Flexible Protection System for Electrical Sources and Systems with Limited Short-Circuit Current Capacity

FLORIAN GRUMM, MARC SCHUMANN, MARC FLORIAN MEYER, MAIK PLENZ, DETLEF SCHULZ
Electrical Power Systems
Helmut-Schmidt-University/University of the Bundeswehr Hamburg
Holstenhofweg 85, 22043 Hamburg,
GERMANY
florian.grumm@hsu-hh.de https://www.hsu-hh.de/ees

Abstract: This contribution describes the layout of a flexible protection system for electrical systems, that are supplied by a source with limited short-circuit current capacity. This system consists of a primary analogue under voltage protection device for AC voltages, programmable solid-state power controllers and a central control logic. Possible application scenarios are described for the protection system. An initial single phase prototype is presented, which is used to test the basic protection features.

Keywords: - under voltage protection, short-circuit current, sources with limited short-circuit capacity, islanded grids, micro grids, solid-state power controller

1 Introduction

The relevance of distributed generators, like photovoltaic systems (PV), wind turbines, bio gas plants and fuel cell systems (FC) have risen tremendously over the past two decades. Their field of application varies from mobile application over the public power supply to an emergency or a backup power supply of critical infrastructure. The majority of these generation units have a short-circuit current that are slightly higher than their rated current. Hence, such systems require special protection configuration to cope with failures. This contribution describes a flexible protection systems for such systems.

1.1 Definition of limited Short-Circuit

To categorize short-circuit limited systems, a definition of a limitation of the short-circuit current level of an energy source is needed. In voltage levels of less than 1 kV the typical protection devices for small electrical system are fuses and circuit breakers. Low voltage fuses with a nominal current I_{n} in between 13A and 35A and the trip characteristic of ”gG” have to trip at the conventional fusing current I_{nF} (1) after one hour according to IEC 60269-3-1 [1]. The characterization “gG” describes a general-purpose fuse for protection of cables and wires (G) which operates even with currents as low as those that cause it to blow in one hour (g).

$$I_{\mathrm{nF}} = 1.6\, I_{\mathrm{n}} \tag{1}$$

Fuse currents I_F that fulfill (2) may be called overload currents and not short-circuit currents; because, they are only slightly higher than the rated current of the source.

$$I_{\mathrm{nF}} < I_F < 3 \cdot I_{\mathrm{n}} \tag{2}$$

Electrical energy sources that supply in case of a bolted short circuit at the terminals currents in the range defined by (2) are defined within this contribution as sources with limited short-circuit current.

1.2 Generators with limited short-circuit current

Particular fuel cells and photovoltaic systems have a low short-circuit current level (SCC). Fig. 1 presents an overview of the approximate short-circuit current of different generator types I_{k} in relation to their rated current I_{rG}. The PV and FC specifications refer to the corresponding sources [2], [3] and [4], respectively.

Fig. 1: Overview and comparison of the approximate short-circuit current of different genaretaor types: photovoltaic system (PV) [2], [3], fuel cell (FC) [4], doubly-fed induction generator (DFIG) [5] and synchronous generator (SG)[5].

Approximate values for doubly-fed induction generators and the synchronous generators are given in [5]. Rotating generators or generators in general connected via a power electronic interface are also limited regarding SCC — typically up to 1.3 times the nominal current over a short period of time [6]–[8]. Here the limiting factors are the power semiconductor devices of the interfaces. Fig. 2 summarizes source and generator configurations with limited SCC capacity. When such a limited source is the only supply of a power supply application, the protection scheme has to be adapted.

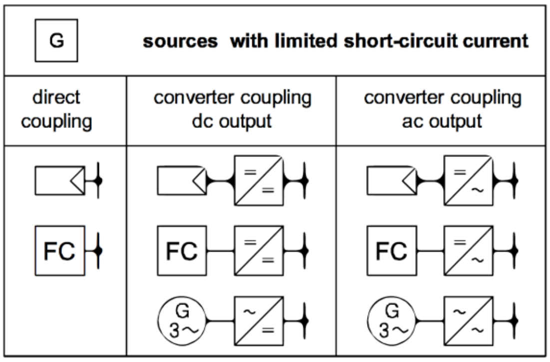

Fig. 2: Sources and generator configurations with limited short-circuit current.

2 Examples of electrical Systems with limited short-circuit current

To emphasize the usage of the flexible protection system, Fig. 3 shows the different scenarios of electrical systems with a nominal voltage $V_n \leq 1$ kV. That V_n have a limited SCC as defined in section 1.1. Although, this limitation might be temporarily.

2.1 Islanded Grid

An aircraft on-board power supply system with a FC system that replaces the auxiliary power unit [9]–[11] represents an islanded grid with a traditional generator. While the aircraft is on the ground: the generators are switched off–the remaining loads are supplied by the FC system. Hence, the SCC is limited to the maximum current of the FC. The same applies for the interesting application of an islanded grid for emergency shelters based on a FC system presented in [12].

2.2 Micro Grid

An example for a micro grid can be the backup generator of an essential infrastructure – an uninterruptible-power-supply using a FC [13], [14]. While the essential grid section is connected to public supply mains the short-circuit power is sufficient at least in Germany – although, more and more conventional power plants are decommissioned [15], [16]. In the case of a blackout, the external grid is disconnected and the short-circuit capacity is reduced to the left power source with limited SCC.

