Implementation of a Solid-State Power Controller for High-Voltage DC Grids in Aircraft

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***Abstract*—Conventional electrical distribution systems onboard aircraft use a three-phase system with a typical voltage of 115 V_{AC} or 230 V_{AC} to supply electrical loads. Future aircraft demand more electric power due to the replacement of hydraulic and pneumatic systems by electrical ones and the increased use of multimedia entertainment systems. However, the aircraft weight can be decreased if a high-voltage direct current (HVDC) grid with a voltage level of ±270 V_{DC} or 540 V_{DC} is implemented to supply the electrical loads. These higher voltages reduce cable weight, but are a new challenge for solid-state power controllers (SSPC), which are used as protection devices for cables and loads. Currently available SSPCs are limited to lower voltages and currents mainly because of the available power semiconductors. A SSPC for aircraft applications with a nominal voltage of 540 V_{DC} and a nominal load current of 10 A has been developed at the Helmut Schmidt University in Hamburg in cooperation with Airbus Group Innovation using SiC-MOSFETs and has been tested. In this paper the design and experimental results are presented. The SSPC is able to supply itself from the high voltage autarkic and can accomplish various functions.**

Keywords: Aircraft, Circuit Breaker, More Electric Aircraft, Silicon-Carbid, Solid State Power Controller

I. Introduction

The demand for passenger and cargo aircraft is predicted to rise in the next decades. Especially due to increasing oil prices the airline demand more efficient and lighter aircraft because the operating costs are up to 50 % of the overall costs [1]. By improving the aircraft the electrical system is of special focus since the electrical power demand is rising. This is accounted by the concept of More Electric Aircraft and the intensify demand of multimedia entertainment systems by the passengers.

Conventional aircraft use a three-phase system with 115 V_{AC} or 230 V_{AC} by either a fixed frequency of 400 Hz or a variable frequency in range of 360 Hz to 800 Hz for most of the electrical consumers [2]. Also a 28-V_{DC}-grid is used to supply loads with a low power consumption. SSPCs were first used on 28 V_{DC} grids in military ground platforms. The fuses and circuit breakers were replaced by more reliable and faster electronic components. The first civil passenger aircraft with a wide use of SSPCs is the A380 from Airbus [3], [4]. A SSPC consists of power semiconductors and several components like shown in Figure 1. SSPCs can be remote-controlled, do not arc and can switch currents within 3 µs [3]. They allow an arc fault protection and an active control of current limits. They can also be used for power management functions. But SSPCs are more expensive compared to circuit breakers and normally depend on an external energy source with a typical voltage of 28 V_{DC}.

At present, MOSFETs made of silicon (Si) are used. Due to the large specific resistance at higher blocking voltages Si is inferior to silicon carbide (SiC) [6]. Besides the lower specific on-resistance at high voltages the maximum allowed temperature is higher (200°C). The use of SiC JFETs need an additional 28 V_{DC} grid because it is a normally on-device.

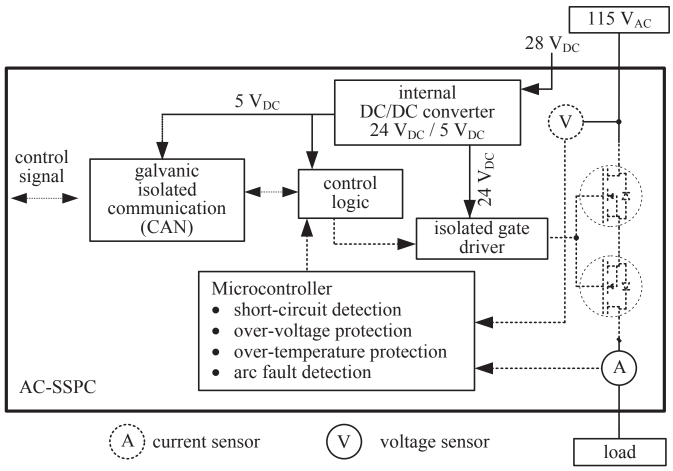

Figure 1. Basic set-up of AC Solid State Power Controller [11]

