# Review of design and challenges of DC SSPC in More Electric Aircraft

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***Abstract*— Solid State Power Controller (SSPC) is gaining popularity, replacing mechanical switches and circuit breakers, in niche markets like electrical power distribution systems of the more electric aircraft. Significant amount of research is being conducted to develop high power SSPCs to cater the dynamic, distributed load management. The 28V SSPCs are widely used for protection and control of the secondary distribution system. Although there are high current SSPCs for low bus voltages, the 270V SSPCs are not mature and high current 270V SSPCs are not available in the market or having limited capability, which would be used in the primary power distribution system of the aircraft. This paper presents the market availability, design challenges the design engineer should be aware of and various approaches adopted to design and develop a high current 270V DC SSPC for more electric aircraft system, its key features which may not have been available in the traditional switches and future trends.**

***Keywords—SSPC, More Electrical Aircraft , fault isolation, short circuit current***

## I. INTRODUCTION

With the rapid development of electrical and electronic technologies and the trend to reduce emissions, the concept of more electrical aircraft (MEA) and all electric aircraft (AEA) is becoming a reality. Some of the latest MEA systems started utilizing the electrical power to drive airframe subsystems, which earlier used to be supplied by the pneumatic, hydraulic or mechanical means like flight control actuations, environmental control system (ECS), ice protection systems (IPS) and many others [1]. Apart from improving aircraft safety and reliability, this has created a challenge to control and manage the increasing power levels via power conversion and distribution stages [2] [3] [4]. In order to optimally and efficiently utilize the available electrical power, intelligent power distribution mechanism and automatic load management has gathered interest among the research community and system integrators. SSPC is one of the main component in this kind of architecture which needs a lot of attention and detailing while designing due to the complex nature of the interface between system power and conversion systems.

Traditionally, contactors are used for making and braking Direct Current in the aircraft as they have high current capability, very low on state resistance hence less power loss, and offer good galvanic isolation because of the air gap [5]. However, electro-mechanical contactors or thermally-activated circuit breakers are not suitable for the increasing voltage ratings because of limitations in contact cycle life due to arcing, increased weight, size, slow operation time, lack of fault current control capability and cost. Hence there is a trend to move towards solid state power controlling in MEA.

SSPC has the primary function of connecting the load to the DC Bus, protecting the load, the wiring installation, and it self from overloads and short circuits. It also has unique features like fault detection and isolation, high reliability, “soft” starting, fast response time, compact, lightweight, lower maintenance, less susceptibility to vibrations, eliminate arcing during tum-off transient, eliminate bouncing during turn-on transient, no degradation during repeated fault isolation, ability to facilitate advanced load management protection and diagnostics, allowing for efficient power distribution architectures and packaging techniques [5] [6].

This paper presents the state of the art and approach for designing a SSPC in the MEA, its technical challenges and various approaches to solve them. The first section explores the market available SSPC’s by different manufacturer and their main features. Next, considerations for device selection are discussed based on power loss, weight and transient behavior. Then the design challenges in high current 270V SSPC, and design calculation methodology are analyzed. Afterwards, various features available or preferred to have in the state of the art SSPC have been discussed. Finally the scope for improvements for the future SSPC has been discussed.

## II. SSPC MARKET

When selecting a SSPC for a particular application, the voltage rating of the bus and the current that the SSPC should break, are important features that need to be considered. Also the trip time and the maximum capacitance that could be connected to the SSPC are few other selection criteria. There are a wide range of high current DC SSPCs available in market from a number of suppliers ranging from 28V DC bus system to 375V DC bus system. Whereas the current rating for the 28V part is available up to 400A, the highest current rating of the commercially available 270V SSPC is 80A from DDC [7] [8]. A summary of the market availability of SSPC is shown in Table 1 [7-16] from which it can be seen that there are high current SSPCs only available at low bus voltages and the current rating drops with higher bus voltage.

