

High Power Semiconductor Devices and Solid State Switches for Pulsed Discharge Applications

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Abstract

Based on long term experience, collected mainly with military applications like Rail Guns and Active Armour, a range of optimized semiconductor devices for pulsed applications was developed by ABB Switzerland Ltd and described in this presentation. The presented devices are optimized for pulsed discharge and fit very well for switching the short but high electrical power demand used for magnetic forming. Devices are available in different versions with silicon wafer diameters up to 120 mm and blocking voltages of over 6500V. Because of the different application requirements a differentiation is made in device technology. Depending on the discharge circuit, devices for low, medium, or high di/dt can be selected and the difference in advantages and disadvantages between both technologies will be described. To minimize the inductance between switching device and freewheeling diode, ABB can integrate this diode monolithic on the switching wafer. These so called reverse conducting devices are very common for magnetic forming applications. Thyristor structures are commercially available up to 8500V with 120 mm silicon wafers and GTO-like structures are available up to 4500V with 91 mm silicon wafers. For higher voltages or higher currents a combination of devices in series and/or parallel connection is required. The presentation will also describe the evolution of complete discharge switching modules in the range of 10kV / 50 kJ, a large discharge system of 21kV / 200kA, and a newly designed high current switch in the range of 15kV / 3MJ. The solid state switch solutions offered today and those shown in the presentation are based on a standard platform of components existing already for several years. For reliability reasons it is of great importance that the switch assemblies for high current pulsed applications are designed in cooperation with the device manufacturer who has in-depth knowledge of the switching behavior of the semiconductor components under pulsed conditions. The advantage of a complete switch assembly is that the whole unit can be tested under application conditions. ABB has a test capability up to 65 kV and 85 kJ stored energy.

Keywords

Semiconductor device, Solid state switch, High current, High di/dt,

1 Introduction

Semiconductor devices have made dramatic progress in power handling over the last decade. 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 tenth's of kA/ μ s are possible. Especially for single pulse or medium pulse repetition rates semiconductor devices are getting more and more competitive in comparison 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 friendliness (no mercury etc.), and flexible mounting position compensate 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 a specific range of semiconductor devices and adapted standard products over the years, which can fulfil 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.

2 Device technology

Semiconductor devices 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 high speed forming, mostly thyristor technology is used. The table below gives a short overview of the different possibilities.

Device type	Max. forward blocking voltage	Max. peak pulse current capability	di/dt	Switch-on	Switch-on/off
Thyristor	≤ 8500 V	120 kA	1.5 kA/ μ s	Yes	No
GTO-like thyristor	4500 V	150 kA	50 kA/ μ s	Yes	No
Integrated GTO-like thyristor	4500 V	150 kA	50 kA/ μ s	Yes	No
GTO	4500 V	4 kA	3 kA/ μ s	4 kA	4 kA
IGCT	≤ 6000 V	4 kA	2 kA/ μ s	4 kA	4 kA
IGBT (Wire bonded module)	≤ 6500 V	1 kA	5 kA/ μ s	1 kA	1 kA

Table 1: Overview of different semiconductor device technologies

For high speed forming the use of capacitor discharge switching is very common because high energy has to be switched into a load in a very short time. The capacitor can be discharged completely and this means that devices with high switch-on capability are selected in the first place if no switch-off capability is needed. For this presentation we will concentrate on the switch-on devices in thyristor and GTO-like thyristor technology.

2.1 Thyristor technology

Thyristor (SCR) technology is a well proven solution which is used for high currents, relatively long pulses, and low current rise rates in capacitor discharge applications. Standard commercial off-the-shelf devices can be used, but it should be taken into consideration that the life-time of such devices is often reduced due to the fact that the manufacturer has not designed and not tested the device to be used outside the datasheet values. Therefore, it is of vital importance to check the capability and the corresponding device life-time with the manufacturer before. Depending on the application, the pulse current, current rise-time, pulse length, and pulse repetition rate, different wafer designs can be selected to fulfil the requirements. Figure 1 shows the evolution of Ø 51 mm thyristor wafers from 1975 till the year 2000. These designs are available in different diameters for different current capabilities. Blocking voltages can be from 1800V till up to 8500V per device for the thyristor designs and up to 6000V for the highly interdigitated designs (GTO-like structure). For higher voltage devices can be stacked in series connection.