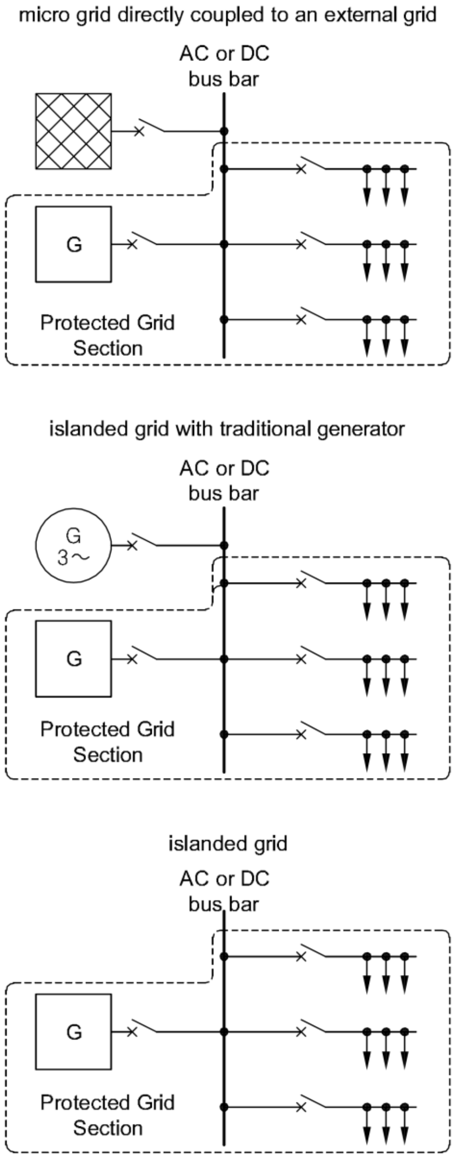

Fig. 3: Grid configuration including generators with limited short-circuit current. The generator configurations are shown in Fig. 2.

3 Design of the flexible Protection System

To protect a grid or source configurations like the ones presented: the protection criteria have to be adapted. A new criteria for the direct source protection can be voltage based (2): the actual source voltage $v_{\text{source}}(t)$ is compared to an admissible low voltage limit $V_{\min}$.

$$v_{\text{source}}(t) \leq V_{\min} \tag{3}$$

However, the load is traditionally protected by a time-current characteristic or an over current (3). The actual load current $i_{\mathrm{load}}(t)$ is compared to the rated load current I_{rload}.

$$i_{\mathrm{load}}(t) \geq I_{\mathrm{rload}} \tag{4}$$

The Fig. 4 shows the main elements, to realize a flexible and adaptable system protection against all kinds of failure the NPS depends on, :

- a several solid-state power controller (SSPC) to control and protect the different loads,
- a primary under voltage protection device (PUVP) to protect the source and
- a central control logic (CCL) for surveillance and additional protection features.

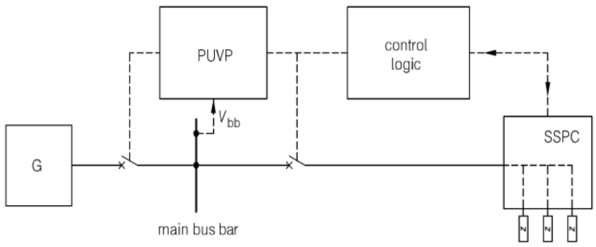

Fig. 4: Block diagram of the protection system

3.1 Primary under voltage protection device (PUVP)

The so called PUVP is a primary protection device, which is described in the European patent application [12]. Fig. 5 shows the principle block diagram for AC voltages. The rectified grid, busbar or source voltage V_{dc} is compared to a reference signal V_{ref1}. This differential signal controls the relay coil current I_{CL} via a current source. The basic switching conditions are (4) and (5).

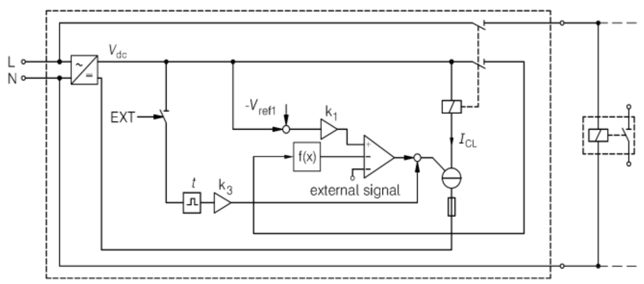

Fig. 5: AC version of the primary under protection device according to [17]

$$\mathrm{k}_1(V_{\mathrm{dc}} - V_{\mathrm{ref1}}) < V_{-} \implies I_{\mathrm{CL}} = 0 \tag{5}$$

$$\mathrm{k}_1(V_{\mathrm{dc}} - V_{\mathrm{ref1}}) > V_{-} \implies I_{\mathrm{CL}} = \mathrm{const} \tag{6}$$

In this application V_{-} is generated by a function block $\mathrm{f}(x)$ (6), that represents a reference circuit with a fixed voltage output V_{ref2}. (7) is the simplified mathematical description of the reference's behavior.

$$V_{-} = \mathrm{f}(x) \tag{7}$$

$$\mathrm{f}(x) = \begin{cases} V_{\mathrm{ref2}} & V_{\mathrm{dc}} \geq V_{\mathrm{ref2}} \\ V_{\mathrm{dc}} & V_{\mathrm{dc}} < V_{\mathrm{ref2}} \end{cases} \tag{8}$$

With (4), (5) and (7) the under voltage trigger value V_{minPUVP} is determined (8).

$$V_{\mathrm{minPUVP}} = \frac{V_{\mathrm{ref2}}}{\mathrm{k}_1} - V_{\mathrm{ref1}} \tag{9}$$

While V_{dc} is greater than the trigger value the stationary current of the relay coil flows otherwise the relay opens (9).

$$I_{\mathrm{CL}} = \begin{cases} I_{\mathrm{stationary}} & V_{\mathrm{dc}} \geq V_{\mathrm{minPUVP}} \\ 0 & V_{\mathrm{dc}} < V_{\mathrm{minPUVP}} \end{cases} \tag{10}$$

A simple diode bridge rectifier is sufficient regarding switching time and power quality [17]. The controlled relay has two switching contacts: one for the inner DC loop and another for the outer AC loop. This outer loop controls the relays of the feeders of the main bus bar. The improvement of this primary under voltage protection is:

- The electronic design is an analogue circuit – consisting of bipolar junction transistors, voltage references and passive elements [17]. The analogue circuit does not cause inaccuracy due to production tolerances because of the high gain of the differential amplifier.
- The device is directly supplied by the protected grid. Hence, it is a primary protection device [17].

