Solutions with Solid State Switches for Pulse Modulators

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Abstract: **This presentation will show solutions with Solid State Switches designed and produced for Pulse Modulators in applications like Particle Beam Accelerators, Radar Power Supplies, Medical Modulators etc. Examples of semiconductor switches using IGCT (Integrated Gate Commutated Thyristor) technology for long Pulse Modulators as well as switches using fast, high di/dt discharge devices for Radar Power Supplies, Environmental applications and Medical Modulators with their advantages and disadvantages are presented. Because of the large field experience with the presented switches, also reliability information is included. For on-off switching with reaction times of less than 5 µs the trend with newer technologies like IGBT will be discussed and stackable pressure contact IGBT devices with increased Collector-Emitter voltage of 4500V will be presented. These devices, which are in volume production with Vces=2500V and are mainly in use for High Voltage DC power transmission systems, will now become available with Vces=4500V for pulsed power applications.**

I. INTRODUCTION

Since more than 15 years several discussions and conferences have taken place about the question "Why Solid State Switches" and about the advantages and disadvantages of this technology. The designs where often made with commercially of-the-shelf semiconductor devices and good enough for prototyping but less as a product with high reliability and long life time. Most volume semiconductor device manufacturers were not really interested in low quantities of special devices which are interrupting the mass production line. ABB has a range of semiconductor products which easily can be adapted and optimized for pulsed power applications. As a service to the user, complete switch assemblies can be offered which also will be application oriented tested before delivery. Because of volume production of optimized devices over several years, there is a high field experience available and therefore very reliable switch designs can be offered in different technologies like SCRs, IGCTs and IGBTs in various packages.

II. SWITCHING TECHNOLOGY

For different applications, there is a need for different switching technology. There is strong improvement in the semiconductors for pulsed applications, but it has to be mentioned that not for all applications the semiconductor device is the optimum product. Especially for very short pulses in nano second range and high currents it is still difficult to realize a reliable semiconductor product. In fig. 1 an overview is given about different devices and technologies which operate in micro second range.

TABLE 1
Range of devices

Device Type	Forward Blocking Voltage	Max. Peak Pulsed Current Capability	Di/dt Capability	Switch On	Switch Off
Thyristor	≤ 8500 V	120 kA	1 kA/µs	Yes	No
Discharge Thyristor	4500 V	150 kA	25 kA/µs	Yes	No
Integrated Discharge Thyristor	4500 V	150 kA	40 kA/µs	Yes	No
GTO	4500 V	4 kA	3 kA/µs	4 kA	4 kA
IGCT	≤ 6000	4 kA	2 kA/µs	4 kA	4 kA
IGBT (Wire Bonded Module)	≤ 6500 V	1 kA	2 kA/µs	1 kA	1 kA
IGBT StakPak (Press Pack)	≤ 4500 V	2 kA	4 kA/µs	2 kA	2 kA

The above table shows 7 different device technologies which are normally used. Depending on the application the switch supplier can select the adequate devices from this list. For systems working with PFN or for crowbars mostly discharge devices are used and depending on current rise rates it will be selected if a normal thyristor will do the job reliable or that highly interdigitated gate structures are needed. In case of highly interdigitated gate-structures, the so called discharge thyristors are used which are based on a GTO structure but have no switch-off capability. The Integrated devices have the Gate-drive unit integrated with the semiconductor switching part and tested as one complete component. It is also possible to integrate a freewheeling diode monolithic on the same switching wafer. The range of switch-on / switch-off devices is divided into IGCT and IGBT technology. The IGBT range is split into standard modules with wire bonded chips and so called StakPak™

press pack devices. For pulsed application mainly the press pack devices are used as the current sharing in the module is better and there is no wire bonding which could result in reliability issues.

III. MODULATOR SWITCHES USING IGCT

The IGCT (Integrated Gate Commutated Turn-Off Thyristor) is original designed to be used in High Power Motor Drive applications. ABB has a range of standard devices which are available with wafer sizes from 51 mm till up to 91 mm in different voltage classes. Fig. 2 shows the three different sizes.