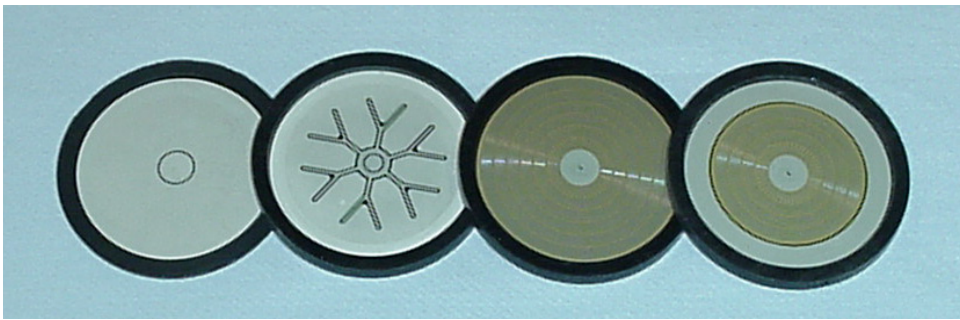


Figure 1: Si-wafers Ø51 mm for $di/dt < 0.1\text{kA}/\mu\text{s}$, $1\text{kA}/\mu\text{s}$, $18\text{kA}/\mu\text{s}$, and $15\text{kA}/\mu\text{s}$; the right one is with a monolithic integrated freewheeling diode

The first wafer shown in Figure 1 is not used for pulsed application because the plasma spread over the silicon area will be too slow. The second wafer design is commonly used for crowbar and dump switch applications with di/dt up to about 1 - 2 $\text{kA}/\mu\text{s}$. The two wafers on the right side of the picture represent the GTO-like wafer structure.

	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
Max. current capability	120 kA @ 1000 μs	150 kA @ 100 μs
Current rise rate	< 1 $\text{kA}/\mu\text{s}$	Up to 50 $\text{kA}/\mu\text{s}$
Driver available	Yes, separate	Yes, integrated

Table 2: Comparison between Thyristor and GTO-Like gate structured devices

These GTO-like structures use a lot of small thyristor segments on one silicon wafer and have a very high di/dt capability.

2.2 GTO-like thyristor technology

Above the GTO-like technology is mentioned. This technology uses the same type of gate structure as GTO devices, but has no switch-off capability. Therefore, it benefits from a very fast switch-on capability of about 1 μs and can handle very high di/dt of up to 50 $\text{kA}/\mu\text{s}$ 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 single devices without driver unit. Triggering can be done with a strong gate pulse in the range of about 500A and di/dt of about 1 $\text{kA}/\mu\text{s}$. These devices are mainly used for crowbar or dump switch applications [2] where triggering events are very limited. For those applications where switching is often required or where repetition rates are high the device can be 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 using a HV cable through the input transformers of the driver units. The HV cable is the isolation between the device levels in the series connection. 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 2 shows the low inductive gate path in a GTO-like thyristor housing.



Figure 2: Low inductive housing, GTO-like wafer and complete device

By integrating the driver unit a so called IGCT (Integrated Gate Controlled Thyristor) will be the result. The IGCT is normally supplied in 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 above, 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. The isolation between the device levels is given by the isolation voltage of a HV closed loop cable, which is sloped through the input transformers of the driver units (See Fig. 4 and 7). Because of the active powering of the driver units it is possible to reach pulse repetition rates of up to several hundred Hertz, the max. pulse rep. rate however depends on the thermal management of the device which can be increased by using air or water cooling. Further details about this will be described with the switch assemblies. Fig. 3 shows a

pulse discharge device with integrated driver unit, including a separate asymmetric and reverse conducting wafer 91 mm. [1]