II. FUTURE GRIDS

It is often suggested to use a high-voltage DC grid (HVDC) in future aircraft with only one voltage level of weather 270 V_{DC}, ±270 V_{DC} or 540 V_{DC} [3], [7], [8], [9]. The voltage value of 270 V_{DC} is obtained by rectifying the conventional 115 V_{AC} of classical aircraft generators. The voltage of ±270 V_{DC} or 540 V_{DC} are obtained by rectifying newer 230 V_{AC} aircraft generators [10]. Thereby, the high voltage leads to cable weight reduction and the DC leads to lighter electronic converters compared to AC/AC or AC/DC converters [1]. Since the DC current does not automatically crosses zero twice per cycle during a fault like in an AC power system, the protection is more complex. Conventional circuit breaker would arc in such a case and are relatively slow in shutting down a failure. If SSPCs are used for primary flight system they are considered essential meaning a claim of a high reliability is necessary.

III. NEW SIC-BASED HVDC-SSPC

To demonstrate the functionality of a HVDC-SSPC in HVDC grids a prototype has to be developed. The following requirements are defined for the new HVDC-SSPC:

- rated voltage of 540 V_{DC}
- short-time high-voltage capable of 1 kV
- nominal current of 10 A
- nominal power 5,4 kW
- low voltage drop

Different I^2t-curves are implemented for different current values of 3 A, 7 A and 10 A imitating a thermal fuse behavior. Additional goal of the research was that the new SSPC should be supplied by the primary voltage and not being dependent on an external 28-V_{DC}-supply. The communication should be realized using the controller are network (CAN), which is the state of the art in aircraft systems. The new SSPC is able to shut off by:

- overcurrent
- over-voltage
- over-temperature 80°C

Additionally, under-voltage and under-temperature ratings can be implemented. Using the voltage and current sensors capacitive loads can be monitored. An additional conventional thermal fuse is implemented on the printed circuit board (PCB) as a backup option in case the SSPC's power switches are faulty, making the SSPC very reliable.

Si-MOSFETs are not suited for this application because of the lower voltage level. The SiC-MOSFETs used are APT40SM120 from Microsemi with the parameters:

- I_D (25°C) = 40 A (I_D: drain current)
- I_D (100°C) = 24 A
- $I_{D\,max}$ = 100 A
- $V_{BR(DS)}$ = 1,200 V ($V_{BR(DS)}$: breakdown voltage)
- $R_{DS(ON)}$ = 80 mΩ ($R_{DC(on)}$: drain-source resistance)
- max. P_V = 215 to 273 W (P_V: power loss)
- V_{GS} = -10 V to 25 V (V_{GS} gate-source voltage)
- E_{AS} = 2.2 J (E_{AS}: avalanche energy)