TABLE I. SSPC MARKET AVAILABILITY

| **SSPC Manufacturer** | **SSPC ratings** | | |
|---|---|---|---|
| | ***Current (A)*** | ***Voltage(V)*** | ***Features*** |
| DDC | 80 | 270 | 300-700us turn off, 8 channels, 100uF capacitive loading/channel, Natural air cooled |
| DDC | 400 | 28 | 25x Improvement in MTBF, Compared with Mechanical Switches |
| Micropac Industries | 60 | 270 | 0.2-3ms rise/fall time, 500uA leakage current |
| Micropac Industries | 220 | 28 | 5mA leakage current, 1-3ms rise/fall time |
| Astronics - COREPOWER | 300 | 28 | Dual redundant central processors |
| Ametek - AMPHION | 30 | 28 | 6mΩ conduction resistance |
| Sensitron | 50 | 375 | Minimal heat sinking |
| Sensitron | 400 | 28 | Minimal heat sinking |
| Leach International | 7.5 | 270 | Vibration up to 20G, hermetic seal |
| Leach International | 150 | 28 | Vibration up to 4G, hermetic seal |

[A] Features listed as available from vendors

TABLE II. POWER LOSS COMPARISON

| Device | ***IGBT*** | ***MOSFET*** |
|---|---|---|
| Power Loss | $I * V_{CE\_SAT}$ | $I^2 * \frac{R_{DS\_ON}}{n}$ |

TABLE III. SSPC TOPOLOGY SELECTION

| Topology | ***A*** | ***B*** | ***C*** |
|---|---|---|---|
| Conduction Loss | 2*Diode loss + 1*Switch loss | 1*Switch loss | 1*Diode loss +1* Switch loss (Afterwards 2*Switch loss) |

At high voltage there is increased forward voltage drop, which resulted from the reduction of the doping concentration in the drift region, in order to achieve higher breakdown voltages in the MOSFET. However with the increasing power demands, there is a need for a high current SSPC. For example in case of a 50kW system which would have nominal currents in the range 200A with 270V bus voltage.

## III. DESIGN CHALLENGES

There are a number of challenges in developing high current SSPC such as maintaining a low steady state power loss, controlling high inrush current, unclamped inductive spike during turn off, and large Safe Operating Area (SOA) requirement due to $I^2T$ trip curve that need to respect during transient and output fault condition.

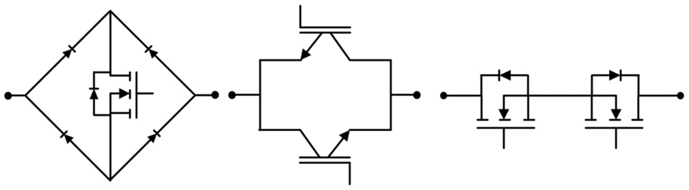
### *A. Steady state power loss*

The power loss associated with the SSPC, poses a significant challenge for the thermal management and will directly impact the size, weight and lifetime [17]. In steady state the junction temperature rise of the power devices will be written as given in equation (1).

$$T_{junction} = Powerloss \cdot R_{th\_j-a} + T_{ambient} \qquad (1)$$

where *Rth_j-a* is the junction to ambient thermal resistance and that is dependent on the heat sink technology used. Higher junction temperature will lead to increase the $R_{ds\_on}$ and there by the conduction power loss of the device. Certain loads will require the SSPC to have bidirectional conductivity and blocking capability. Steady state power loss can be very significant in this case. Figure 1 shows three possible topologies/switch configurations for bi-directional SSPC.

From Table 2 it can be observed that the use of MOSFETs can reduce the total power loss because it is divided by the number of parallel switches (n). Moreover, the on state resistance of a MOSFET has a positive temperature coefficient which supports parallel device operation. The power diodes around this power level, generally have a forward voltage drop of 1.5 V, and the IGBTs have more conduction loss than paralleled MOSFETs (Table 3), so topology C has the least power loss among the 3 configurations shown in Figure 1. In this topology, initially the connection will be through a switch and a diode in series. Subsequently the diode will be short circuited through the second switch.