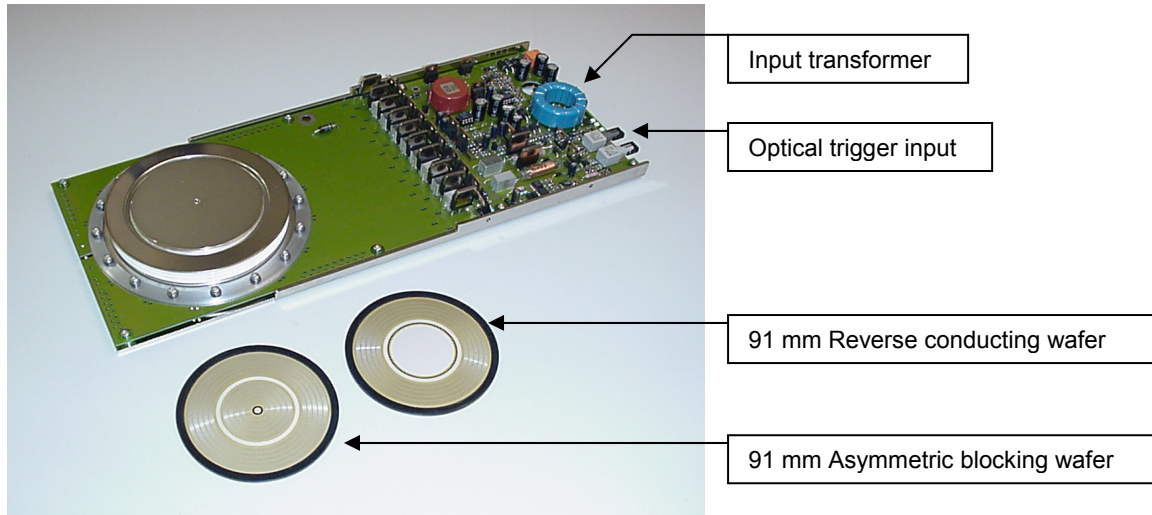


Figure 3: Discharge device p/n: 5SPY 36L4506, $V_{drm}=4500V$ complete with driver unit

By integrating the driver unit a so called IGCT (Integrated Gate Controlled Thyristor) will be the result. It has to be mentioned that standard IGCT devices have turn-on and turn-off capability; those devices designed for discharge applications have turn-on capability only and are optimized for very fast turn-on with high current rise rates.

3 Switches

3.1 Reverse conducting discharge switch 210 kA / 21 kVdc / 100 μ s

In 2005, a prototype switch for magnetic forming was designed and produced using reverse conducting devices ABB p/n 5SPR 26L4506. Table 3 shows the basic specification which had to be fulfilled.

Parameter	Normal condition	Short circuit condition
Max. charge voltage	21 kV	21 kV
Peak pulse current forward	210 kA	420 kA
Peak pulse current reverse	90 kA	150 kA
Current rise rate (di/dt)	3 kA/ μ s	9 kA/ μ s
Pulse duration	100 μ s	50 μ s
Pulse form	Damped sine wave	Damped sine wave
Pulse rep. rate	1 Shot / Min.	1 Shot / 10 mins
Lifetime	20.000 Shots	1.000 Shots

Table 3: Specification for reverse conducting 210 kA / 21 kV switch assembly

For the specification shown in Table 3 the reverse conducting 91 mm discharge device, 5SPR 26L4506, with integrated driver unit was selected. To withstand the 21 kVdc charge voltage, 8 devices of $V_{drm}=4500V$ / $V_{dc}=2800V$ have to be used in series connection. To fulfil the requirement of 210kA nominal current and 420kA short circuit

condition, three devices in parallel are needed. This means for the total switch $N_s=8$ and $N_p=3$ devices, in total 24 devices are used. The circuit diagram is shown in figure 4.

