High Current, High Voltage Solid State Discharge Switches for Electromagnetic Launch Applications

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***Abstract*—This presentation is about the work done on design, built-up, production and test of ready-to-use solid state switch assemblies using Thyristor- or IGCT technology. The presented thyristor switch assemblies, using 120 mm wafer size, are made to switch 3MJ stored energy into a load. The maximum charge voltage of the assembly is 12 kVdc, current capability more than 260kA@tp=3.3ms and a pulse repetition rate of up to 6 shots per minute with convection air cooling. New very large thyristors with 150 mm wafer diameter will be available from fall 2008. As second a 70 kA/21kVdc switch using IGCT technology will be presented. The switch is designed for fast discharge in the micro-second range and has a very high di/dt capability. Because for the IGCT switches a reverse conducting design can be used, damped sine waves can be handled without the use of separate anti-parallel diodes. The thyristor and IGCT switches come complete with power supplies, driver units and if required also with air- or water cooled heat sinks. Reliability figures will be mentioned as well as information collected during long-term testing. The switches are supplied as complete power blocks and all components are produced on mass production line and therefore benefit from the volume production experience and quality monitoring system. It will be concluded that ABB has long term experience with production of components and switches for highest energy in pulsed power applications like electromagnetic launch and magnetic forming.**

Keywords: Solid State, Thyristor, IGCT, Discharge Switch

I. INTRODUCTION

Semiconductor devices have made dramatic progress in power handling during the last decade. The today's technology and production capabilities make it possible to produce devices with high blocking voltage combined with very high current handling. Depending on the design and the device structure also very high current rise rates in the range of up to several ten thousands Ampere per micro second are possible. Especially for single pulse or medium pulse repetition rates semiconductor devices are getting more and more competitive to conventional technologies like Thyratrons, Ignitrons, Spark-Gaps and Mechanical Switches. The main advantages are the reliability, lifetime and almost no maintenance of the semiconductor switches if the characterization is done right. Main advantages like longer life-time, environmental friendly (no mercury etc.) and flexible mounting position are compensating the higher initial cost of a solid state design. The type of semiconductor used and the rating of the device are extremely important for a reliable operation and need an in-depth know-how of the application and the switching device. ABB has developed over the years a specific range of semiconductor devices and adapted standard products which can fulfill the requirements for pulsed applications. Beside the semiconductor devices, ABB is also in the position to supply complete custom made ready-to-use solid state switch assemblies including clamping, triggering, cooling and with application oriented testing. The presentation describes both, the loose semiconductor components as well as some custom made solid state switches for single pulse or low repetition rate pulsing.

II. DEVICE TECHNOLOGY

Semiconductors for pulsed applications can be divided in Turn-On and Turn-Off devices. Turn-On devices are Thyristors (SCR's) and in the group of Turn-Off devices we find the GTO's (Gate-Turn-Off Thyristor), IGCT's (Integrated Gate Controlled Thyristor) and IGBT's (Insulated Gate Bipolar Transistor). For high energy short pulse discharge applications, like electromagnetic launchers or magnetic forming, mostly the thyristor technology, or GTO-Like thyristor is used. Table 1 gives a short overview of the different possibilities.

Device Type	Forward Blocking Voltage	Max. Peak Pulse Current	di/dt kA/µs	Switch On	Switch On/Off
Thyristor	≤ 8.5 kV	120 kA	1.2	Yes	No
GTO-Like Thyristor	4.5 kV	150 kA	50	Yes	No
Integrated GTO-Like thyristor	4.5 kV	150 kA	50	Yes	No
GTO	4.5 kV	4 kA	3	4 kA	4 kA
IGCT	≤ 6.0 kV	5 kA	2	5 kA	5 kA
IGBT Wire-bonded industrial module	≤ 6.5 kV	1 kA	5	1 kA	1 kA
IGBT Press-Pack module	2.5 kV (4.5 kV under Development)	10 kA	6	4 kA	2 kA

Table 1: Device technologies in comparison.

