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SEMICONDUCTOR SWITCHES ARE SUCCESSFULLY REPLACING THYRATRONS IN DEMANDING APPLICATIONS

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Abstract

A presentation is given about semiconductor devices and solid state switch assemblies which are successfully used in Pulsed Power Supplies for Radar-, Medical-, and Environmental applications. A description will be given about devices with high current rise rates. Also described is the construction of switch assemblies for which it is very important to have a low induction. Very low induction can be reached with reverse conducting devices, using a monolithic integrated diode on the device switching wafer, and low inductive semiconductor housings. The specifications, test results, operation life time and cost calculation of this type of switches is discussed. The technology offered today is capable to reach pulse repetition rates of up to 1300 Hz, current rates of several kA and blocking voltages of < 30 kV and is available from volume production lines. This type of solid state switches is now proven in the field for more than 3 years.

SEMICONDUCTOR DEVICES

For repetitive discharge applications like modulators etc. ABB is offering a wide range of optimized semiconductor components [1], which can be used for switching under the specific pulse application conditions. This means that the discharge devices offer a very high di/dt combined with a very high current capability for pulse lengths in the range between approximately 1 µs and some milliseconds. These optimized devices are produced in the mass-production line and therefore benefit from good availability, reproducibility and combine also a very high quality level. Most of the bipolar devices have integrated driver units and can be easily stacked in series connection. The picture No. 1 shows the silicon wafer sizes, 51 mm, 68 mm and 91 mm, which are used for the high di/dt, high current discharge devices.

Fig. 1, Silicon Wafers 51, 68 and 91 mm

All three versions can be produced as reverse conducting, reverse blocking or asymmetric design. Most common blocking voltages are Vdrm=4500V. A max. continuous. DC voltage of 2800V, or 3600V for < 1 min is recommended because cosmic ray can damage the silicon if the DC voltage is too high. With the mentioned limitation at about 2800Vdc the FIT rate will be 100 for the semiconductor device and about 450 for the integrated driver unit. These devices are designed as capacitor discharge components which are very rugged because of their mechanical construction as press-pack, one wafer, bipolar device and therefore have no problems with burn-out of wire-bondings or current mis-sharing like the case is in IGBT modules designed for industry or traction. The devices offer a very high di/dt and high pulse current capability. Fig. 2 shows the mechanical construction of such a device with the low inductive housing which is important for pulse applications.

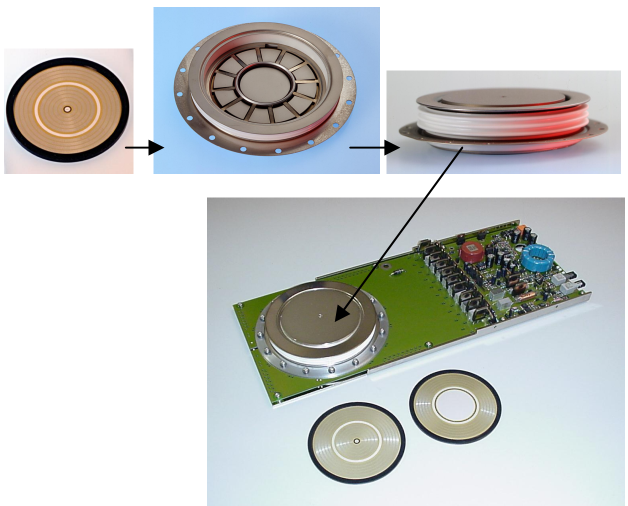

Fig. 2, Wafer 91 mm, Low-Inductive Housing, Device complete and Device mounted in driver board

To reach the required low induction, the semiconductor housing has an annular gate connection and the driver board is surrounding the power device. The driver board is in most of the cases integrated with the semiconductor device. There is an optical receiver as trigger input and optical transmitter for status monitoring. The driver board is powered by a closed loop current source power supply, which is a separate item. The advantage is that series connection of devices is easily done by sloping the closed loop cable through all the input transformers of the driver units. [2] The isolation voltage of the closed loop cable should be at least 2x higher as the total charge voltage of the series connected devices. Fig. 3 shows a current source power supply with output power of 25 kHz / 4A.

The amount of devices in series connection which one power supply can handle is depending on pulse repetition frequency and pulse length.