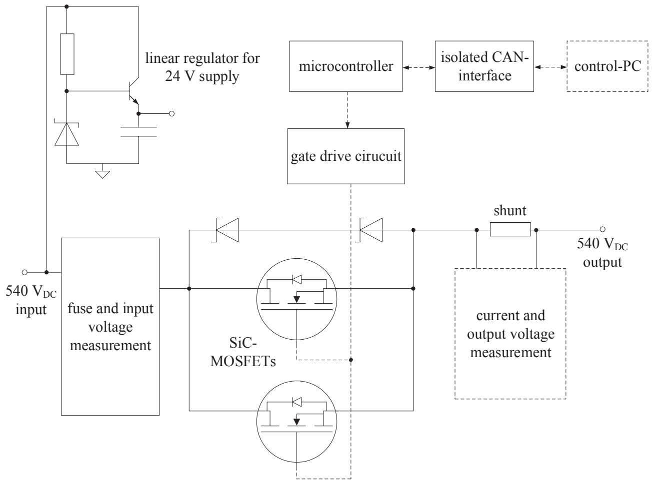

Figure 2. Schematic of the new HVDC-SSPC

Higher voltage spikes than the MOSFET rating, due to inductive load switching, are suppressed by two transient voltage suppressor diodes (TVS-diodes) in series connection, each having a rating of 450 V. Positive voltage spike for source to drain are not blocked due to the inherent body-diode. The schematic showing the basic modules is shown in Figure 2. The main components are the two parallel SiC-MOSFETs, the gate drive circuit including the isolated DC/DC-converters, bias power supply (linear regulator) and input/output circuits to measure and to control the device. Two SiC-MOSFETs in parallel are sufficient to satisfy the maximum allowed voltage drop at nominal load current. Using several sensors to determine the input voltage, output voltage, the load current and the temperature turns the SSPC into a monitoring system. The current is sensed using a high voltage current shunt monitor of type AD8212 combined with a pnp-bipolar junction transistor (BJT) to withstand the high voltage. The SSPC shall be activated with a CAN bus. Thereby, the SSPC can communicate the electrical and thermal measures to the main controller.

The semiconductor losses P_V are:

$$P_V = 2 \cdot (5\mathrm{A})^2 \cdot 80\mathrm{m}\Omega = 4\ \mathrm{W}$$

Choosing low energy parts, the own power consumption P_E of the device is:

$$P_E = 24\mathrm{V} \cdot 14\mathrm{mA} = 0{,}34\ \mathrm{W}$$

The power loss P_{npn270} produced by the npn-BJT of the linear regulator is:

$$P_{\mathrm{npn270}} = (270\mathrm{V} - 24\mathrm{V}) \cdot 14\mathrm{mA} = 3{,}4\ \mathrm{W}$$

To cool the npn-BJT a big cooling device with a thermal resistance of 6 K/W is used.

The SSPC is autarkic because it is supplied from the main high DC voltage using a linear regulator shown in Figure 3. The npn-BJT (*BJT1*) is blocking the main part of the high voltage and is controlled in such a way by the zener diode *ZD* with a breakdown-voltage of 28 V that the voltage across the capacitor C_{DC} is nearly constant 28 V. The resistor R_Z is limiting the maximum current through the zener diode. Test showed that to activate the microcontroller an input voltage of at least 120 V is necessary.

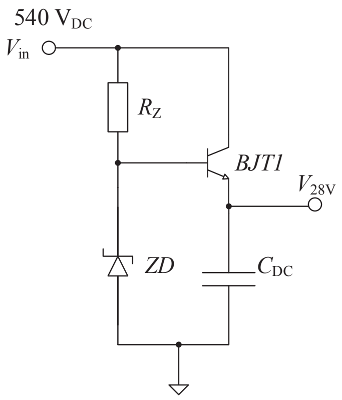

Figure 3. Linear regulator to achieve an autarkic HVDC-SSPC

A picture of the top side of the HVDC-SSPC showing the main components can be seen in Figure 4. At the bottom-side only small surface mount devices are installed (e.g. CAN-transceiver, temperature sensor, backup thermal fuse, TVS-diodes).