For electromagnetic launch, like rail guns or active armor and for high speed magnetic forming, the use of capacitor discharge switching is very common as high energy has to be switched into a load in very short time, but pulse repetition rates are very moderate. Normally is it possible to discharge the capacitor completely, which means that in the first place devices with very good switch-on capability are selected if no switch-off capability is needed. For this presentation we concentrate on the switch-on discharge devices (closing switches) in Thyristor- and so called GTO-like Thyristor technolgy as these offer the highest current capability but are not in the position to switch-off any current.

In Figure 1 the different silicon wafers and gate-structures are shown.

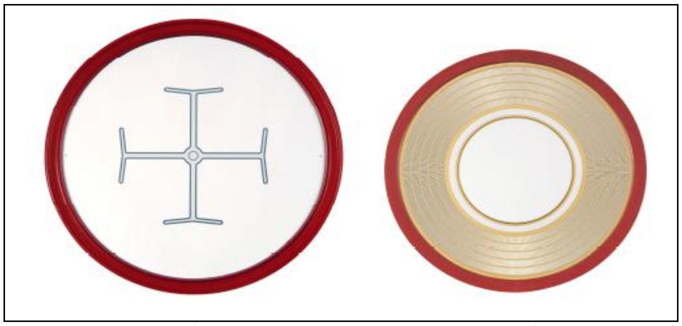

Fig.1 Thyristor Wafer 120 mm GTO-Like Wafer 91 mm with integrated diode

Main difference between the two wafers is the gate-structure which gives advantages or dis-advantages for specific applications. As the large thyristor wafer can handle a very large current at longer pulse durations, the GTO-like wafer has a much finer gate structure and can handle therefore a much higher current rise rate. With the GTO-like gate structure ABB has the possibility to integrate also the freewheeling diode monolithic on the same silicon wafer. This can be an advantage if the discharge pulse is a damped sine wave and very low inductance is needed.

	Thyristor structure	**GTO-like structure**
Max. Wafer Size	≤ 120 mm	≤ 91 mm
Forward Blocking	up to 6500V	4500V
Reverse Blocking	up to 6500V	18V
Reverse Conducting	Not possible	Possible
Current Capability	120 kA @ 1ms	150 kA @ 100 µs
Current Rise Rate	< 1 kA/µs	up to 50 kA/µs
Driver available	Yes, Separate	Yes, Integrated

Table 2: Technology comparison [1]

III. Thyristor Discharge Switches

A. Discharge Switch for a 3MJ Stored Energy system

A switch design was made for a 3 MJ discharge system with a peak current of 260kA, charge voltage of 12kVdc, pulse width 3.3ms and a pulse repetition rate of 6 shots per minute. The target was also to get the system working without active cooling, therefore the switch is designed for convection air cooling. Because of the limited space an optimized solution had to be found between device blocking voltage and current capability. As the current rise rate of the system is clearly below 1 kA/µs, a thyristor structure with a wafer size of 120 mm was selected. Life-time and reliability calculations have shown that the use of 6 devices with 4.2kV blocking voltage in series and 3 devices in parallel are required. A combination of total 18 pcs 4.2kV 120mm devices, ABB p/n 5STP 57U4200 [2] is offering the optimum performance in a switch assembly for this application. The thyristor devices are selected and grouped on reverse recovery charge (Qrr) and voltage drop (Vt) as these are used in series and parallel connection. Qrr is selected in a bandwidth of 5% and the voltage drop is selected in a bandwidth of 90 mV. An RC protection circuit is used per device level and because of the space restrictions the size of the snubber capacitor had to be reduced. Therefore a metal oxide varistor (MOV) was added to limit the reverse voltage overshoot. One trigger generator is used to switch on all devices simultaneously by means of an inductive coupling. The trigger generator has an optical trigger input and two optical feedbacks. One feedback is to indicate that the unit is ready to trigger and one feedback to indicate that the trigger pulse successfully has passed. A current pulse through a closed loop high voltage cable is used to activate the input transformer on the trigger-board at each thyristor level. The HV cable is the isolation medium between the different thyristor trigger levels. In Fig. 2 the circuit diagram of the switch assembly is shown.