Fig. 2. IGCT devices with 91, 68 and 51 mm wafers

For the German Electro Synchrotron DESY in Hamburg several switches were supplied for the long pulse klystron modulators in the Tesla Test Facility (TTF). These 100 kJ modulators [1] are equipped with IGCT switches using 7 devices in series connection. The same type of switch was also supplied to several other European customers. The pulse repetition frequency of the modulators is 10 Hz and in 2008 a modification was done to increase the pulse repetition frequency to 30 Hz. The IGCT switching devices are in the position to handle this increase by changing from convection air cooling to water cooling. Also the snubber resistors were changed to water cooled versions.

TABLE 2
Basic specification IGCT / DESY switch assembly

Turn-Off current (Nominal operation)	2000 A
Max. Turn-Off current (Gun spark)	4000 A
Pulse width	1700 µs
Pulse repetition Rate	30 Hz
Di/dt pulse current	325 A/µs
Max. continuous DC Voltage	13 kV
Max. Peak Voltage (limited by snubber)	21 kV
Max. Peak Voltage Reverse	4 kV
Stray inductance	5 µH
Cooling	De-Ionized Water
IGCT Switching devices (7 in series)	5SHY 35L4510

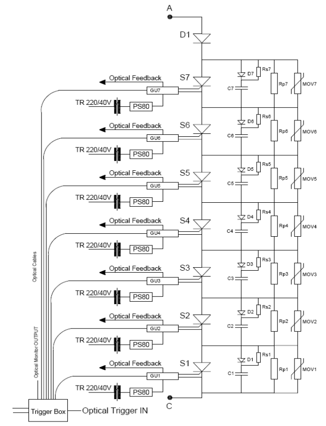

Fig 3. Circuit Diagram

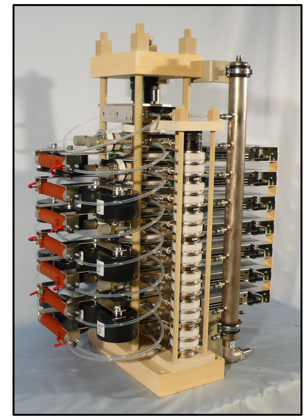

Fig. 4. Assembly complete
P/N: 5SVG 073507E01

Because the proven reliability of the original 12 switches, which have already cumulated more than 320.000 operation hours (2008) over the last years, without loosing any devices, there was no further change in the lay-out of the assembly. The upgraded switch is also the prototype for the new linear accelerator at DESY. In fig. 3 the circuit diagram of the switch is given. There are seven asymmetric blocking IGCT devices, each blocking 4500V forward and 17 V reverse, in series connection and one additional diode to give a reverse blocking capability of about 4 kV. Fig. 4 shows a picture of the complete switch assembly with an additional stack of press pack MOV's. With 7 devices in series connection there is redundancy of one device continuously and two devices for several minutes, which will allow controlled switch-off.

The same design but for lower power, using reverse conducting smaller size IGCT's was produced for prototype switches for the CERN Linac 4 accelerator. A reverse conducting device with monolithic integrated diode was selected because of some reverse current from the load. Here also two versions are made one for 10 Hz pulse repetition frequency and one for 50 Hz repetition rate. The difference between the two versions is that the 10 Hz assembly is convection air cooled and the 50 Hz version is water cooled.

TABLE 3
Basic specification IGCT / CERN switch assembly

Turn-Off current (Nominal operation)	300 A
Max. Turn-Off current (Gun spark)	800 A
Pulse width	1300 µs
Pulse repetition Rate	10 Hz
Max. continuous DC Voltage	12 kV
Max. Peak Voltage (limited by snubber)	20 kV
Voltage Reverse	0 V
Stray inductance	3 µH

Devices used in the CERN switch are 5SHX 08F4510 and also here 7 pieces are used in series connection to get redundancy of two devices without interrupting the switch function.

