SOLID STATE SWITCHES ARE SUCCESSFULLY REPLACING THYRATRONS IN DEMANDING APPLICATIONS

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Abstract

This presentation will describe a new generation of solid state switches using reverse conducting Integrated Gate Controlled Thyristors (IGCT) for short pulse discharge applications. This technology is already installed in field applications since more than 6 years and has developed a proven reliability which is clear above that of today's thyratrons. The presentation will show the technology, the design, the built-up and the test of a 6.5kVdc / 1.5kA / 10µs / 6kA/µs / 1300Hz solid state switch assembly using three semiconductor devices in series connection and air cooling. The presented design is in use in several applications for pulse modulators in Radar Power Supplies, Medical Systems, Ocean Research and Food Sterilisation. The high reliability is proven by field experience. The switches can also be produced for different voltages by using series connection of devices, and for higher currents by using larger silicon wafer sizes and/or optimized cooling.

1 Introduction

Basic design of the IGCT is the GTO device. The GTO's which are used mainly in traction applications are nowadays for new designs replaced by IGBT's. The IGCT however is placed in a different application segment and mainly used as switch On-Off device in very high power drives and frequency converters as the design combines the rugged GTO structure with an integrated driver unit, making it easier handling for the equipment builder. By optimizing the GTO wafer structure, the semiconductor housing and placing the driver unit around the device, the result was a component with very strong switching behaviour. These devices are standardized an in production since the last 10 years. Standard IGCT devices are also used for long pulse modulator switches used for Free Electron Laser applications [1]. Fig. 1 shows some standard version IGCT's. For pulsed discharge applications, ABB is using the same principle but has further optimized the semiconductor wafer and driver unit for the specific demand. This presentation will only explain the specific discharge version of a 51mm reverse conducting IGCT used in a switch assembly for radar power supplies, medical modulators and related applications.

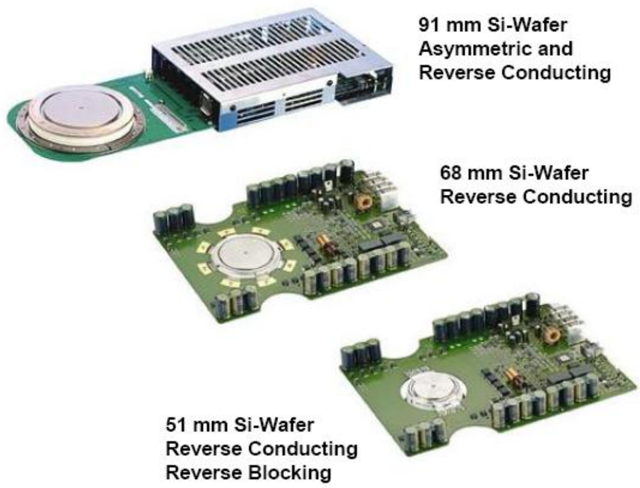

Fig. 1. Standard range of IGCT devices produced by ABB.

2 Discharge Device

For the specific capacitor discharge applications normally a high current rise rate is required. Depending on the application, values between 1.5 – 8 kA/µs are very common, therefore a normal phase control thyristor will fail after short time. By using silicon wafers with optimized GTO-like structure, which have several hundred small thyristor islands in parallel, the high di/dt can be easily handled. Very fast switch-on is required to reach the short steep pulse currents and this can be done by having a low doping profile as well as a strong gate-pulse which is entering the gate-structure from multiple sides. Depending on wafer size it can be 2, 4 or 12 gate-entrances. By using a driver unit which is arranged around the device, the induction between driver and gate is reduced to an absolute minimum, allowing strong gate currents. To avoid a separate freewheeling diode, this diode can be monolithic integrated on the silicon wafer, resulting in a very compact switching device with very low induction. The driver unit for the discharge device is only in the position to switch-on the semiconductor, there is no switch-off capability. The device will block again automatically after the energy has left the system. Fig. 2 shows a typical discharge IGCT using a 51 mm reverse conducting wafer. The monolithic integrated diode is visible at the outside rim.