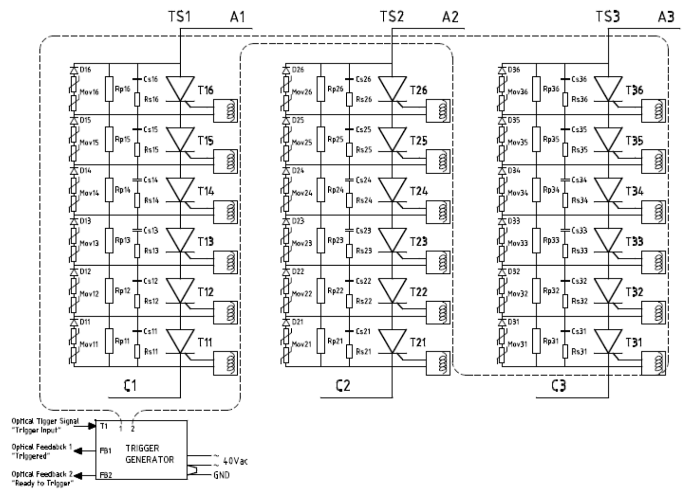

Fig. 2: Circuit Diagram 260kA / 12 kVdc thyristor switch assembly

Thermal calculations have been done and the assembly is designed to handle 6 shots per minute with a recommended waiting time of approx. 5 minutes in between the bursts if only air convection cooling is used. Between the device levels large nickel plated aluminum plates are mounted to support the snubber components and to dissipate the heat which is generated after every shot. The mechanical built-up consists of 3 identical stacks with each 6 thyristor devices in series connection. The three stacks are electrically connected in parallel together in the application, which is a capacitor module with 3 MJ stored energy. The clamping force on each stack is 135 kN which is created by aluminum alloy mounting clamps. The base-plate is made of reinforced glass fiber epoxy, which also contains the trigger generator. Overall dimensions are H=620xW=690xD=390 mm and the total weight is approx. 200 kg. In combination with the thyristor switch assembly a large freewheeling diode assembly consisting of 15 devices ABB 5SDD 50N5500 with 100 mm wafers is used. The test at the manufacturer is done on the individual wafers, the individual devices, on device-level with RC and MOV, and on stack level. The application oriented test is done at the equipment maker who builds the complete capacitor module and the complete system. A picture of the complete thyristor switch assembly is shown in Fig. 3.

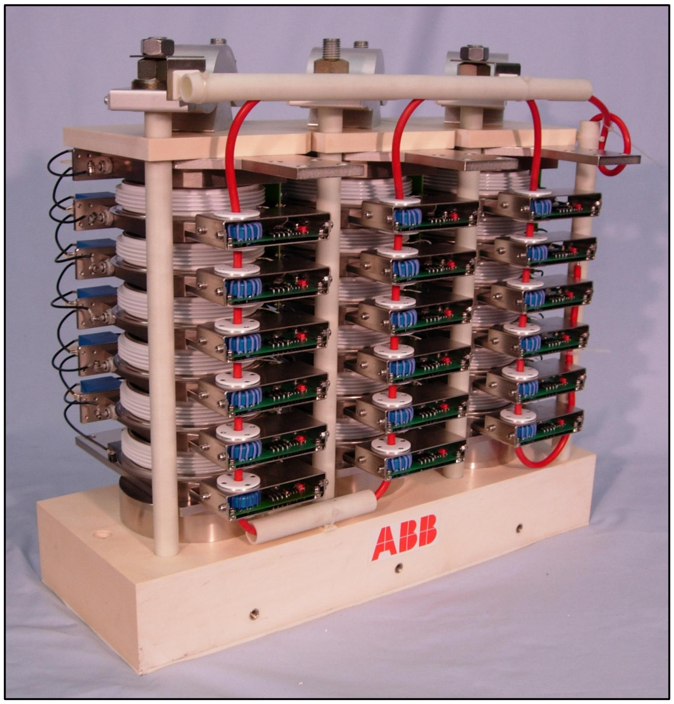

Fig.3: Thyristor Switch Assembly A-STP 5742U-18-CC

A substantial volume of these thyristor and diode assemblies is built and successful in use.