Fig. 6 shows detailed electronic schematic of PUVP. While $\boxed{1}$ represents the current source comprised of a bipolar junction transistor BJT and precision voltage reference (PPR), $\boxed{2}$ is the differential amplifier configuration build of two BJT. The function f(x) is set up by the resistors and the Zener diode Z_3 in $\boxed{3}$. V_{ref1} is the Zener diode Z_1 in $\boxed{4}$.

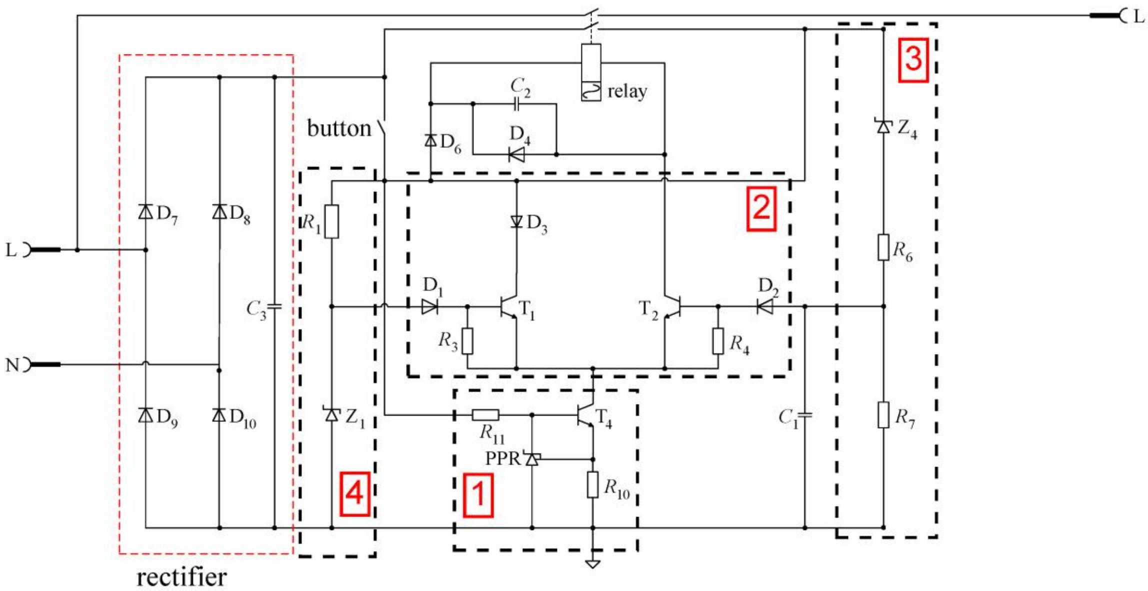

Fig. 6: Detailed schematic of the undervoltage protection device

3.2 Programmable Solid-State Power Controller (SSPC)

Traditionally SSPCs are used in newer aircraft on board power supply designs to protect and manage loads [18]–[22]. Fig. 7 shows the block diagram of a SSPC and its basic elements: anti serial MOSFETS (see Fig. 7), voltage and current sensors, micro controller, and a bus interface. Typically, such a SSPC needs a secondary power supply, like the 28V. However, recent investigation approaches indicate: it is possible to design a lightweight internal power supply that is connected directly to the main grid [22], [23]. Yet it is difficult to include SSPCs into low voltage micro grids because they have to cut off fault currents before the maximum aperiodic SCC occurs otherwise the solid-state switches will be severely damaged. A concept for such a SSPC is shown in [24].

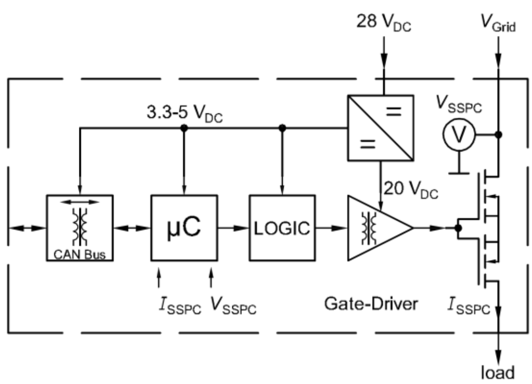

Fig. 7: Block diagram of an AC solid-state power controller

Due to the micro controller, the measurement sensors and the can bus interface, these devices are quite versatile and have the following protection features.

3.2.1 Basic protection features

An over load or fault current can be managed by a certain limit, e.g. (3). A more sophisticated approach is the digital implementation of a time-current characteristic, compare [20], [22], [23]. Over/under voltage tripping is realized by certain limits (2) or by time-voltage curves, e.g. the requirement in [23]. A protection against frequency shifts is implemented by surveillance of the grid voltage period.

3.2.2 Additional features

Due to the communication interface a central control instance in interaction with SSPCs is capable of power management. In case of an overload specific loads are switched off. Similar to the power management is the feeder balancing – the balancing algorithm creates an equally loaded three-phase system [22], [24].