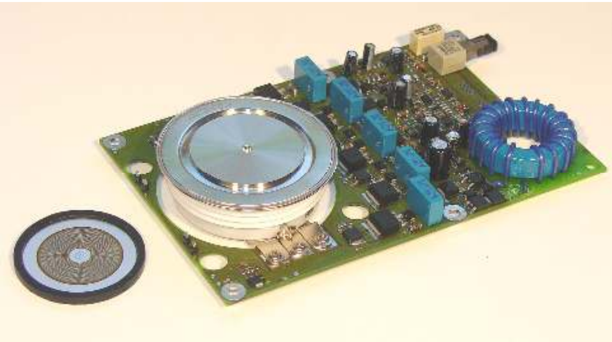

Fig.2. 5SPR 08F4522, Discharge device 4500V with integrated driver unit and reverse conducting wafer.

The IGCT devices are available with blocking voltages of 4.5kV and 6kV. For the pulsed applications ABB is mainly using the optimized 4.5kV versions. For higher voltages devices can be stacked in series connection. The components are special designed for series connection, using a torroidal input transformer for powering the driver unit by a separate current source power supply. The isolation voltage of the closed loop powering cable will give the isolation between the different driver levels. The driver unit is triggered by an optical trigger signal.

3 Thyratron Replacement Switch Design

For different applications several designs with discharge devices were made to replace thyratrons in systems with charging voltages between 5 and 25 kV. For this presentation a typical example of a switch design was selected which was built per specification shown in Table 1. This switch assembly is fully qualified and in volume production for radar power supplies.

Max. Charge voltage	6.5 kVdc
Pulse Current (single pulse)	3.6 kA
Pulse Current (@1300Hz)	1.4 kA
Di/dt	6 kA/µs
Pulse Form	Damped sine wave
Pulse Duration	Typ. 2 µs, Max.10 µs
Pulse repetition rate	1200 Hz
Ambient temperature	-10 … +50°C
Forced air cooling	24 liters / sec
Weight incl. trigger box	11.5 kg
Auxiliary power	24Vdc / 50W

Table 1. Basic specification of pulse power switch assembly SPR 08F45-3-AC-PA02

The required pulse form in the capacitor discharge system is a short damped sine wave, therefore reverse conducting semiconductor devices P/N 5SPR 08F4522 with Vdrm=4500V and Vrrm=0V are selected and used. Especially for the high reliable application as radar switch, three devices are used in series connection to reduce the DC voltage to a moderate 2166V. This will give the devices a very low FIT rate of only 1 FIT. By having three devices in series there will be also no influence on life time due to cosmic ray. To power the driving units a current source power supply is used. The output power is 25kHz / 4A which is distributed to the driver units with a closed loop high voltage cable. The isolation voltage of the cable will give also the isolation between the driver levels, as these are on cathode potential of every level. The circuit diagram of the switch assembly is shown in Fig. 3.

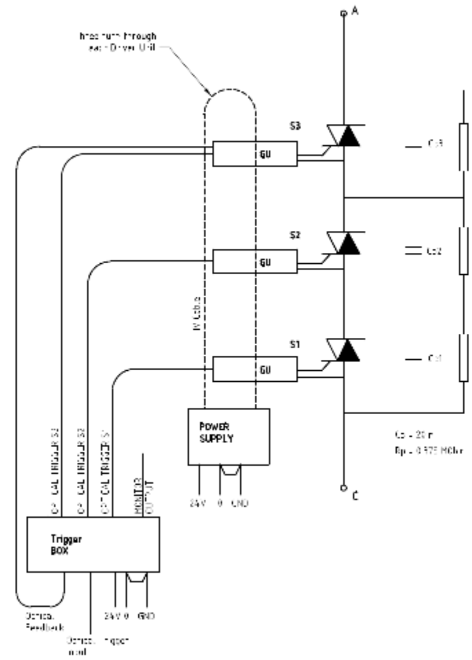

Fig. 3. Principle circuit diagram of the switch assembly

Because of the relative high pulse repetition rate of 1200Hz, the driver units have to be re-charged in a short time. Therefore is was required to have the closed loop cable turned three times through every driver input transformer. The total power consumption of the power supply is about 40W under the given condition. To monitor the function of the power supply one of the driver units in the assembly has an optical status output with will avoid triggering the switch if the driver units are not enough charged.