IV. High di/dt Discharge Switches

A. High di/dt Reverse Conducting Discharge Switch.

As mentioned under the heading Device Technology, the thyristor devices are offering good behaviour under specific conditions, but in case of very short pulses or with high current rise rates, the so called GTO-Like thyristor can be the better choice. These devices are using the gate structure of GTO's but are optimized for fast turn-on like and have no turn-off capability. Therefore they benefit from very fast switch-on capability of about 1 µs, and can handle very high di/dt of up to 50 kA/µs by using a 91 mm wafer diameter. Depending on the overall diameter, between 800 and 2600 small thyristor islands are located in parallel on the silicon wafer. The devices are available with 51mm, 68mm and 91 mm wafer diameters and can be asymmetric blocking (Forward 4500V, Reverse 18V) or reverse conducting, with an integrated freewheeling diode. The advantage of the monolithic integrated freewheeling diode is that there is almost no induction between the switching component and the freewheeling diode which is otherwise located in a separate stack assembly. The GTO-Like devices are available as so called High Current Thyristors without driver unit. Triggering can be done with a strong gate pulse in the range of about 500A and di/dt of about 1 kA/µs. These devices are mainly used for crowbar- or dump switches [3][4] and active armor applications, where triggering events are very limited. Also multichip devices, containing 3 series connected wafers, for single shot applications are available [5]. For those applications where switching is often required or where repetition rates are high, the devices are normally delivered with an integrated driver unit reducing the inductive path between driver and device substantially. The driver units are specially made for use with series connected devices and are energized by a separate current source power supply with an inductive coupling to the input transformers of the driver units. The current source has an output of 25 kHz and 4A and can drive up to 8 devices in series, depending on device size and pulse repetition frequency. Figure 4 and 5 show the low inductive gate path in a GTO-like Thyristor housing and the corresponding 91 mm wafer.

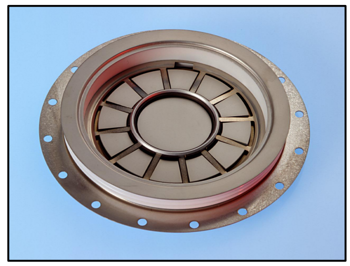

Fig 4: Low inductive housing Fig 5: 91 mm wafer

By integrating the driver unit, a so called IGCT (Integrated Gate Controlled Thyristor) will be the result. The IGCT is normally supplied as Switch-On / Switch-Off version. For pulsed discharge applications, ABB has a driver unit which is optimized for Switch-On only. The combination of the optimized wafer and driver unit results in a product which is unique in this field. As mentioned these devices have blocking voltages up to 4500V and for higher voltages series connection is required. The driver unit is designed for easy series connection by means of an inductive coupling with a separate current source. Because of the active powering of the driver units it is possible to reach pulse repetition rates till up to several hundred Hertz. The maximum pulse rep. rate however is depending on the thermal management of the device which can be increased by using air- or water cooling. Fig. 6 is showing a pulse discharge device with integrated driver unit, and separate asymmetric and reverse conducting wafers.

Fig. 6: Integrated discharge switching device with asymmetric and reverse conducting wafer.

With reverse conducting devices ABB has made switch assemblies for several applications and prototypes for large magnetic forming equipment. Because the discharge pulse is a damped sine wave, there is a need for a freewheeling diode. Especially for magnetic forming the inductance must be as low as possible and therefore a design with reverse conducting devices was chosen. In table 3 the main data of the discharge switch under normal- and short circuit conditions are given.