3.2.3 Self Test Feature

Typical failures of MOSFETs are short or open circuits. In case of a short-circuit the protective function of the SSPC is no longer given. As can be seen in Fig. 8 each pair of anti serial connected MOSFETs are driven by a different gate driver. This setup enables a self test as described in [20] that

Florian Grumm,
Marc Schumann, Marc Florian Meyer,
Maik Plenz, Detlef Schulz

monitors the switch function without interruption of the load supply.

To perform a self test each MOSFET pair are switched off for a short period of time. The voltage is measured during the two conditions: switch off and on. When the MOSFETs are working properly (10), the voltage drop during switch off V_{off} of a pair is higher than during switch on V_{on}.

$$V_{\mathrm{off}} > V_{\mathrm{on}} \tag{10}$$

The difference can be observed in the measurement in Fig. 9 from [20]. A defect SSPC is recognized when the voltages between the state switch off and on are equal, because of the short-circuit of the MOSFET. In case of defect SSPC two possible solutions exist. A simple warning to the user via the central logic accompanied by the disconnection of the affected feeder. Another solution is self-healing. In this case each MOSFET pairs require a fuse in series. Than all MOSFET pairs except the faulted pair are switched off; the fuse in series to the faulty MOSFET pair is triggered. As a consequence, the faulted pair is disconnected and the SSPC is usable again yet its current capacity is reduced and the overcurrent parameter has to be adapted.

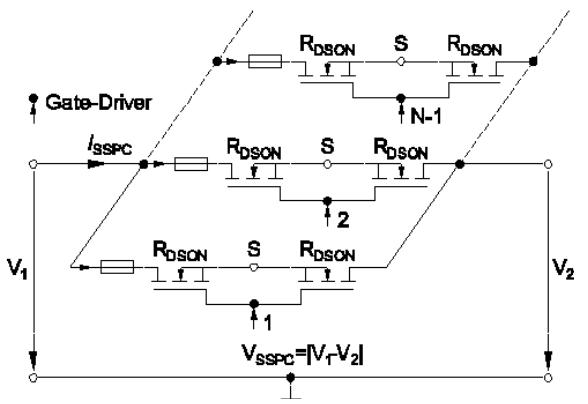

Fig. 8: Schematic of anti serial connected MOSFETS from [20]

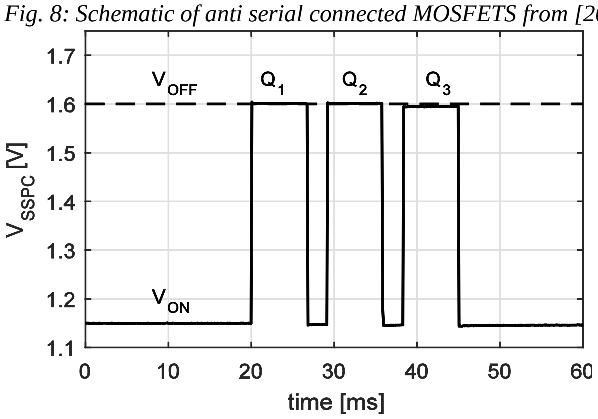

Fig. 9: Voltage drop during self-test of anti serial MOSFET pairs from [20]

3.3 Central Control Logic (CCL)

As mentioned, the CCL can provide power management and feeder balancing. Yet, its main functions within the NPS are:

- secure system start-up,
- manage under voltages and over loading with load shedding when possible,
- identify and clear faults on sections between main bus bar and SSPC/load.

3.3.1 Secure start-up

The CCL controls the relay contacts of the feeder. This provides a secure start-up of the system. All loads are switched on consecutively.

3.3.2 Load shedding in case of under voltages or over loading

Two cases of load shedding are implemented by the CCL:

1. Hence, the installation site of the CCL is the distribution cabinet, the busbar voltage or source voltage V_{bb} is provided. Load shedding is activated when the rms-voltage $\tilde{V}_{\mathrm{bb}}$ sinks below V_{minCCL}. Fig. 10 shows the principle voltage ranges and limits of the protection system. If a voltage recovery cannot be achieved, the system is shutdown.

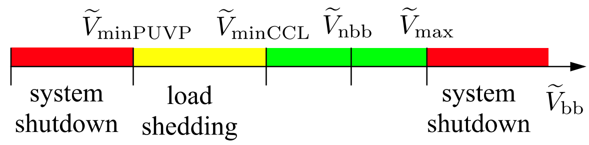

Fig. 10: Voltage limits and the corresponding system reactions. $\tilde{V}_{minPUVP}$: voltage limit of the primary under voltage protection device; $\tilde{V}_{minCCL}$: voltage limit of the central control logic; $\tilde{V}_{nbb}$: nominal bus bar or source voltage; $\tilde{V}_{max}$: maximum voltage of the bus bar or source; $\tilde{V}_{bb}$: bus bar voltage.

2. Each SSPC measures its load current $i_{\mathrm{load\,i}}(t)$; the information of the mean or rms current values or the current phasors is transferred via the bus interface to the CCL. Currently the NPS is configured to start load shedding when a predetermined maximum rms system current $\tilde{I}_{\mathrm{rSystem}}$ is exceeded (11). So, the SSPC transfer the rms load current values $\tilde{I}_{\mathrm{load}\,i}$ via can bus interface.

$$\sum_{i=1}^{N} \tilde{I}_{\mathrm{load}\,i} > \tilde{I}_{\mathrm{rSystem}} \tag{11}$$

3.3.3 Faults on lines/cables

When, phasors of $\underline{V}_{\mathrm{bb}}$, load voltage $\underline{V}_{\mathrm{load}\ i}$ and current $\underline{I}_{\mathrm{load}\ i}$ are measured: the line impedance of each feeder $\underline{Z}_{\mathrm{feeder}\ i}$ can be determined (12), when the measurement is synchronized via the bus system.