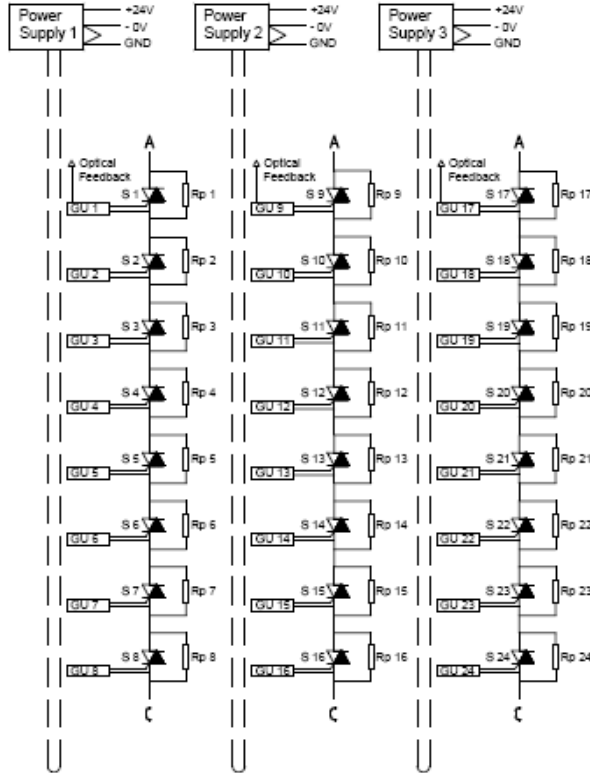


Figure 4: Circuit diagram 21 kV switch

Because reverse conducting devices are used and no switch-off is required no snubber circuit is needed, only voltage sharing resistors in parallel with each device level. Three independent stacks were used in parallel to avoid hard parallel connection of 3 devices. This configuration allows also the use of one single stack if less power is required. Every stack can handle the 70 kA nominal and the 140 kA short circuit condition. The driver units are optical triggered from a light distribution box and this box can be selected to fire 1, 2, or all 3 stacks simultaneously or sequential. The figures below show measurements on one of the stack assemblies.

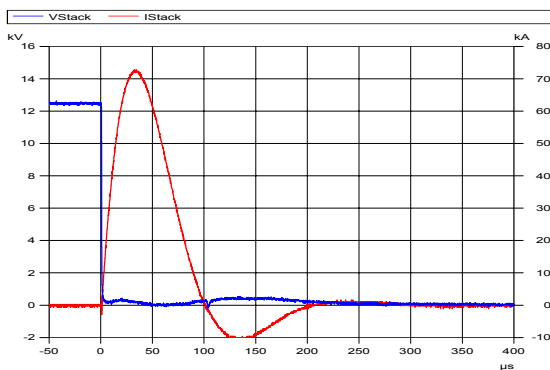


Figure 5: Single stack pulse test

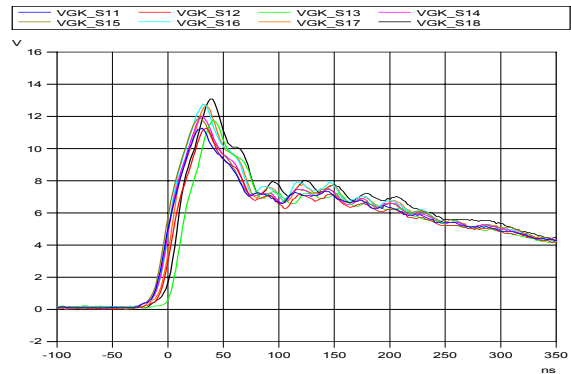


Figure 6: Gate signal delay at turn-on

Figure 5 shows a picture of one of the single stack assemblies (out of three) with the current source power supply. The current source power supply can feed all 8 driver units with 25kHz / 4A by means of an inductive coupling (input transformer). Air convection cooling can be used as the pulse repetition rate for this application is 1 shot per minute. For higher rep. rates forced air cooling or water cooling can be applied. In case of higher rep. rates, water cooling is preferred to keep the dimensions as compact as possible.