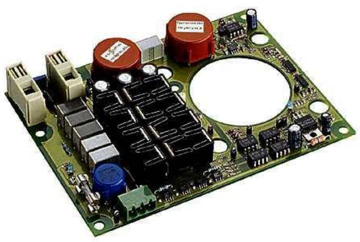

Fig. 3, 5SPP 25X4000, Current Source Power Supply

SOLID STATE SWITCH ASSEMBLIES

Instead of loose components most OEM’s prefer to receive a ready-to-use switch, which will fit into their application. Also the semiconductor supplier prefers to deliver a complete switch assembly for the simple reason that the switch assembly can be fully tested before leaving the factory. ABB offers a wide variety of different solid switches from high current single pulse discharge switches to repetitive on-off switches for laser power supplies. A complete assembly will integrate the semiconductor devices, the device driver units, the clamping system, the triggering and if required also the water- or air cooled heat sinks. As example, a solid-state switch assembly is presented in this paper which was designed for thyratron replacement in radar applications and is successfully in use since longer time. Because the design is used at the moment for several other applications, like pulsed corona discharge, medical accelerators etc., it is becoming now a standard in the pulsed power market place. The switch presented is built-up with 3 semiconductor devices in series connection using 51 mm reverse conducting wafers. Table 1 shows the specification of the switch assembly.[3]

EXAMPLE OF A 1.3 kHz SWITCH

Forward Blocking:	13.5 kV
Reverse Blocking:	0 V
Max. Charge Voltage:	8.5 kV
Pulse Current:	2.0 kA
Pulse Duration:	2.5 µs
Current Rise Rate:	5.0 kA/µs
Pulse Repetition Rate:	1.3 kHz
Cooling:	Forced Air
Ambient Temp.:	-10 … +50°C
Semiconductor Device:	5SPR 08F4522 (3)
Power Supply:	5SPP 25X4000 (1)
Trigger Box:	Separate (1)
Clamping system:	Glass Fiber Epoxy 18 kN

Table 1, Specification of the Switch

Fig. 4 shows the circuit diagram including the trigger box and optical cables for triggering the driving units and the feedback from the first driver board. The feedback is used to monitor the function of the power supply, and will avoid that the trigger box will give a trigger pulse if the driver unit capacitors are not fully charged.

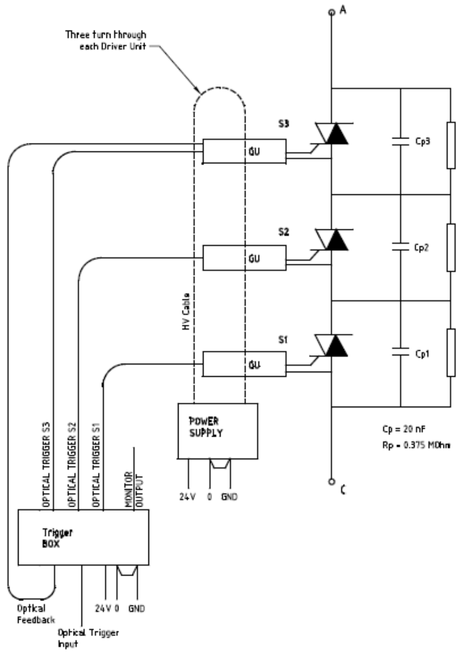

Fig. 4, Circuit Diagram Solid State Switch, including optical cables for triggering and monitoring

The mechanical built-up of the switch was done with air cooled heat sinks from Webra and the clamping system was made of Glass Fiber Epoxy which offers good mechanical strength as well as good isolation. The Glass Fiber Epoxy can be easily machined and is a very good isolator. A Bellville spring pressure pack is used to have the right clamping force applied to the devices.

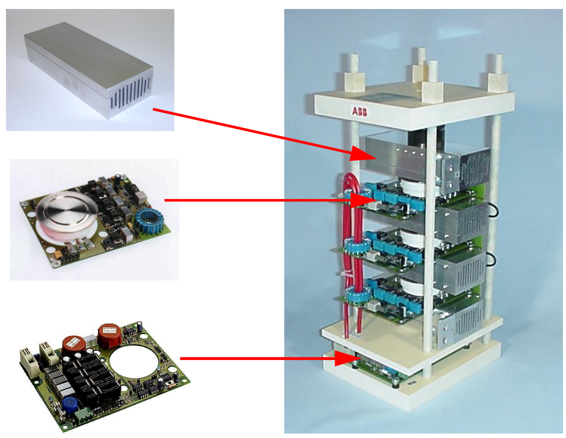

Fig. 5, Solid State Switch Assembly built-up with heat sink, semiconductor, power supply and insulated clamping system.

The demand in the radar power supply was for a switch with air cooling. By using air cooled heat sinks the thermal capability of the design is limited and a comparison with water cooled heat sinks has shown that the water cooled version can handle approx. 2 x the current capability without changing any other components in the stack-assembly.

SWITCH TEST RESULTS

Fig. 6 shows the test circuit how the switch assembly was tested.