$$\underline{Z}_{\mathrm{feeder}\ i} = \frac{\underline{V}_{\mathrm{bb}} - \underline{V}_{\mathrm{load}\ i}}{\underline{I}_{\mathrm{load}\ i}} \qquad (12)$$

A fault can be recognized by a change in the line impedance. For short low-voltage cables and lines between the main bus bar and the SSPC the 50 Hz-impedance can be neglected $Z_{\mathrm{feeder}} \approx 0$. Therefore, the fault identification is simplified to (13): the comparison of the measured rms-values $\tilde{V}_{\mathrm{load}\ i}$ and $\tilde{V}_{\mathrm{bb}}$. Faulty feeders are disconnected by the CCL via the feeder relay at the main bus bar.

$$\frac{\tilde{V}_{\mathrm{load}\ i}}{\tilde{V}_{\mathrm{bb}}} \approx 1 \qquad (11)$$

4 Single Phase Prototype of the protection system

The Fig. 15 shows the schematic layout of an initial single phase prototype of the NPS. The CCL is an arduino mega combined with a can bus interface shield, an isolation amplifier to measure the bus bar /source voltage and a touch screen as user interface. It is installed in a 19´´ housing, that also includes the feeder relays and the PUVP, cf. Fig. 11. There are six feeder relays, that have a nominal current of 10 A. Each relay coil is controlled via a solid-state relay of the CCL. Fig. 12 shows the PUVP. The black box is a single pull double through relay from Fig. 11.

Another 19´´ housing hosts nine AC SSPCs and eight DC SSPCs. Three AC SSPCs are on one inset, cf. Fig. 13. A backplane within the housing provides the secondary voltage supply and the can bus interface for the SSPCs insets. The current rating of an AC SSPC is 20 A.

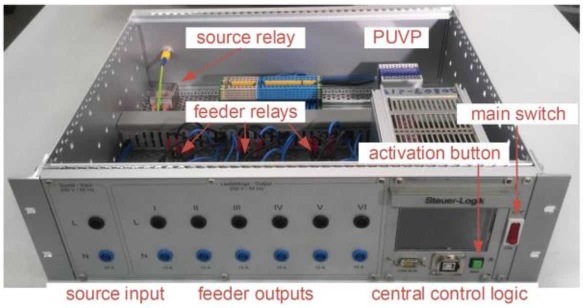

Fig. 11: Picture of the 1900 housing, that functions as power distribution cabinet.

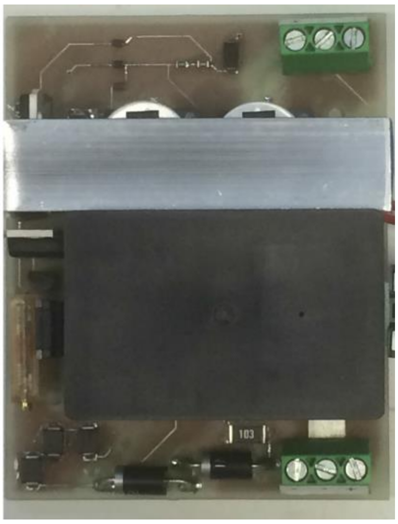

Fig. 12: Picture of the primary undervoltage protection device

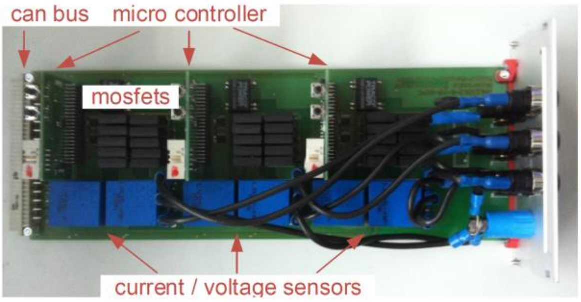

Fig. 13: Picture of triple ac SSPC inset for the line replacement module. The line replacement module can host three triple ac SSPC.