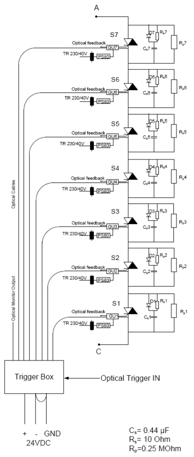

Fig. 5. Circuit Diagram

Fig. 6. Reverse Conducting Switch Assembly complete P/N 5SVG 073508E01

IV. MODULATOR SWITCHES USING DISCHARGE DEVICES

For those applications where PFN are used or only discharge functions are needed, ABB is offering fast switching, high current, and high di/dt devices. These devices have highly interdigitated gate structures, are related to GTO designs and combined with a low inductive driver unit and semiconductor housing, it is a unique product for pulsed applications. Asymmetric and reverse conducting versions are available from volume production. A solid state switch design was made to replace thyratrons in radar power supplies for Airport Approach radar systems using the specification as listed in table 4 below.

TABLE 4.
Basic specification discharge switch assembly

Max. DC charge voltage	6.5 kV
Peak pulse current	1.5 kA
Pulse width	5 µs
Current Rise Rate	6 kA/µs
Pulse repetition Rate	1300 Hz
Pulse wave form:	Damped Sine
Cooling	Forced Air
Ambient temperature	-25 …. 50°C
Semiconductor devices	7 x 5SPR 08F4522

Because of the high reliability needs for this application, extensive tests were done on prototypes over a period of more than two years, which resulted finally in a production order for several hundred switches of which most are in service on the North American continent. The switch is built up with a series connection of 3 reverse conducting devices having 51 mm Si-wafers, including integrated driver units and a current source power supply. The power supply feeds the driver units with 25kHz / 4A through an inductive coupling with a HV cable, which is also the isolation between the 3 driver levels. The driver units are optical triggered and air cooled heat sinks are sandwiched between the semiconductor devices for cooling. Forced Air cooling is required because of the relative high frequency of up to 1300 Hz. Fig.7 shows the circuit diagram and fig.8 the discharge device.

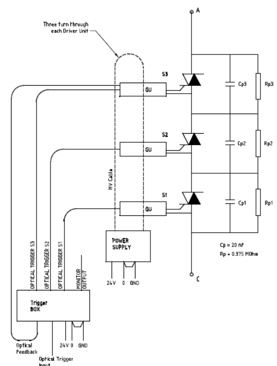

Fig. 7. Circuit Diagram

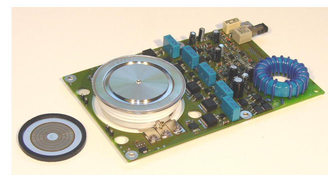

Fig. 8. Reverse Conducting Discharge Device P/N 5SPR 08F4522

The switch is built-up in a glass fiber epoxy assembly which can be mounted in any position in the modulator cabinet. With this solution the maintenance costs could be reduced to an absolute minimum and life time is expected to be at least 10 x longer as the corresponding thyratron version.

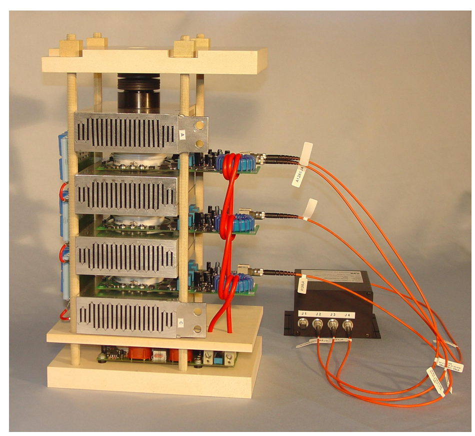

Fig. 9. P/N 5SPR 08F45-3-AC, Switch assembly complete including optical trigger box.