A. MOSFET with diode bridge

B. Two anti parallel IGBTs with reverse blocking capability

C. Two common Source MOSFETs

Figure 1 Topologies for Bi-directional Current Switch

### *B. Transient state power loss*

Capacitive loads may be common in the MEA distribution system. These lead to inrush currents flowing through the SSPC during turn on. The traditional method is to have a separate pre-charge resistor during the initial period and then bypass it with the main switch. Some of the recent innovative trends in pre-charging involve a buck converter connecting an inductor in series to the pre-charge path [18], gate voltage ramping by RC network [19], active control by optimal trajectory of the channel current [20] and multiple switches working in phase shifted sequence [21] with current limiting.

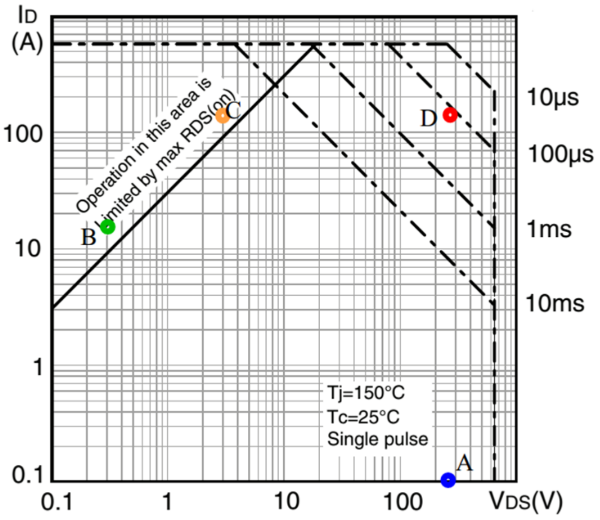


Figure 2 Operating points in the SOA curve of STE145N65M5 [42] when 12 devices are paralleled: A- Turned OFF, B-Turned ON (Steady State), C-$I^2$Tmax (over load), D-Short circuit fault (instant trip)

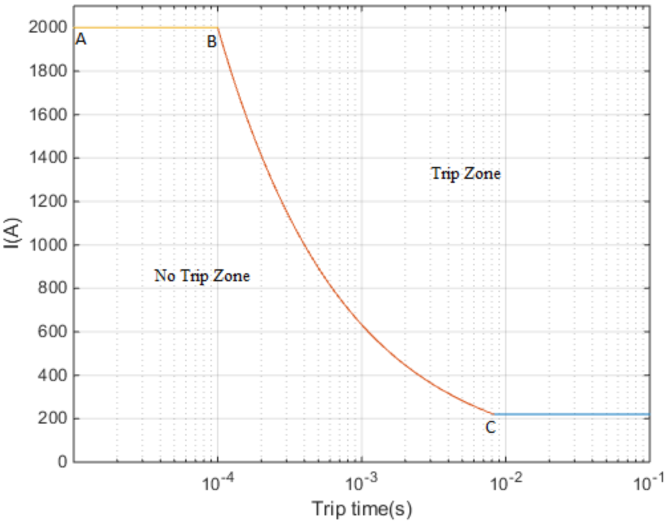


Figure 3 $I^2$T trip curve: A-Maximum let through fault current, B-highest current in the constant thermal energy ($I^2$T) line at the maximum time the SSPC let through Imax ,C-Minimum current that tripping would occur.

In a low impedance fault, both the voltage across the device and the current through the device will rise rapidly. This state should be isolated from a load transient and must be detected fast to avoid damage to the system and the SSPC. When the SSPC is in the normal state or faulty state, the SOA of MOSFET should not be exceeded. The SOA of the commercially available MOSFET STE145N65M5 and its different operating points when used in a 200A, 270V application with 12 switches paralleled are depicted in Figure 2.