Parameter	Normal Condition	Short Circuit Condition
Max. Charge Voltage	21 kV	21 kV
Pulse Current Forward	210 kA	420 kA
Pulse Current Reverse	90 kA	150 kA
Current Rise Rate (di/dt)	3 kA/µs	9 kA/µs
Pulse Duration	100 µs	50 µs
Pulse Form	Damped Sine	Damped Sine
Pulse Repetition Rate	1 per min.	1 per 10 min.
Calculated Lifetime	20.000 Shots	1.000 Shots

Table 3: Specification of 210kA / 21 kVdc switch

The switch is designed for 21 kVdc is with a series connection of 8 devices 5SPR 26L4506 [6] with a blocking voltage of 4500V each. These devices are closing switches only and are capable to handle the required high current rise rating of up to 9kA/µs. The 8 devices in series will give a DC voltage of 2625V per device level which is well under the specified Vdc=2800V for 100 FIT cosmic ray reliability. To reach the 210kA nominal, and the 420kA short circuit condition, 3 devices have to be used in parallel connection, which gives a peak current per device of 70kA. The reverse current is about 30kA per device, which is taken by the monolithic integrated diode part of the switching wafer.

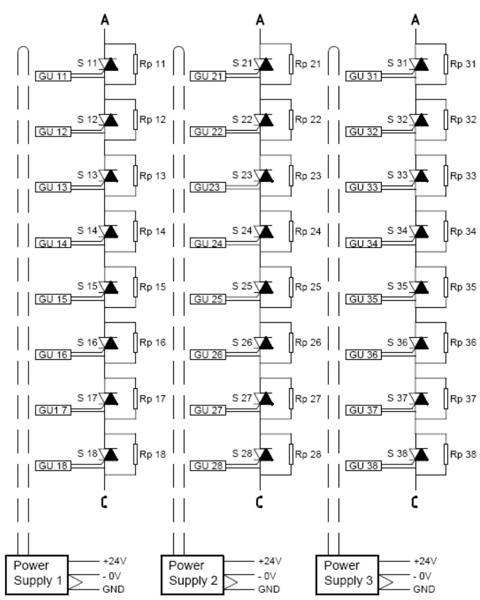

Fig. 7: Circuit diagram 21kV / 210 kA discharge switch consisting of 3 identical stacks

The switch is built-up from 3 individual stacks, each containing 8 devices in series connection, total 24 devices. The individual stacks are connected in parallel, with a small series inductor, in the discharge system. The life-time of the system is related to load in the switching devices. In the presented case the calculated life-time is more than 20.000 shots, but can be increased if air- or water cooling is implemented. Alternative is to add more stack-assemblies in parallel to share the current over more devices. An increase from 3 to 6 devices in parallel will increase the life-time to over 2 Million shots. Tests till up to 1 Million shots with 37kA per device where done without any failure or degradation of the wafers.

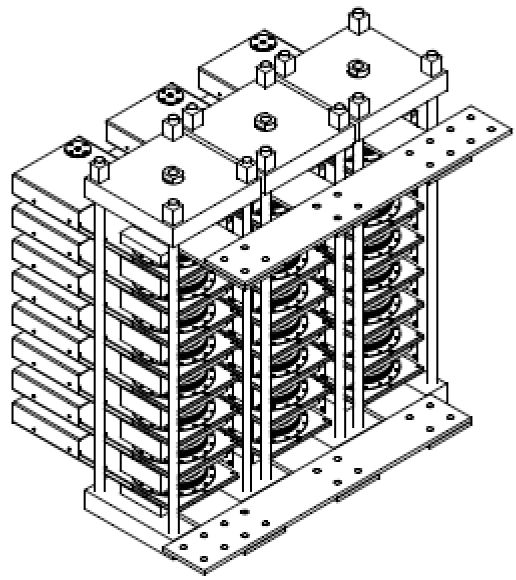

Fig. 8: 21kVdc / 210kA Reverse Conducting Switch complete

The integrated driver units of the devices are activated optically from a light distribution box by optical cables. The light distribution box is selective and can trigger 1, 2 or all 3 stacks individual or simultaneously, depending on the demand. Every stack has one optical feedback which is monitoring if the driver units are energized by the power supply. In case the driver units should not be energized or have not enough charge, the trigger box is locked and will not send a trigger signal to driver units. The switch was tested per stack because of the high energy demand which was not available at the manufacturer. Final full tests were made in the end-users equipment.