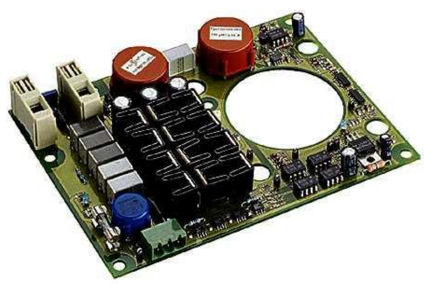

Fig. 4. Current source power supply 5SPP 25X4000

The three switching devices, the power supply and the sharing R / C's are built-up in a fully isolated stack assembly made from glass fiber epoxy and a the semiconductor devices are clamped with 16 kN. The clamping force is created by a bellville spring pressure pack. Because of the high frequency the devices have to be cooled. For the radar application it was important to have air cooling and therefore air cooled heat sinks were sandwiched between the switching devices. To avoid corrosion the aluminium heat sinks are nickel plated in the same quality as the contact area of the devices. The required continous power could be reached with forced air and 6 liters/s per heat sink, which results in 24 liters/s for the total switch. The maximum air inlet temperature is limited to 50°C. Independend of the project needs, tests were also done with the same assembly, but using water cooled heat sinks. The result was that the pulse current could be increased to 2.7 kA which means by almost a factor of two. By using water cooling the assembly will get also more compact. Because the switching devices are reverse conducting there is no need for a snubber circuit, only voltage sharing resistors and a small capacitor are added over every level. The driver units are all triggered simultaneously by an optical trigger pulse which is created by a light distribution box. This box is a separate item which belongs to the delivery and has specific settings for safe operation of the switch. The trigger input from the user's logic is normally optical, but can also be electrical on request. Fig. 5 shows the complete ready-to-use assembly including the optical trigger box and optical cables.

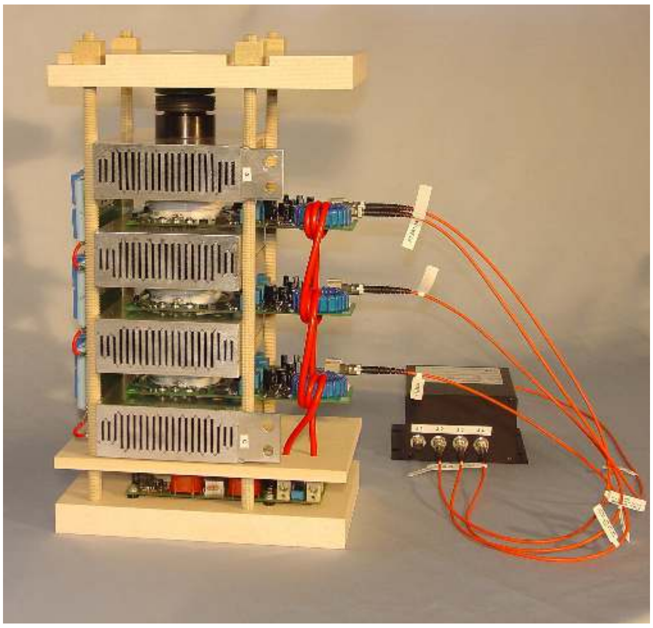

Fig. 5. Switch assembly complete with optical trigger box

4 Tests and Test Results

The semiconductor devices used in the switch assembly are produced on the mass production line for IGCT devices and therefore benefit from the in-line quality assurance as well as full outgoing factory inspection and individual routine tests. The semiconductor device is tested together with the driver unit before assembling into the stack. Finally the complete assembly will be tested under application conditions. Especially for use in the radar application a separate qualification was defined and done under all combined maximum conditions.

4.1 Device Test

Routine tests are done on wafer level and device level up to full blocking voltage of Vdr=4500V. The devices are in the production line tested and selected in groups of 3 on leakage current within a band of 0.1 mA. The pre-tested driver unit is than added and an outgoing inspection is done on the integrated product.

4.2 Assembly Test

After assembling all the parts together as a switch, the complete assembly is tested for following parameters:
- Voltage sharing between devices
- Gate voltage delay
- Current consumption power supply
- Pulse current test
- Frequency test (Vdc=5.6kV, I=1200A, f=1325Hz, t=5min.)
- Isolation test

The test circuit is shown in Fig. 6). The measured values are protocolized and are part of the product documentation supplied to the customer.