When turning off highly inductive loads, the di/dt will create a voltage spike which could damage the load or the switching device. A transient voltage suppressor (TVS) / metal oxide varistor (MOV) is used across the switch in [22] [23] to avoid this. When the feeder cable is long, the cable inductance could be significant and could create a voltage spike that might exceed the switch rating, during turn off. However, in certain DC SSPC MEA applications this problem will not be present if there is a DC link capacitor connected to the SSPC with less cable inductance.

In transient states, the thermal diffusivity which is a race between thermal energy storage and thermal energy transport of the device will influence the power-to-failure of the device [24]. The transient thermal impedance will vary with the pulse duration allowing the device to carry more current for a short time. SSPCs should have an instantaneous trip current, 10 times greater than the nominal current. The peak let through current is defined as the fault current flowing through the SSPC, 100us after the fault condition [25]. Reducing this limit will increase the probability of false tripping which is highly undesirable [26] [27]. The instantaneous tripping is for short circuit faults and the $I^2$t section is for overload conditions [28]. The $I^2$t value of the trip curve should be less than the weakest link in the network which could be the load, wire or the switch itself. Since faster trip times could be achieved with SSPC compared to circuit breakers, depending on the $I^2$t value selected, weight saving on cable harness is possible. Figure 3 shows an $I^2$t trip curve for a SSPC having maximum $I^2$t as $400A^2$s in a 200A nominal current SSPC. The ambient temperature also needs to be considered when implementing this curve [29] since different zones in the MEA might have different temperature profiles. Adhering to this curve will require more parallel devices to share the fault current. In the case of repetitive failure in multiple attempts, the thermal memory effect has to be taken into account.

Apart from these challenges there is an inherent problem of leakage current in solid state devices, and the leakage current in a SSPC should be limited to 1mA, when it is in off state [25]. This is non trivial since a capacitor could charge with this leaking current overtime. An innovative approach of having an active discharge to avoid this problem is proposed in [30] where the load side of the SSPC is grounded using a switch when it is in off state.

## IV. DESIGN CALCULATION

An iterative process is needed to calculate the required number of switches that needs to be paralleled since the design parameters are interdependent. Assume $R_{DSon@TJ=100^0C}$ for the on state resistance, and define ambient temperature (ambient temperature is a non-trivial parameter since in most of the aero applications this value will be high – close to $70^0$C – and with this the power dissipation would increase), and Maximum temperature rise in junction with respect to ambient - ΔT. Find the required MOSFETs to be paralleled n by,

$$\mathrm{n} = \frac{\mathrm{R}_{\mathrm{th}} \cdot I^2 \cdot R_{DSon@Tj=100^0 C}}{\Delta T} \qquad (2)$$

the conduction loss per device by,

$$\mathrm{P} = \frac{I^2 \cdot R_{DSon@Tj=100^0 C}}{n^2} \qquad (3)$$

and find the actual junction temperature rise by,

$$\Delta T = P \cdot R_{th} \tag{4}$$

With the new $T_j$, the new $R_{DSon}$ could be read from the device datasheet and it can be used to get a realistic value for the number of required parallel MOSFETs n, Junction temperature and power loss with few iterations using (2)-(4). So the number of switches need to be paralleled would depend on the current through the switches, $R_{th}$, ambient temperature and ΔT for a given switch. For example if STE145N65M5 MOSFET is to be used in a 270V DC SSPC with the nominal current of 200A, with $R_{thCase\text{-}Amb} = 0.2^0C/W$, ambient temperature at $90^0C$, and the $\Delta T<2.5^0C$, the number of switches required to parallel would be 12. The total power loss for the paralleled MOSFETS would be 66W and it would be doubled when used in bidirectional mode. The voltage drop across the SSPC would be approximately 660mV in the bidirectional case. In this configuration the paralleled MOSFETs would be able to sustain a short circuit fault current 10 times higher than the nominal 200A, for a time period of 100us. This trip time does not violate the SOA curve of the device as shown in Figure 2 point D. By having the current shared among more MOSFETs the power loss could be minimized which would result in weight savings by having smaller heatsinks. However, with more devices the gate driver design gets complex requiring more space in the circuit layout. Moreover, there can be current unbalances when MOSFETs are paralleled which lead to unequal conduction loss. This may cause current over shoots in transient conditions and exceed the SOA of a single device. This is a result of device parameter mismatch, the on state resistance and the gate threshold voltage. [31]