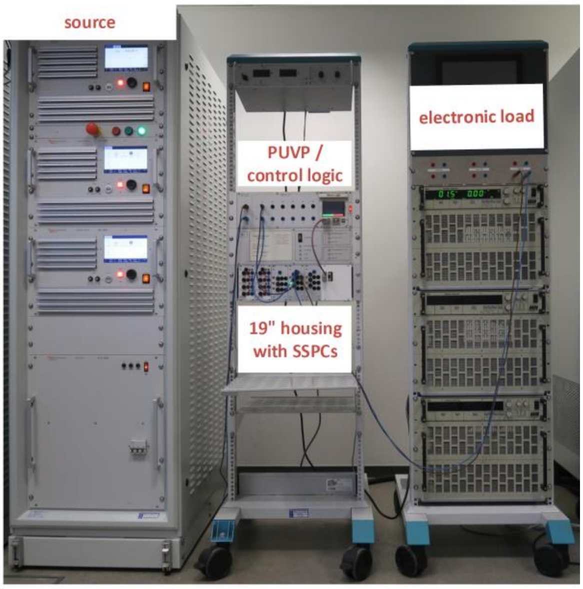

Fig. 14: Picture of the laboratory setup to evaluate the functionality

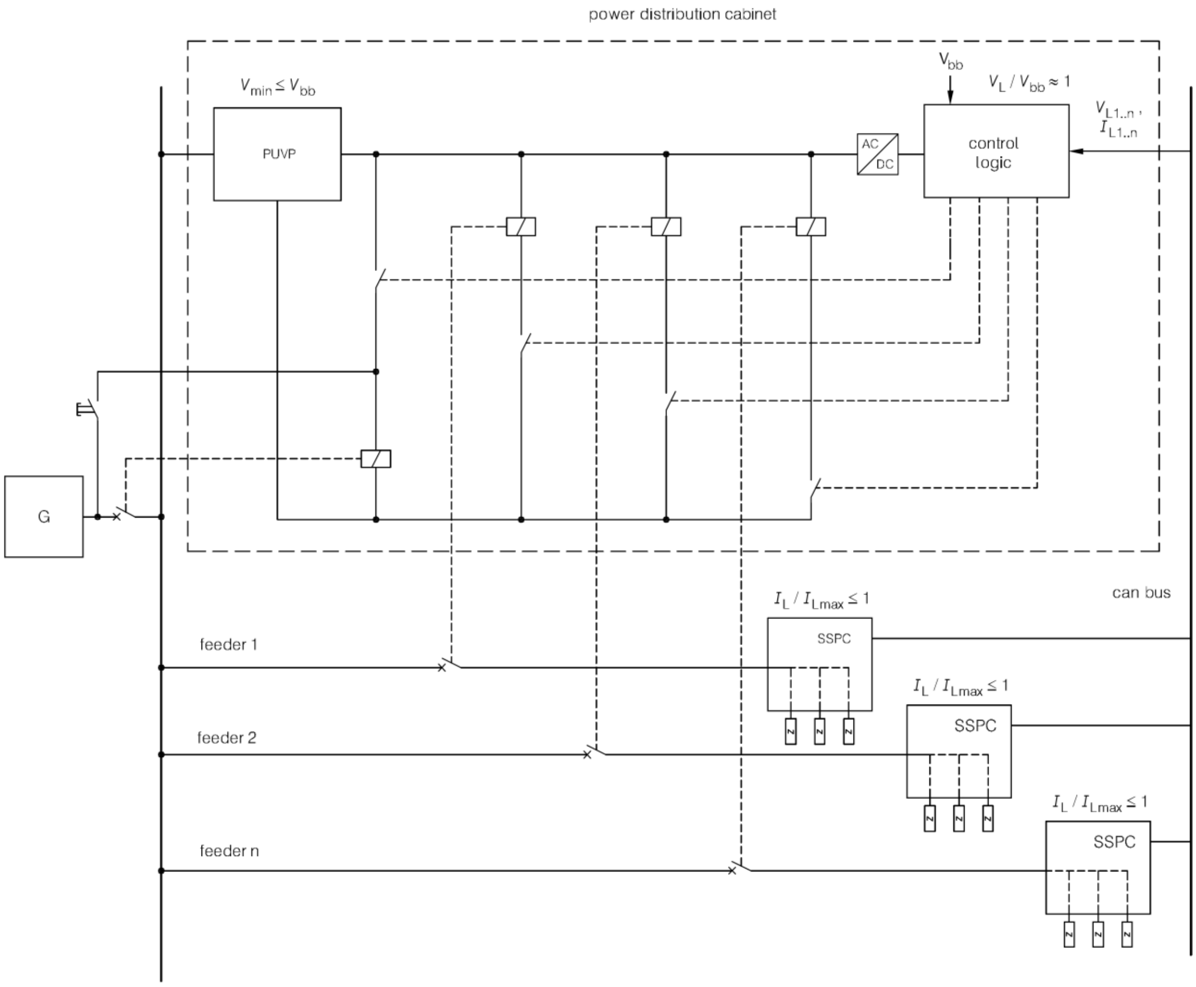

Fig. 15: Schematic overview of the novel protection system according to [4], [5]

4.1 Test Results of the Initial Prototype

This sections describes the test results of the initial prototype. Only the basic functions were evaluated. For the tests the NPS was integrated into a basic test bench, shown in Fig. 14. Tab. I lists the used equipment. The following scenarios evaluate the basic functions:

1. *Fault detection and clearance by the PUVP:* The source has current limitation, so that its voltage breaks down to less than V_{minPUVP} when a current step occurs. The load shedding due to an under voltage is disabled.
2. *Line fault between feeder output and SSPC:* An additional electronic load is connected at the input of the SSPC. When a load step occurs the voltage at the SSPC breaks down. This resembles a low impedance line to neutral fault.
3. *Load shedding due to a system over load:* A base load is set and after a short time a load step occurs, so that $I_{\mathrm{max\,System}}$ is exceeded.
4. *Frequency shift:* The source is programmed to change the frequency from 50 Hz to 75 Hz.

For reasons of clarity only the rms values of voltage and current are shown in the figures.

Table 1: Test Bench Equipement

Equipment	Specifications	Manufacturer
load	16X13.3Ω +/-10%(7.5 A)	Heine Resistors GmbH
scope	wavePro 725Zi 2.5 GHz 40/GS/s	Teledyne LeCroy
source	4-quadrant amplifier PAS 5000	Spitzenberger & Spies GmbH & Co. KG
sensor	ADP305 High Voltage Differential Probe	Teledyne LeCroy
electronic load	ZSAC5644	Höcherl & Hackl GmbH
sensor	AP015 Current Probe	Teledyne LeCroy

4.1.1 Fault detection and clearance by the PUVP

Fig. 16 shows the measurement results of a voltage break down – $t_{\text{fault}} = 0$ s – at the source output/main bus bar. As can be seen, when the source voltage drops below $V_{\text{minPUVP}} = 180\,V$ the system shuts down and disconnects the source from the main bus bar. From fault to clearance it takes $t_{\text{sw}} = 0.46\,s$. This time is split into the dropping of the source voltage and the reaction time of PUVP. The reaction time of the PUVP is approximately: $t_{\text{PUVP}} = t_{\text{sw}} / 2 = 0.23$ s.