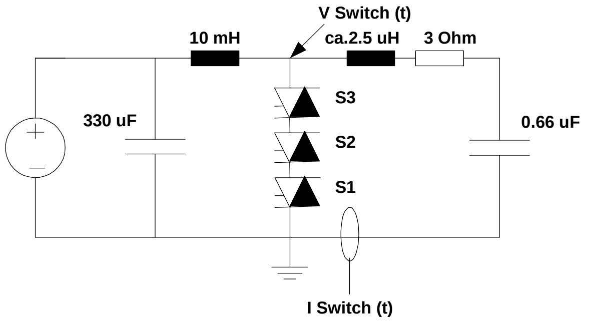

Fig. 6, Test Circuit

The test in ABB was done as far as possible under application conditions. At first the leakage current of the single devices was measured at 4.5kV, 50Hz, 25°C, half sine wave. On stack level following tests were performed at Tvj=25°C:
Voltage sharing Vak S1-S3 @ Vstack=9kV
Gate Voltage delay S1-S3 @ turn-off VGK=5V
Frequency Test @ Vstack up to 8.5 kVdc
Pulse Current up to 1.8 kA
Frequency 800 – 1300 Hz, tp=6.6µs, ton=30µs

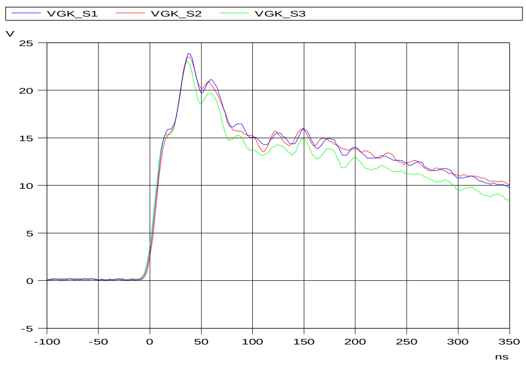

Fig. 7, Gate Voltage delay between S1-S3

Fig. 7 shows that the gate voltage delay between the device levels S1-S3 is less than 5 ns @ Tvj=25°C. A frequency test was done at V-stack = 8.5 kV, I-Stack = 1850A, f = 800 Hz, t-pulse = 6.6 µs, Ta = 30°C. The current pulse in Fig. 8 is showing a small negative part, which is taken by the diode integrated on the same silicon wafer. In this case the light distribution box is programmed to give triggering light to the device for 30µs to be sure that all the energy has left the switch before recharging of the capacitor can take place.

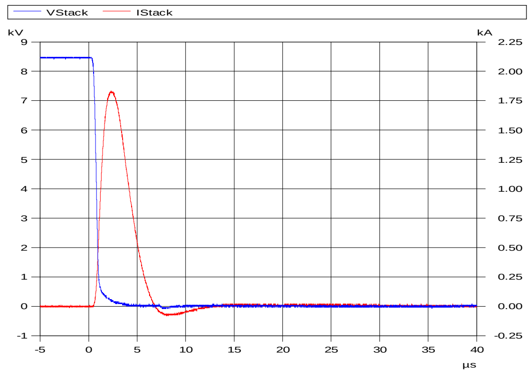

Fig. 8, Frequency Test @ V-stack = 8.5 kV
I-stack = 1.850A, f=800 Hz, tp=6.6µs, ton=30µs, Ta= 30°C, Rth=246 K/W, Pressure- Drop = 250 Pa.

Also the energy per pulse, power losses, current capability and junction temperature of the device were measured and monitored at different frequencies. Table 2, shows the results of these measurements.

Pulse Rep. Freq.	**V - Stack**	**I - Stack**	**E/Pulse per Stack**	**Power loss per Device**	**Tj**
[Hz]	**[V]**	**[A]**	**[mW]**	**Device [W]**	**[°C]**
1300	4210	890	350	152	67
1300	6340	1350	900	390	**125**
1000	6250	1340	740	247	91
1000	7340	1580	1050	350	116
800	7350	1600	900	240	89
800	8420	1840	1275	340	114

Table 2, Power Matrix for a 3-level switch with 3 x 51 mm Reverse Conducting Devices 5SPR 08F4522

The junction temperature should be limited to max. 115°C to avoid long term reliability problems. With improved cooling, for example if the same switch should use water cooled heat sinks and water cooling it could handle Ip=2500A @ 1300Hz. The existing switch with air cooling was tested under all maximum conditions in a clime chamber to ensure that the performance was guaranteed over a temperature range of -25 … +50°C ambient temperature. To ensure the full operation spec at +50°C a wider heat sink, 116 mm instead of 64 mm, hat to be installed. The switches are in production today with the 116 mm wide heat sinks.