## V. FEATURES IN SSPC

In general a DC SSPC should connect a DC load to a DC bus having a source and apart from normal on / off operation, it should protect the load, the wiring harness and itself from overloads and short circuits. There are instances where SiC JFETS are used for 30A, 270V aircraft power system designs [26] and GaN in low voltage SSPC applications for fail safe SSPC designs [32]. These wide band gap materials allow wider operating temperature range for the switches [33]. However wide band gap semiconductor usage is still not proven in aerospace.

Arc fault is considered as one of the main reasons behind aircraft power distribution system failure [34]. When circuit breakers were used in aircraft power distribution system protection, arc fault detection was done by a separate arc fault circuit breaker (AFCB). This is due to the slow response time of the circuit breakers. Also circuit breakers / contactors are having poor performance with the rising DC bus voltage and this is a reason why these isolators are not preferred in 270V DC bus applications. The problem is worse in DC contactors given DC has no zero crossing points. This is not the case for an SSPC as it has a controlled turn off [35]. With the SSPC, an arc fault detection algorithm could be implemented in the SSPC itself with additional components and it could have even faster detection and trip times [6] [36]. Arc faults could be broadly categorized in to series and parallel arc faults. A series arc fault current which would have less current magnitude than the trip current, due to its high impedance nature, could easily go undetected. So the arc detection algorithm must distinguish the normal load transients from the arc fault. There is ongoing research into arc fault detection for an SSPC by monitoring the currents and voltages (time domain analysis), by comparing the harmonic current signatures in the frequency domain or by analyzing transient behavior through wavelet transformations [36].

When parallel switches are utilized, a single switch failure may go undetected. However, the current shared by each switch will increase which would affect the mean time before failure. As a solution, SSPCs have a built in test (BIT) to identify any faulty switches before each power up and if a fault is detected it will report to the controller so that the SSPC could be replaced at the next opportunity [32]. There are patented methods of detecting issues with the gate and adding a failsafe feature by using test signals by first activating a test gate and apply a small load to the SSPC [32]. In various attempts to make the SSPC fail safe an electro mechanical switch was used in series with the solid state switch in early designs. So if the solid state switch is shorted, the mechanical switch will act as the secondary means of isolation [37] [38] [39] [18]. In another method a fuse is used as the secondary switch [39] and the bond wires of the solid state switch can be used as this fuse [40] [33] . Also there are models which explores the effects of the stray capacitance in the switches and how the system stability depends on it [6].

Electro Magnetic Interference could cause false tripping and a novel method which attempts to address this [41] measures the break-down current in TVS devices connected at the input and output of the SSPC. This will reduce nuisance trips since it has the ability to distinguish between a current surge as a result of lightning and the actual over current fault. Also having reduced fault current thresholds and asynchronous voltage and current measurements could lead to false tripping.

## VI. CONCLUSION

The current developments and trends in SSPC for MEA application is presented. The challenges in developing high current 270V SSPC, market availability, device selection based on thermal management, various features of the SSPC and a design calculation methodology for the SSPC are summarized. In the future with increasing aircraft electrification, SSPC current ratings will grow and there will be stringent requirements on efficiency, false tripping and response times. With the availability of wide band gap devices with very low on state resistance, the current capability of the SSPC could be increased for higher bus voltages like 270V. Improvements in thermal management will enable lower junction temperatures for the switching devices even with more power dissipation. Nevertheless if the load current profile is known, that intelligence could be included in the protection logic which would help to avoid false trips. Also with faster communication mediums like optical, coordinated fault isolation and protection would be possible using SSPCs in MEA.