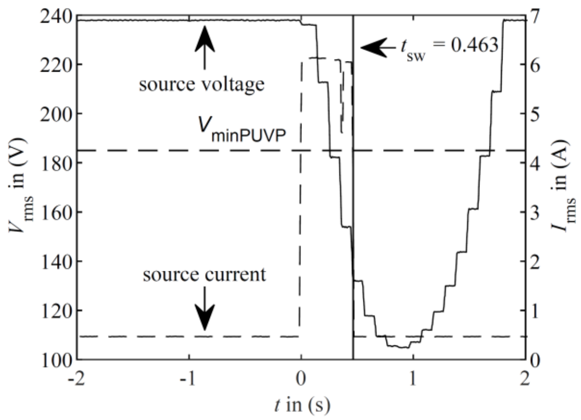

Fig. 16: Measured fault detection and clearance by the PUVP. The system is shut down due to a voltage break down of the main bus bar or source.

4.1.2 Line fault between feeder output and SSPC:

Fig. 17 shows the results for low impedance fault on the connection between the feeder output and the SSPC. At $t_{\text{fault}} = -2$ s the voltage at the SSPC breaks down. The fault is identified and cleared. Yet, it takes more than 5 s.

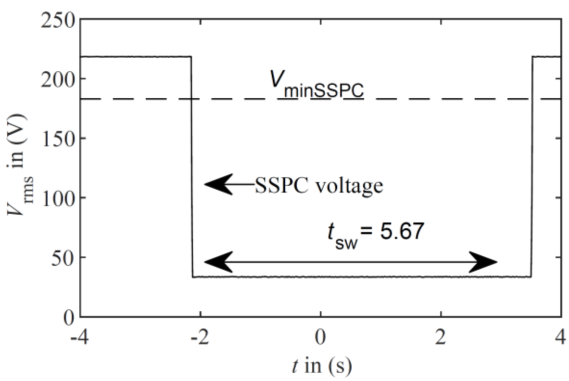

Figure 17: Measured line fault between feeder output and SSPC: feeder disconnection due to a voltage drop between main bus bar / source and SSPC.

4.1.3 Load shedding because of system over load:

And Fig. 18 shows a load shedding due to a system over loading. At $t_{\text{overload}} = 0$ s an additional load is turned on. As can be seen the over load is identified and cleared within 2.14 s.

4.1.4 Frequency shift

Fig. 19 shows the reaction of the NPS to a frequency shift of the grid voltage. Only the current is presented because it can be seen when the system is shutdown. At around $t_{\text{shift}} = -0.57$ s the period is changed. This is identified by the SSPCs, so the CCL shuts the system down within 0.4 s.

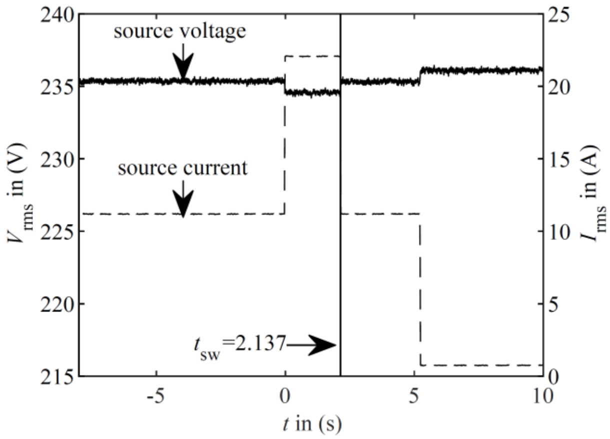

Fig. 18: Measured load shedding because of system over load: simple power management intervention.

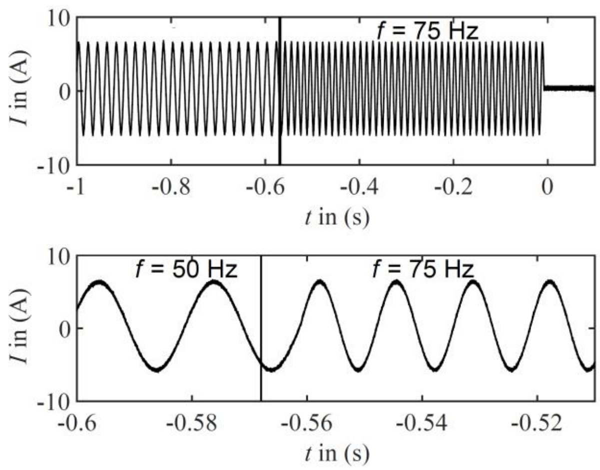

Fig. 19: Measured frequency shift: system shut down due to a false frequency measured by a solid-state power controller

5 Conclusion

This contribution presents a design of a protection system for power supply application with a limited short circuit current capacity. This system is highly flexible and adaptable because of the used solid-state power controllers in combination with central control logic. An initial prototype is used to validate and show the basic functions of the system. Although the basic protection features have all functioned, the prototype's reaction are to slow regarding fault clearances which depend on the central control logic. The calculation capacity of the used micro controller board – arduino mega – is too small. In addition, the data rate of the set up can bus network is not sufficient due to some emc difficulties. Hence, the next steps are to replace the used micro controller with a more appropriate device and to redesign the can bus network.

References

[1] IEC 60269-1:2006 Low-voltage fuses Part 1: General requirements

[2] R. J. Bravo and C. Ly, "Electronic-coupled generators short circuit impacts," in 2015 Seventh Annual IEEE Green Technologies Conference, 2015, pp. 158–161.

[3] Z. Liang, X. Lin, Y. Kang, B. Gao, and H. Lei, "Short circuit current characteristics analysis and improved current limiting strategy for three-phase three-leg inverter under asymmetric short circuit fault, "IEEE Transactions on Power Electronics, vol. 33, no. 8, pp. 7214–7228, 2017.