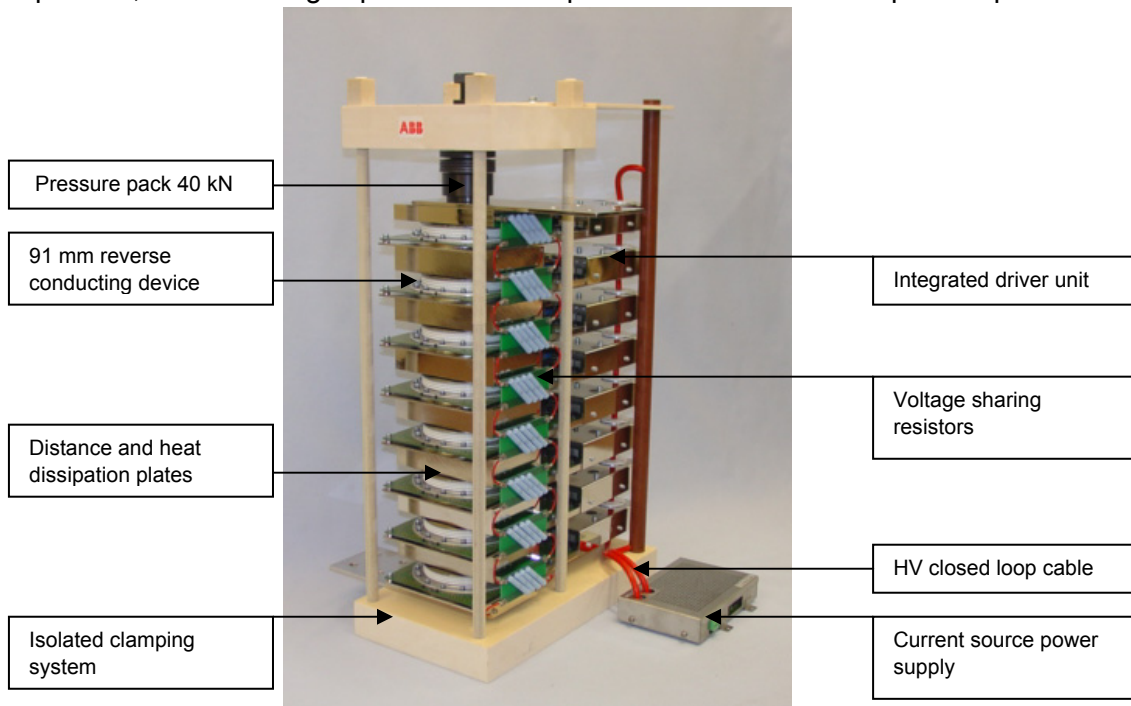


Figure 7: Discharge switch assembly 21 kVdc / forward 70 kA / reverse 30 kA

3.2 10 kV / 50 kJ Discharge switch device / module

The German-French Research Institute, I.S.L. Saint-Louis / France has developed a 50 kJ capacitor discharge module in 1995, which includes the 10.5 kV / 50 kJ capacitor, the semiconductor switch, the inductor, and a triggering system. A few hundred of such modules were made. 200 of them were used for a 10 MJ rail gun facility and some for other pulsed power supplies. Over the last 10 years, the design was optimized and miniaturized. This construction is also of interest for magnetic forming applications. The capacitor is a 50 kJ can with a multichip thyristor p/n 5STF 07Z1350 as switch and a freewheeling multichip diode p/n 5SDA 27Z1350. Both have a blocking voltage of 13.5kV.



Figure 8: Multichip diode 5SDA 27Z1350 and multichip thyristor 5STF 07Z1350

For active armour applications the current rise rate is higher as this type of thyristor can handle, and therefore a device with a GTO-like wafer structure was selected. The solution were 3 switching devices 91 mm and one diode 91 mm in series connection. The use of discrete devices resulted in a total height of 106 mm, an overall diameter of 120 mm, and a weight of 6.2 kg. Because for this single shot application cooling is not a serious issue, all 4 wafers were put into one special housing and by additionally reducing the thickness of the copper pole pieces a total height of 54 mm could be achieved. This height was reached by using standard production material such as standard Molybdenum discs, standard gate connections, and standard optimized wafers 91 mm.