LIFE TIME

Solid state switches do not have an infinite lifetime. 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, which means high temperature rise per pulse, will mean "shorter life time" for the device. Every pulse will result in a temperature step in the silicon, and therefore consumes some tiny part of the life-time of the device. The designer of the solid state switch has to consider corresponding design rules depending on the application and type of devices selected. A good design will take into consideration at least following aspects:

1- Max. Charge Voltage per device level (Cosmic Ray)
2- Current per device area (Wafer size)
3- Temperature cycle per pulse
4- Cooling method
5- Mechanical clamping

The end of life of a press pack semiconductor will result in a short circuit of the device. In case of series connected devices one or two redundant devices can be mounted in the stack to avoid that the switch will stop operating after one device level should fail. ABB can calculate the expected life-time of solid-state switches if the operation and application conditions are known. Such a calculation will take into account the pulse current, pulse length, waveform, dc-charge voltage, pulse rep.rate, and silicon junction temperature. The presented solid state switch assembly used at continuous 400 - 600 Hz operation in a radar power supply has an calculated life-time of about 12 years which is more than 7 x longer as a thyratron tube under the same conditions. Fig. 9 shows the contact fingers of two 91 mm wafers used for pulsed operation.

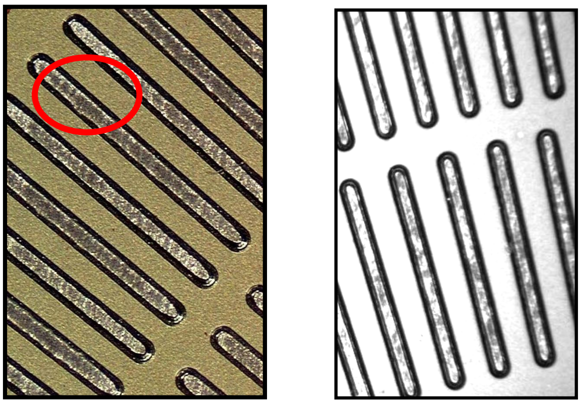

Fig. 9, Wear-Off at contact fingers

The right wafer was used under moderate conditions during a period of 5 years; the contact fingers do not show any deformation. The wafer on the left side was used during more than 6 years under very harsh pulse conditions and was over clamped. The contact fingers in the red circle are strongly deformed and will create a Gate-Cathode short within time.

COST

In many applications, which were traditionally equipped with thyratrons, solid-state switches become now attractive alternatives and new designs mostly take only solid state switches into account. Still some improvements are needed, especially at the high voltage levels (15 kV and up), as series connection of many semiconductor devices will increase the total cost of the switch assembly. High voltage means also more device levels and will add cost. Therefore it is important to find the optimum solution between charge voltage, pulse current and cost. It is often more economic to use a pulse transformer with a higher ratio as to run a semiconductor switch with high voltage and low current. Because of the advantages of solid-state switches with respect to reliability and maintenance, the system cost is in favour of the solid-state version after about 3 – 4 years operational use. Table 3 shows a comparison for a typical application in a radar power supply. In this cost the man hours and off-time of the system is not taken into consideration, only the hardware.

	Thyratron	**Solid State**
Charge Voltage	9 kV	9 kV
Pulse Current	2.5 kA	2.5 kA
Pulse length	10 µs	10 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	**US$ 4.000,-**	**US$ 9.000,-**
Tube cost US$ 2.300,-	Included	----
Replace tube every 18 months at US$ 2.300,-	US$ 16.100,-	
Operation cost over a period of 12 years	**US$ 20.100,-**	**US$ 9.000,-**

Table 3, Cost comparison of two different technologies

It has to be mentioned that for higher voltages the cost advantage of the solid state switch solution are getting smaller compared to thyratron solutions. This has to do with the fact that a high voltage thyratron tube is in relation to the lower voltage ones not much more expensive. The solid state switch however needs more device levels and will get proportionally higher in cost. Therefore today the economic level for a thyratron replacement with solid state is between 8 – 15 kVdc operating voltage. Higher voltage can be still interesting as the solid state switch has no problems with longer pulse lengths of over 20 µs, were a thyratron will become some disadvantages.

CONCLUSION

Since more than 15 years ABB has been producing in volume a wide range of reliable semiconductor components and solid state switches which are optimized for pulsed power applications. Solid-state switches are successfully replacing tubes in many applications, also operating at higher frequencies. Multiple applications and field experience over the last years have shown that the reliability of the solid-state switches is superior to tube solutions. Despite the initially higher cost of a solid-state switch assembly, operation over time is more economical than with a thyratron. The given example is only one of a large range of solid state switch assemblies produced by ABB Switzerland Ltd / Semiconductors.

REFERENCES

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