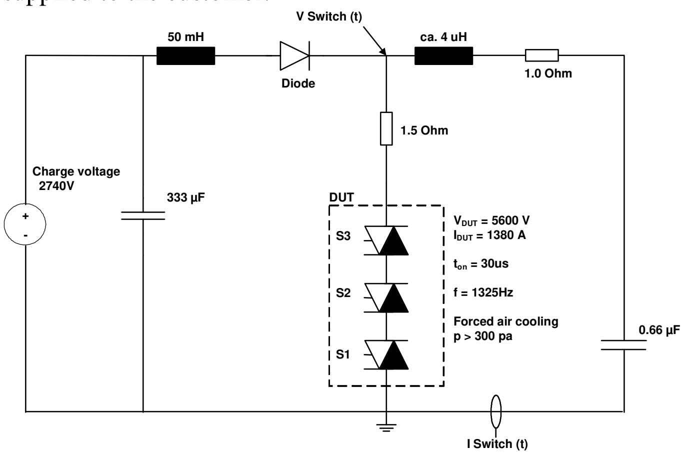

Fig. 6. Principle Diagram from test set-up

The first measurement on the complete assembly is the blocking voltage test on device level at Vdr=4.5kV, half sine wave, 50Hz without sharing resistors. The second test is the voltage sharing of the devices on stack level at Vdc=5.6kV. The difference between V_{AK} S1 and V_{AK} S3 is normally less than 100V but limitation is set at 300V. One of the important issues for series connection of the discharge IGCT's is to switch on at the same time to avoid that one of the devices should will block for a short time a different, probably higher, voltage as the other devices. Therefore the gate voltage delay is measured and monitored to assure that it is within the specified limitation of max. 30 ns. The gate voltage delay of all three devices is shown in Fig. 7) and well within this limitation. After these tests a functional pulse test is done with the RLC circuit shown in Fig. 6 with resonance charging, Vdc=5.6kV, I=1200A, f=1325Hz, t-pulse=5µs and t-on=50µs. The pulse current and voltage is shown in Fig. 8. Finally an isolation test is done for 1 min at Vdc=13kV between Anode, Cathode and the 24V input of the inductive power supply.

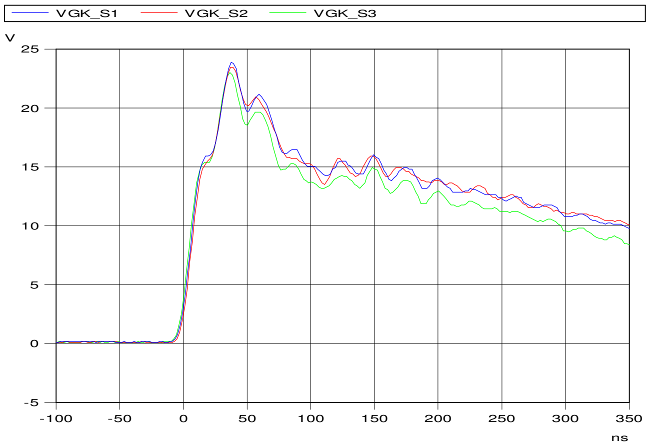

Fig.7. Gate Voltage Delay between S1 – S3

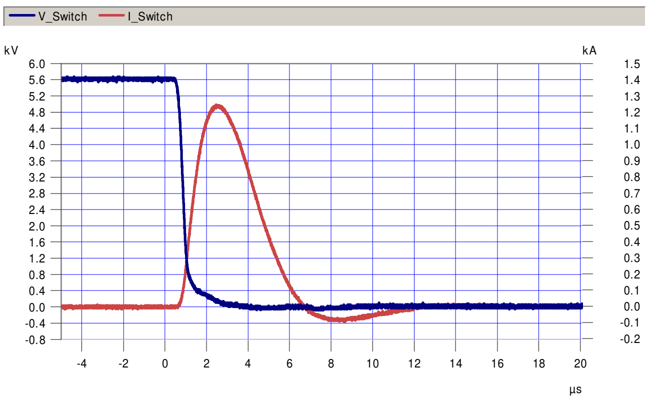

Fig. 8 Switch Pulse Current and Voltage

5 Life Time

Solid state switches do not have an infinite life time. The life time of semiconductor components or solid state switches is mainly limited by mechanical stress. These mechanical issues have to do with temperature steps in the silicon. Large temperature steps per pulse will mean a shorter life time for the device and therefore it is very important to take care of following aspects:

1- Max. Charge Voltage per device level (Cosmic Ray) should be less than 2800Vdc.