With the indicated 1300 Hz, the frequency limitation of the IGCT technology is nearly reached. For higher pulse repetition rates IGBT technology has to be used.

V. IGBT's FOR MODULATOR SWITCHES

Despite the ruggedness of the IGCT devices, the switching speed is often for short reaction times not sufficient enough to safe switch-off the current in case of gun sparking. The typical reaction time of the IGCT is T-on (90%) in approx. 3µs and T-off (90%) in approx. 6 µs. If faster reaction times are required the technology has to be changed to IGBT which technology is in the position to respond in the range of approx. 1.5 – 2 µs including. the driver delay time. ABB and other semiconductor suppliers have a range of industrial type IGBT modules which are mainly used for energy conversion, motor drives and traction application. These modules are built-up with multiple chips in parallel connection and therefore the current sharing in the module is normally not designed for pulsed applications. In addition the chips have wire bonded connections which can be a reliability problem if used under pulsed stress conditions. In case of series connection the wire bonded modules will have an open connection in case of failure and the switch will stop operating. Fig. 10 shows a substrate as part of a wire bonded module.

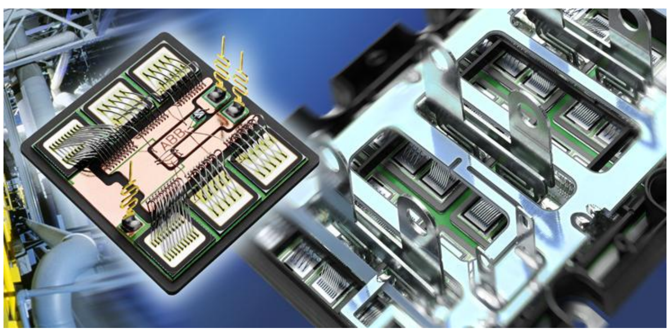

Fig. 10. Wire bonded Substrate (left) and open housing of a industrial design IGBT module (right)

To avoid this type of reliability problems, the solution for pulsed applications is to use press pack IGBT modules. ABB is producing since 2001 so called StakPak™ press pack IGBT devices in high volume for High Voltage DC Transmission (HVDC) systems. These devices have a blocking voltage of 2500V and can handle currents up to 4 kA. Since production capacity was completely full for this type, no capacity was left for any other voltage classes. In 2008 it is foreseen to start production of the 4500V/1200A (2400A Pulsed) StakPak IGBT module especially designed for pulsed power applications. The advantage of the StakPak construction is that it has a unique mechanical construction which makes the devices very easy to stack without any precautions for clamping force and pressure distribution over the individual chips. Every chip is covered by its own small Bellville spring and pressure can be added to the device and stack till the housing frame of the device is taking the surplus pressure, which means that over clamping is not possible. The design will allow flexibility to combine all required combinations of IGBT and Diode chips in the Sub-modules. Fig. 11 shows a picture of device and sub-module of the 4500V version.

Fig. 11. Sub Module Emitter Side (1200A pulse rating) — Complete Module Collector Side

All relevant parts like heat sinks and driver units which are available for the 2500V version, will also become available by the end of 2008 for the 4500V version, which will be rated for approx. 2400A in pulsed applications.

VI. CONCLUSION

Solid state switches for long pulse modulator applications using IGCTs are extremely reliable and successfully in use since the last years. IGCT discharge switches for Radar Power supplies, X-ray and environmental applications were successfully applied to several hundreds of modulators and are actually used in professional systems. ABB has long term experience with press-pack IGBT devices and is increasing the blocking voltage for these devices to 4500V to be in the position to serve those applications where the switching delay and frequency of the IGCT is not sufficient enough.

VII. REFERENCES

[1] A.Welleman, W.Fleischmann, W.Kaesler, *Solid State ON-Off Pulse Switches using IGCT Technology*, IEEE Int'l Pulsed Power Conference PPC2007, Albuquerque NM, June 2007.