5SPB 36Z1350	
Forward blocking	13.5 kV
Reverse blocking	4.5 kV
Max. charge voltage	10.0 kVdc
Peak pulse current	120 kA
Pulse duration	100 µs
Current rise rate	10 kA/µs
Overall dimensions	H=53 x Ø=120 mm
Clamping Force	40 kN
Weight	3.0 kg

Table 4: Target data of new multichip device 5SPB 36Z1350 / 13.5 kV

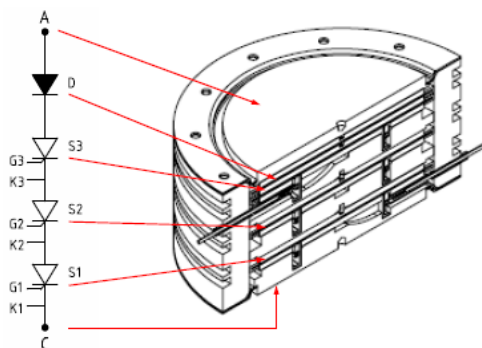


Figure 9: Built-up of multichip device



Figure 10: Device complete with 91mm wafers in front

ABB has done the testing on wafer level and voltage blocking tests on the device, the application oriented tests were done at ISL [3] in combination with the 50kJ / 10kV capacitor. In total, more than 300 discharges were made with the devices. All devices survived the tests based on the target specification. Table 5 shows test results on one device.

I-pulse (kA)	di/dt (kA/µs)	t-pulse (µs)	Shots
110	2.2	125	210
80	12.5	25	20
10.5	24	50	2

Table 5: Test results 5SPB 36Z1350

It has been detected that the pulse test with $24 \text{ kA}/\mu\text{s}$ is on the limit of the capability. The reason is that the gate connection is made with a one pin entrance through the housing, which limits the trigger di/dt . The originally used 26 mm thick discrete devices have annular gate connections and 12 entrances to the wafer, resulting in a much higher di/dt capability. By limiting the specification of the multichip construction to a maximum di/dt of $10 \text{ kA}/\mu\text{s}$ @ $100\text{kA} / 50\mu\text{s}$ it can comfortably fulfil the target specification for magnetic forming or other pulsed discharge applications. The thermal recovery time depends on the current value and pulse length. The picture below shows the evolution over the last 10 years of the 50 kJ capacitor discharge module by reducing the mechanical sizes of the capacitor and switches, resulting in a higher performance and 62% less size.

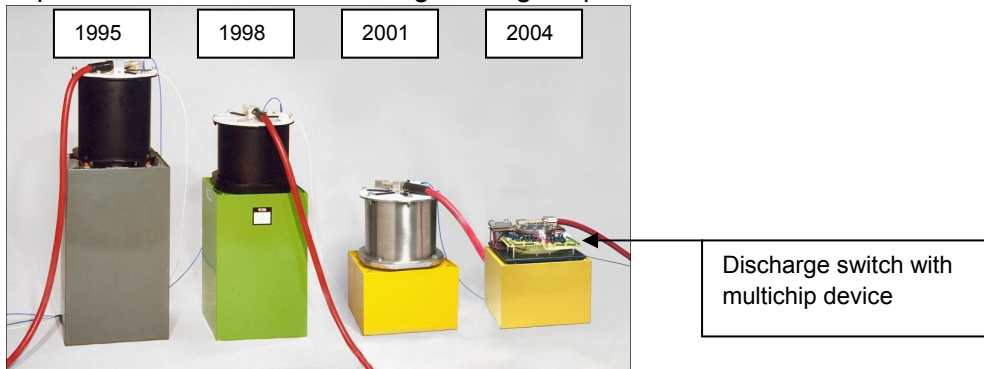


Figure 11: Evolution of 50 kJ discharge modules, the right one with $1.2 \text{ MJ}/\text{m}^3$

3.3 Low di/dt , long pulse, discharge switch for 260 kA / 15 kVdc

A design was made for a large 200MJ (Rail Gun) system using a series connection of $N_s=5$ and parallel connection of $N_p=3$ thyristors with 120 mm wafer size. The devices are rated for $V_{\text{drm}}=5200\text{V} / V_{\text{dc}}=3300\text{V}$ ABB p/n 5STP 52U5200. The requirement for the switching module in the application is for $I_{\text{pulse}}=260 \text{ kA} / V_{\text{dc}}=15 \text{ kV} / t_{\text{pulse}}=3 \text{ ms}$ pulse / $di/dt=165 \text{ A}/\mu\text{s} / \text{action}=113 \text{ MA}^2\text{s}$. To reach the 200 MJ, several switching modules will be used in parallel. Because of high reversal voltage after the pulse the thyristors needed a protection circuit, which is designed with $R_s / C_s / R_p$ and MOV. The triggering is done with a simple driver unit per device level, which is inductively coupled with a trigger generator. The isolation between the driver units is given by a HV isolated closed loop cable whose current will trigger all 15 thyristors simultaneously.