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## REFERENCES

[1] R. Jones, “The More Electric Aircraft: The Past and the Future? Elec. Machines and Sys. For MEA. IEE Colloquium, Nov. 1999

[2] B. Sarlioglu and C. T. Morris, “More electric aircraft: Review, challenges, and opportunities for commercial transport aircraft,” IEEE Trans. Transp. Electrif., vol. 1, no. 1, pp. 54–64, Jun. 2015.

[3] J. A. Rosero, J. A. Ortega, E. Aldabas, L. Romeral, Moving towards a more electric aircraft, IEEE Aerosp. Electron. Syst. Maga., vol. 22, no. 3, pp. 3-9, March 2007.

[4] P. Wheeler and S. Bozhko, "The more electric aircraft: Technology and challenges", IEEE Electric. Mag., vol. 2, no. 4, pp. 6-12, 2014

[5] A. Bailey, “Protection and switching of large loads for the more electric aircraft,” inProc. 13th EPE, 2009, pp. 1–15.

[6] D.Izquierdo , A. Barrado , C. Raga , M. Sanz and A. Lazaro, "Protection devices for aircraft electrical power distribution systems: State of the art", IEEE Trans. Aerosp. Electron. Syst., vol. 47, no. 3, pp. 1538-1550, 2011.

[7] RP-28009N0-270V Multi-channel solid-state power controller manual, Rev C-3/12, Data Device Corporation, Bohemia, NY.

[8] RP-26311000NX-28V 400A, 4-Channel, High-Power Solid-State Power Controller product brief, Data Device Corporation, Bohemia, NY, 2014.

[9] 53290- 270V DC Industrial Power Controller, Rev K, Micropac Industries, Inc., Garland, TX, 2014.

[10] 28V 220A Non-Isolated Power Controller, Data Sheet, Micropac Industries, Inc., Garland, TX.

[11] 1426 Series, Electronic Circuit Breaker Unit, Corepower- Astronics Advanced Electronic Systems, Kirkland, WA.

[12] 10676B01E30- AMPHION Solid State Power Controllers, Ametek Aerospace, Wilmington MA.

[13] SPDP50D375-DC Solid State Power Controller Module, Sensitron Semiconductor, Deer Park, NY.

[14] Boa Series- 4 Channel Board, Sensitron Semiconductor, Deer Park, NY, 2016.

[15] P152- Standard Solid-state Power Controllers, LEACH international, Buena Park, CA.

[16] P700- Standard Solid-state Power Controllers, LEACH international, Buena Park, CA.

[17] Zhenning Liu, Randy Fuller and Wayne Pearson, ‘SSPC Technologies for Aircraft High Voltage DC Power Distribution Applications’, SAE International 2012.

[18] Narendra Rao, Vlnod Kunnambath, Prashant Purushotham, Ezekiel Poulose, Randy Fuller, Zhenning Liu, High power DC SSPC with capability of soft turn-on large capacitive loads, U.S. Patent No US 8716997, May 6, 2014.

[19] Gregory I. Rozman, Steven J. Moss, Solid state power controller gate control, U.S. Patent No US 2014/0320194, Oct. 30, 2014

[20] Izquierdo, D., Barrado, A., Fernandez, C., Sanz, M., and Lazaro, A. SSPC active control strategy by optimal trajectory of the current for onboard system applications. IEEE Transactions on Industrial Electronics, Vol. 60, 11 (Nov. 2013), 5195–5205.

[21] Gregory L Rozman, J Oshua C- Swenson, Vietson M. Nguyen, SSPC for soft start of dc link capacitor, U.S. Patent No US 8519686, Aug. 27, 2013.

[22] T Feehally, A J Forsyth, “A MOSFET based solid-state power controller for aero DC networks”, Power Electronics, Machines and Drives (PEMD 2014) April 2014 Page(s):1 – 7.

[23] Philippe Baudesson, Hocine Boulharts, Device for protecting a speed controller against overcurrent U.S. Patent No US7965484, Jun. 21, 2011.

[24] Steven H. Voldman, Electrical Overstress, Wiley, 2014, pp 36-42.