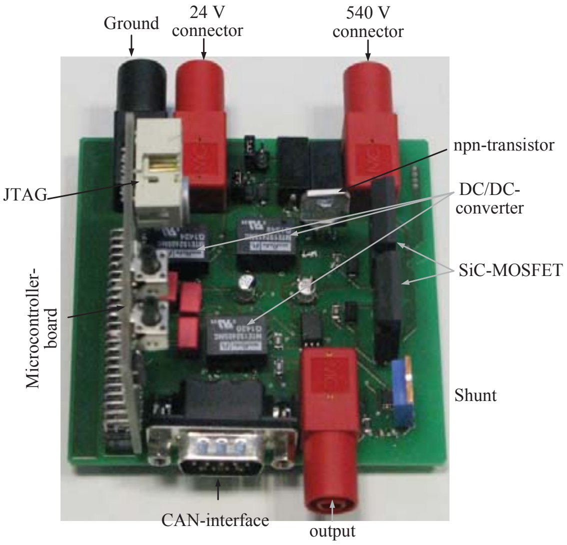

Figure 4. Toplayer of the HVDC-SSPC showing the main components

The complete SSPC is inserted into a case made of transparent Makrolon (polycarbonate) allowing visual inspection, as shown in appendix Figure 9. It can withstand temperatures up to 150°C and voltages beyond 10 kV. Small drills distributed on the case allow air circulation. The npn-BJT as well as the SiC-MOSFETs are equipped with heat sinks.

IV. Experimental Results

The basic test setup for the experiments is shown in Figure 5. The voltage V_{IN} is generated by multiple DC power supplies of type SM 660-AR-11. The load is represented by a Chroma 63803 electrical load. The measurements have been done using an oscilloscope LeCroy WaveRunner HRO 64Zi and temperature camera FLIR I7. The SSPC should withstand the requirements made in MIL-STD-704 rev. F extrapolated to $540V_{DC}$. The SSPC is typically activated allowing a load to be supplied and the electrical parameters to be monitored. In case of improper operation conditions the SSPC turns-off and sends a failure message via CAN to the control-PC.

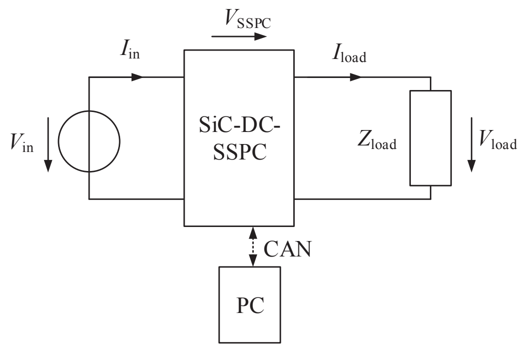

Figure 5. Basic test setup

The following tests have been accomplished:

- test by maximum MOSFET voltage (MOSFETs turned-off)
- switching at high voltage and different current ratings
- measuring the SSPC temperature by 270 V and different current ratings
- testing thermal fuse behavior (I^2t behavior)

The temperature curve at V_{in} = 270 V_{DC} at different load currents is shown in Figure 6. With uninterrupted load currents of 3 A, 7 A, 10 A and 15 A the device's temperature has been measured every 10 s, starting from a room temperature of 25°C. At the lowest load current of 3 A the steady-state temperature of 40°C is reached after 60 s. The hottest part in this case is the npn-BJT of the linear regulator. The final temperature at a current of 7 A is 85°C and at 10 A is 125°C.

The device attains temperatures up to 150°C at a load current of 15 A. In all cases, except for 3 A, the hottest part has been the SiC-MOSFETs According to aerospace requirements, requiring the SSPC temperature to be lower than 90°C, the SSPC is suited for loads that demand up to 7 A. Above 7 A the device has to be equipped with a bigger passive heat sink or an active cooler.

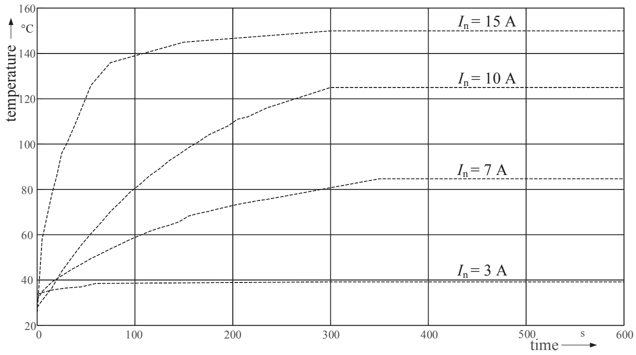

Figure 6. Temperature curve by V_{in} = 270 V_{DC} and different load currents

Another test with increasing currents shows the thermal fuse behavior of the SSPC in case the programmed nominal current limit is exceeded. Therefore, the time is measured after the load current is flowing, being 0 A before. Two different nominal currents I_n (3 A and 7 A) were tested. With a preset current rating of 3 A, a load current of 4 A is turned off after 7 s. A load current of 6.5 A is accepted for 2.5 s. As can be seen in figure 7, the SSPC turns off immediately if the maximal overcurrent is reached. This thermal fuse behavior can easily be adapted by software.