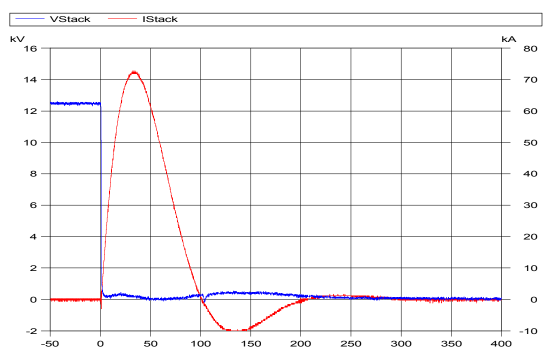

Fig. 9: Voltage and Current Wave-Form though one stack

In Fig. 9 the current switching current is 70kA per stack and the negative part through the diode is good visible. As it is very important that all devices are switching-on simultaneous at the same time, the gate signal delay was also measured. In Fig. 10 the differences in gate signal delay are visible, and show a deviation of only a few nanoseconds

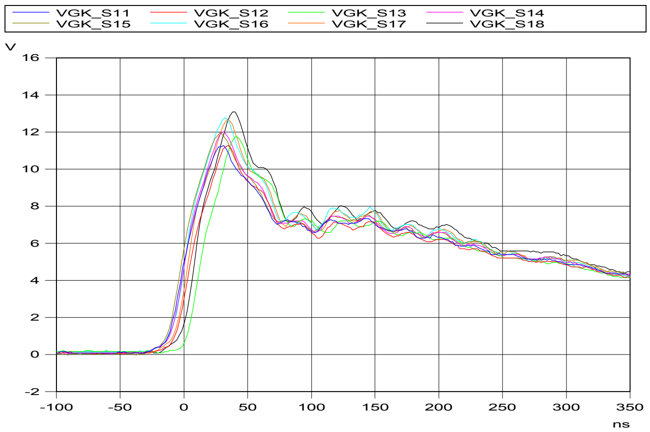

Fig. 10: Gate signal delay of 8 devices in one stack

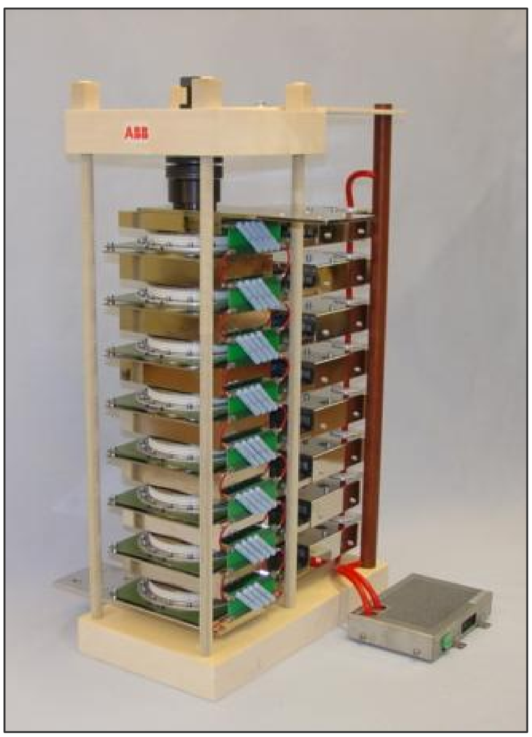

Fig. 11: Picture of one stack (70kA / 21kV) with closed loop power supply.

Each stack has its own current source power supply which is sufficient to energize all 8 devices in series connection. The dimensions of one stack assembly is approximately H=720 x D=440 x W=220 mm. The complete assembly with 3 stacks has a width of 680 mm and a total weight of approx. 150 kg.

V. Conclusion

It has been shown that initial investment has resulted in production of large size high power solid state switch assemblies which are now in use for military applications as well as for industrial and research systems. With the long term experience ABB has in producing reliable high power devices, and the know-how to produce application oriented switch designs in combination with the understanding of the specific end-user needs has resulted in a further step in development of solid state switches. For higher current per device area, ABB will start the production of high voltage thyristors with 150 mm wafer size in 2008. Beside the presented large discharge switch assemblies also high voltage solid state switches with higher repetition rates are available as thyratron / ignitron replacements and successfully in use in several military, industrial, environmental and medical applications.

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