[4] I. Erlich, F. Shewarega, S. Engelhardt, J. Kretschmann, J. Fortmann, and F. Koch, "Effect of wind turbine output current during faults on grid voltage and the transient stability of wind parks," in 2009 IEEE Power & Energy Society General Meeting, IEEE, 2009.

[5] F. Grumm, A. Lücken, D. Schulz, and J. Storjohann, "Device for protecting an electric power supply device and electrical energy supply device with such a protective device (in German: Schutzvorrichtung für eine elektrische Energieversorgungseinrichtung und elektrische Energieversorgungseinrichtung mit einer derartigen Schutzvorrichtung)," pat. DE102015115284B3, Nov. 24, 2016.

[6] F. Grumm, A. Lücken, D. Schulz, and J. Storjohann, "Device for protecting an electric power supply device and electrical energy supply device with such a protective device," pat. EP16187767, Mar. 29, 2017.

[7] H. Tao, J. Duarte, and M. Hendrix, "Line-interactive UPS using a fuel cell as the primary source," IEEE Transactions on Industrial Electronics, vol. 55, no. 8, pp. 3012–3021, Feb. 22, 2008.

[8] M. Harfman-Todorovic, L. Palma, M. Chellappan, and P. Enjeti, "Design considerations for fuel cell powered UPS," in 2008 Twenty-Third Annual IEEE Applied Power Electronics Conference and Exposition, IEEE, 2008.

[9] F. Grumm, A. Lücken, D. Schulz, and J. Storjohann, "Protection device for electric power grids, energy source, energy supply network and use of such a protection device," pat. EP15178059, Jan. 27, 2016.

[10] A. Lücken, F. Grumm, J. Storjohann, D. Radekopp, and D. Schulz, "Low voltage protection for sources with limited short-circuit current (in German: Unterspannungsschutz für Quellen mit geringen kurzschlussströmen),"in Konferenz für Nachhaltige Energieversorgung und Integration von Speichern NEIS 2014, Sep. 18, 2014.

[11] I. Moir and A. Seabridge, Aircraft Systems: Mechanical, Electrical and Avionics Subsystems Integration, ser. Aerospace Series. Wiley, 2011.

[12] D. Izquierdo, A. Barrado, C. Raga, M. Sanz, and A. Lazaro, "Protection devices for aircraft electrical power distribution systems: State of the art," IEEE Transactions on Aerospace and Electronic Systems, vol. 47, no. 3, pp. 1538–1550, 2011.

[13] A. Lücken, "Integration of fuel cells into aircraft board supply (in German: Integration von Brennstoffzellen in Flugzeugbordnetze)," PhD thesis, Helmut-Schmidt-University, Hamburg, 2014.

[14] K. Rajashekara, J. Grieve, and D. Daggett, "Hybrid fuel cell power in aircraft," IEEE Industry Applications Magazine, vol. 14, no. 4, pp. 54–60, 2008

[15] K. Kato, M. Okamoto, E. Hiraki, T. Tanaka, M. Koganei, and F. Miura, "A ubiquitous power with DC micro-grid for sectional compact emergency shelters," in 2011 IEEE Ninth International Conference on Power Electronics and Drive Systems, IEEE, 2011.

[16] F. Grumm, M. Plenz, M. F. Meyer, K. Lehmann, and D. Schulz, "Investigation of technologies and parameters influencing the short circuit current level of low-voltage distribution networks," in Conference on Sustainable Energy Supply and Energy Storage Systems NEIS 2018, Sep. 21, 2018, in print.

[17] S. Friedman, "Solid-state power controller for the next generation, "IEEE Aerospace and Electronic Systems Magazine, vol. 7, no. 9, pp. 24–29, 1992.

[18] T. Schröter, "Power management on aircraft," PhD thesis, Helmut-Schmidt-University /

University of the Federal Armed Forces Hamburg, Hamburg, 2013.

[19] M. Terörde, F. Grumm, D. Schulz, H. Wattar, and J. Lemke, "Implementation of a Solid-State Power Controller for High-Voltage DC Grids in Aircraft," Power and Energy Student Summit (PESS) 2015, 2015.

[20] F. Grumm, M. Meyer, M. Terörde, E. Waldhaim, and D. Schulz, "Self-testing solid-state power controller for high-voltage-dc aircraft applications," Conference on Sustainable Energy Supply and Energy Storage Systems (NEIS 2016), 2016.

[21] A. E. Kevin, F. Grumm, M. F. Meyer, M. Plenz, and D. Schulz,"Concept of an adaptable protection device for low voltage networks,"in VDE/IEEE Power and Energy Student Summit 2018, W. Wellßow, Ed., Jul. 4, 2018. [Online]. Available: http://nbn- resolving.de/urn: nbn:de:hbz:386-kluedo-53434.

[22] M. Terörde, "Load balancing methods for electrical onboard power supply of airliners (in German: Lastumverteilungsverfahren in elektrischen Bordnetzen von Verkehrsflugzeugen)," PhD thesis, Helmut-Schmidt-University / University of the Federal Armed Forces Hamburg, Hamburg, 2014,

[23] M. Terörde and D. Schulz, "New real-time heuristics for electrical load rebalancing in aircraft," IEEE Transactions on Aerospace and Electronic Systems, vol. 52, no. 3, pp. 1120–1131, 2016.

[24] W. J. Hughes, "Solid-State Secondary Power Distribution," U.S. Department of Transportation Federal Aviation Administration, Tech. Rep. DOT/FAA/TC-13/19, 2014.

[25] A. Lücken, T. Kut, H. Langkowski, D. Schulz, and S. Dickmann,"Concept analysis of an electrical fuel cell integration in modern aircraft," in International Conference on Clean Electrical Power (ICCEP),2013, Clean Electrical Power (ICCEP), IEEE, 2013.