2- The current per silicon wafer area must be well within the limits for the temperature steps, A junction temperature of Tvj=115°C should not be exceeded.

3- The cooling method is important to keep the junction temperature as low as possible. (Selection of heat sinks, ambient temperature in combination with airflow)

4- The mechanical clamping must be uniform to reach a proper thermal management and to avoid damage of contact fingers on the silicon wafer.

The end of life of a press pack semiconductor device results normally in a short circuit failure mode. In case of series connected devices, one or more redundant devices can be mounted in the stack to avoid that the switch will stop operating after one device should fail. In the switch presented there is no full redundancy and in case of one device failure the switch has to be turned off within a some seconds to avoid damage to the snubber circuit and other components. The presented switch assembly has a calculated life time of more than 20 years continuous operation under the given conditions, which is more than 10 x longer as a thyratron under the same conditions.

6 Cost Comparison

In many applications, which were traditionally equipped with thyratrons, solid state switches become attractive alternatives since the last few years. New systems are mostly designed from the beginning already with solid state switches in discharge or even switch-off mode. Still some improvements are needed, especially for higher repetition frequencies and for higher voltage levels. As the devices used have a blocking voltage of average 4500V, there have to be a series connection of several levels to reach voltage in the range of 15 – 20 kV. This will increase the cost of a solid state switch assembly where the price of a thyratron is less depending on blocking voltage. Therefore it is important to find the optimum solution between charge voltage, pulse current and the cost. It is often more economic to use a pulse transformer with a higher ratio as to run a semiconductor switch at high voltage and low current. Because of the advantages of solid state switches with respect to reliability, maintenance and life-time, the system cost is in favour of the solid state version after about 3 – 4 years operational use. Fig. 9 shows a comparison for a typical application in a radar power supply or medical modulator for a charging voltage of 8.2 kV. In this comparison the maintenance costs and system-down costs for the thyratron version are not taken into consideration and should be added.

	Thyratron	**Solid State**
Charge Voltage	8.2kVdc	8.2 kVdc
Pulse Current	2.3 kA	2.3 kA
Pulse length	8 µs	8 µs
Current Rise Rate	5 kA/ µs	5 kA/µs
Pulse Rep. Rate	400 Hz	400 Hz
Filament heating	Yes	Power Supply
Triggering circuit	Yes	Yes
System cost complete	**€ 3.300,-**	**€ 6.750,-**
Tube cost € 1.700,-	Included	----
Replace tube every 18 months at € 1.700,- / each	€ 11.900,-	
Operation cost over a period of 12 years	**€ 15.200,-**	**€ 6.750,-**

Fig. 9. Cost comparison between the two different technologies based on a practical example.

Worst case, if the solid state switch should have a fatal failure after about 10 years, it is still more beneficial as a thyratron system because there were no maintenance and system-down costs. For applications with current pulse lengths above 10 -

15µs the solid state version has additional advantages as the pulse length for the semiconductor device is less critical as for a thyratron. This because of the better cooling possibility and no material emission in a semiconductor switch assembly.

7 Conclusion

Since more than 15 years ABB has been producing in volume a wide range of semiconductor components and solid state switches which are optimized for pulsed power applications. Solid state switches are successfully replacing thyratrons in many applications. An increased field experience with this technology has resulted in fundamental knowhow about the long term reliability of devices and switches operating under short pulse conditions. Multiple applications are already equipped with this technology. Despite the higher initial costs of a solid state switch, operation over time is more economical as that of a thyratron solution. The given example of a solid state switch is only one of a large range of switches produced by ABB Switzerland Ltd, Semiconductors.

References

[1] A. Welleman, W. Kaesler, "Solid State On-Off Switches Using IGCT Technology" *IEEE-PPPS2007, Albuquerque NM, USA, June 2007.*

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