[25] AS4805-General standard for SSPC, SAE Aerospace Standard, 2007.

[26] X. Feng and A. V. Radun, “SiC based solid state power controller,” in 23th Annu. Applied Power Electronics Conf. and Expo., Austin, TX, 2008, pp. 1855-1860

[27] Stavnes,M.W.;Hammoud, A.N.; “Assessment of safety in space power wiring systems”, Aerospace and Electronic Systems Magazine, IEEE Volume 9, Issue 1, Jan. 1994 Page(s):21 - 27

[28] Zhang, Yuan; Liang, Yung C. "Over-current protection scheme for SiC power MOSFET DC circuit breaker", Energy Conversion Congress and Exposition (ECCE), 2014 IEEE, On page(s): 1967 – 1971.

[29] A. Barrado., D. Izquierdo ; C. Raga ; A. Lazaro ; M. Sanz,.SSPC model with variable reset time, environmental temperature compensation and thermal memory effect. In Proceedings of the Applied Power Electronics Conference and Exposition (APEC ’08), Feb. 24—28, 2008,1716—1721.

[30] Rocco Divito, Zhenning Z. Liu, Randy J. Fuller, That Nguyen, Method of providing a secondary means of overload protection and leakage current protection in applications using solid state power controllers, U.S. Patent No US 7586725, Sep. 8, 2009.

[31] Helong Li, Stig Munk-Nielsen, Xiongfei Wang, Ramkrishan Maheshwari, Szymon Beczkowski, Christian Uhrenfeldt, W.Toke Franke "Influences of device and circuit mismatches on paralleling silicon carbide MOSFETs", IEEE Trans. Power Electron., vol. 31, no. 1, pp. 621-634, Jan. 2016.

[32] Robert Dennis Holley, N. Evan Lurton, Fault Tolerant Fail-safe Link, U.S. Patent No. US 8891218, Nov. 18, 2014.

[33] A. Barrado, D. Izquierdo, M. Sanz, C. Raga, A. Lazaro: Behavioural Modelling of Solid State Power Controllers (SSPC) for Distributed Power Systems, Applied Power Electronics Conference and Exposition APEC 2009, February 2009.

[34] Lynwald Edmunds, Michael Lavado, Srini C. Sekar and Thomas E. Potter, 'Arc Fault Protection, Application Techniques for Aircraft Circuit Breakers', SAE International 2006.

[35] Zhenning Liu, Randy Fuller, Methods of improving the lightning immunity for an SSPC based aircraft electric power distribution system, U.S. Patent No. US8059378, Nov. 15, 2011.

[36] Guangjun Liu, Yin Ni Cao, Yugang Liu, Zhenning Liu 'A Survey on Arc Fault Detection and Wire Fault Location for Aircraft Wiring Systems', SAE International 2008.

[37] T. Kwa-Sur, Y. Lifeng and N. Dravid, "Modeling the protection system components of the Space Station electric power system", IEEE Transactions on Aerospace and Electronic Systems, vol. 30, no. 3, pp. 800-808, 1994

[38] Randy Fuller, Zhenning Liu, High power solid state power controller (SSPC) solution for primary power distribution applications, U.S. Patent No US8861162, Oct 14, 2014

[39] Zhenning Liu, Randy Fuller, Wayne Pearson, Solid state power control system for aircraft high voltage dc power distribution, U.S. Patent No US9197056, Nov 24, 2015

[40] Divito, Rocco, Liu, Zhenning, Fuller, Randy, and Nguyen,That, Method of Providing a Secondary Means of Overload Protection and Leakage Current Protection in Applications Using Solid State Power Controllers, U.S. Patent No. 7,586,725, Sept. 8, 2009.

[41] Zhenning Liu, Randy Fuller, Methods of improving the lightning immunity for an SSPC based aircraft electric power distribution system, U.S. Patent No US 8059378, Nov. 15, 2011.

[42] STE145N65M5- Datasheet Rev 1, STMicroelectronics, Nov 2013.