt reached 20.5 kA/µs. Subsequently, the device under test failed at a peak current level of 10 kA and a di/dt value of 24.5 kA/µs.

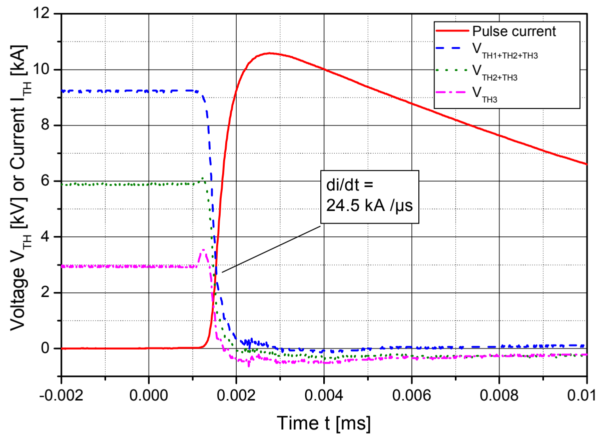


Fig. 8: Condition 3 – Current pulse (solid red curve) with a peak current of 10.5 kA and a di/dt of 24.5 kA/µs. The other dotted curves reflect the voltage sharing over the 3 individual thyristor wafers of the device.

Cond.	*C / RL*	*Wp*	*Ip*	*dI/dt*	*Ip, fail*	*dI/dt (fail)*
1	865 µF / short	35 µs	100 kA	9 kA/µS	-	-
2	250 µF / short	20 µs	80 kA	12.5 kA/µs	100 kA	14.5 kA/µs
3	20 µF / 833mΩ	50 µs	9 kA	20.5 kA/µs	10.6 kA	24.5 kA/µs

Table 2: Summary of results with prototype devices under 3 different test conditions.

Table 2 shows a summary of the results attained. Under two conditions the multi-chip thyristor failed at elevated di/dt levels of 14.5 kA/µs and 24 kA/µs corresponding to peak currents of 100 kA and 10.6 kA, respectively. For condition 2 (14.5 kA/µs) voltage peaks indicate that the destruction could be explained by hard off-switching conditions. In the case of condition 3 only one of the three thyristor chips failed. The multichip device was still usable with a reduced blocking capability of 9 kV. A subsequent defect examination reveals a local destruction close to one gate stripe. This would seem to suggest that the failure mechanism is local overheating due to an inhomogeneous current distribution, probably caused by the high di/dt value. In total more than 300 experimental shots with the prototypes were done to qualify the product.

B. Commercial Industrial device

Based on the results with the prototype devices it was decided to produce the multichip device with an industry standard, hermetically sealed ceramic press-pack housing instead of the epoxy housing prototype version. The advantage of the ceramic housing is mainly for long term reliability reasons. In this configuration the device is specified for 13.5 kV peak off-state voltage and 100 kA pulse current (tp≤100 µs). The device housing is filled with dry nitrogen to have a controlled atmosphere inside. The creepage distance from anode to cathode is 68 mm.

Fig. 9: Multichip device ABB p/n 5SPB 36Z1350 with industrial ceramic housing and corresponding switch and diode wafers on the right

With the ceramic device comparison test were done to verify if there were any differences in behaviour. Fig. 10 gives a comparison of the wave-forms of prototype device and the industrial version. The waveforms of the prototype device reflect results already published in [1]. Except of minor differences concerning clamping and connecting the devices, the tests of the commercial device have been performed under identical conditions as compared to the prototype. The testing condition is different from those mentioned above. While the dI/dt was moderate (about 2 kA/µs), the pulse duration (120 µs) and therefore the action was quite high. The capacitor charging voltage was about 10 kV and slightly higher for the prototype device, which could explain the difference in the current waveforms. In all, 25 charging-discharging cycles with peak currents of about 100 kA (similar to the waveforms in Figure 10) have been carried out with the commercial device without noticing any unusual behaviour.

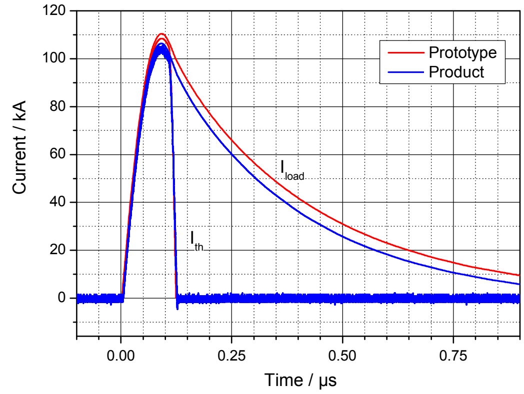


Fig. 10: Comparison of current waveforms of thyristor and load current of prototype and industrial device.

VII. REVERSE CONDUCTING VERSION

Beside the tested versions of the asymmetric blocking multichip devices (Vdrm=13.5kV / Vrrm=4.5kV), ABB has now also a Vdrm=13.5kV / Vrrm=0V reverse conducting version available for applications like pulse modulators were a freewheeling diode is required in case of the pulse form is a ringing sine wave. Because the cooling possibility of multichip devices is only limited possible, the switching frequency and peak current have to be limited to an acceptable level. The reverse conducting version is still under investigation and not fully tested under all conditions. Fig. 11 shows the device with 3 switching wafers which have monolithic integrated freewheeling diodes to minimize induction between switch and diode. The diode size is approximately 30% of the wafer area, which is not available for the thyristor and therefore the peak current and the di/dt capability of the reverse conducting device is 30% less as the described 5SPB 36Z1350.

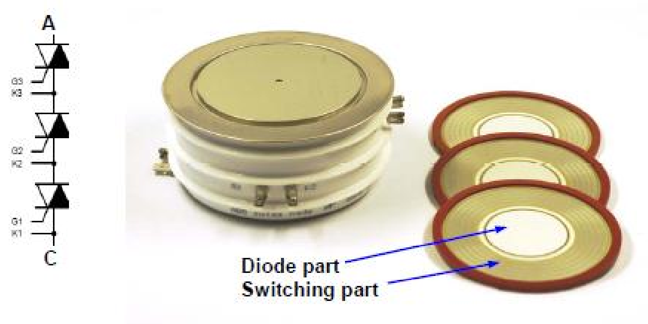


Fig. 11: New reverse conducting version 5SPR 26Z1350

VIII. CONCLUSIONS

The multichip devices 5SPB 36Z1350 shown in this presentation are extremely compact and reliable compared to the power switching capabilities. The devices have a di/dt capability basically equal to that of individually packaged, 4.5 kV fast switching thyristors (ABB 5SPYB 36L4500L) used in ISL pulsed power applications. Nevertheless, the gate current rise rate is limited due to the pin-type connectors, which present an important drawback as compared to the low inductance ring gate connectors of single-wafer packages. For this reason the gate current pulse was limited to 800 A peak current and 400 A/µs dI_{gate}/dt. In order to achieve still higher dI/dt values with multichip thyristors, further work will focus on a higher gate voltage. Till to date, the ISL gate units have been charged to 30 V, which was adequate in case of individually packaged fast switching thyristors. Using a low inductance gate path, the gate current easily attained 2 kA in 2 microseconds. The devices are fulfilling the requirements for compact and light weight discharge systems working with high di/dt single pulse or low repetition rates. Further development on these products is done by ABB and ISL.

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