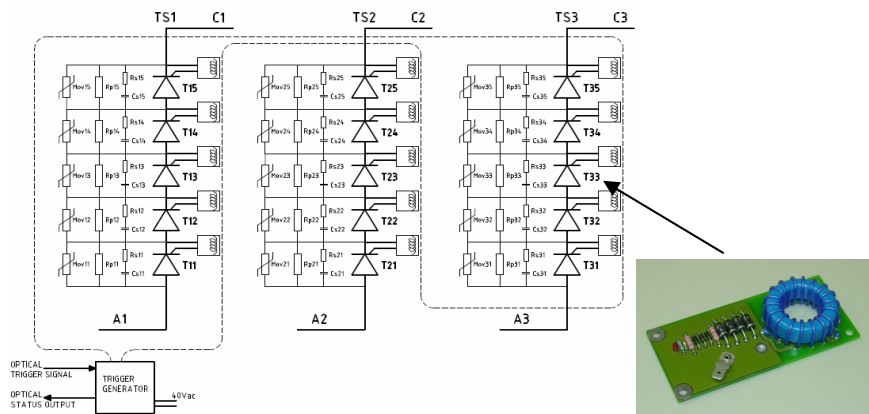


Figure 12: Circuit diagram 260 kA / 15kV / 3 MJ switch module and a picture of the inductive coupling for simultaneous triggering

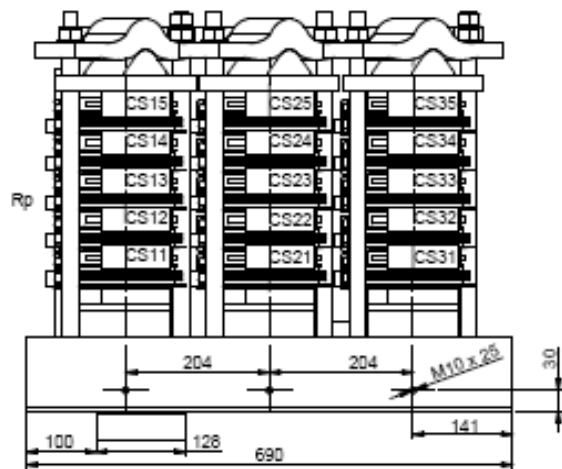


Figure 13: Design drawing of 260kA 15kVdc thyristor module

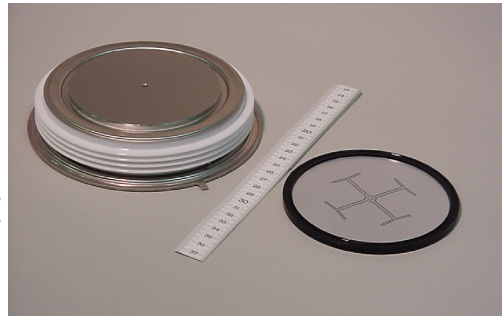


Figure 14: ABB thyristor p/n 5STP 52U5200.

The overall size of the thyristor module is $W=690 \times H=570 \times D=250$ mm. The thyristors are assembled with 135 kN clamps on a glass fiber epoxy base which has a thickness of 100 mm. The trigger generator is located under the base plate. The temperature increase of the thyristor wafer after the shot is about 110°C . Because the assembly is used at low rep. rates of some shots per minute large aluminum blocks between the devices will dissipate the heat with air convection. For higher pulse repetition rates active cooling or more devices with lower blocking voltage have to be used.

4 Conclusions

It has been shown that solid state switches are state of the art today. ABB produces a wide range of reliable semiconductor devices and switches, which are optimized for pulsed applications. Solid state switches successfully replace electronic tubes and other technologies in many applications. Due to deliveries in all kinds of systems and close connections to research institutes and governmental organisations, a wide practical experience has been built up. The initial higher cost of a semiconductor switch is compensated by the higher reliability and practically no needed maintenance.

References

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