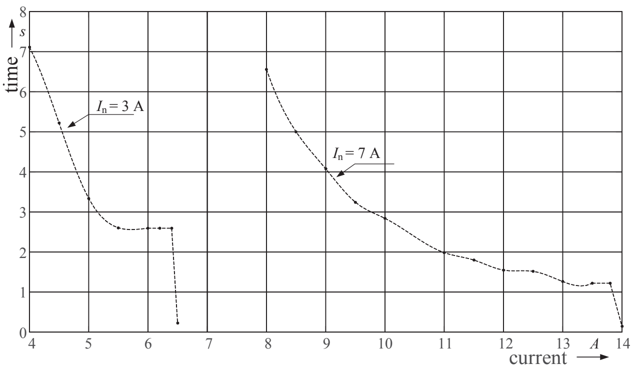

Figure 7. Reaction time of programmed fuse behavior

To demonstrate the basic SSPC-operation of fast switching, a load current has frequently been turned-on and off every 500 µs with a nominal load current of 3 A and a voltage of 540 V by the HVDC-SSPC as shown in Figure 8. The turn-on time is 20 µs and the turn-off time 3 µs. The turn-on time is higher due to the used DC-source. This fast switching is sufficient for the aircraft application.

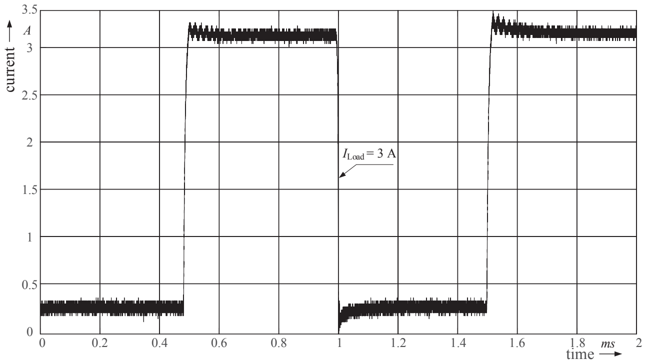

Figure 8. Nominal load current of 3 A turned-on and off via the HVDC-SSPC

All experimental tests prove the correct functionality of the HVDC-SSPC.

V. Conclusions

The problem of building a suited solid-state power controller for future high-voltage DC grids in aircraft is addressed. A prototype of a new HVDC-SSPC has been described in detail. Therefore, SiC-MOSFETs have been used instead of Si-MOSFETs. The HVDC-SSPC has been tested on a test bench and could fulfill all requirements. Thereby, fault protection and power management in DC grid with voltages up to 540 V_{DC} can be ensured. Future enhancements can include arcing detection and soft-start capability to minimize inrush currents.

Appendix

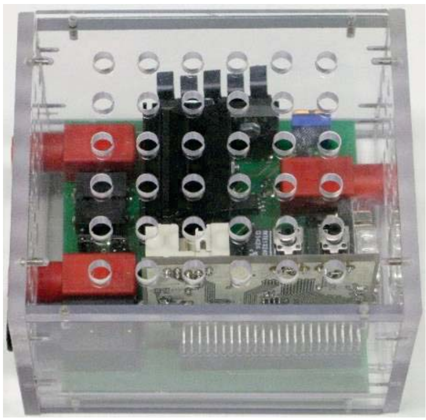

Figure 9. The complete HVDC-SSPC with the polycarbonate case

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