Fast-acting Protection as a Key Enabler for More-Electric Aircraft Interconnected Architectures

Theodoros Kostakis[1]*, Patrick J. Norman [1], Stuart J. Galloway[1], Graeme M. Burt [1]

[1] Department of Electronic & Electrical Engineering, University of Strathclyde, 99 George Street, Glasgow, United Kingdom
*theodoros.kostakis@strath.ac.uk

Abstract: Driven by anticipated fuel-burn and efficiency benefits, the More-Electric Aircraft (MEA) concept is a technological shift in the aviation industry which seeks to replace mechanical, hydraulic and pneumatic functions with electrical equivalents. This shift has greatly increased the electrical power demands of aircraft and has made MEA networks larger and more complex. Consequently, new and more efficient electrical architectures are required, with interconnected generation potentially being one design approach that could bring improved performance and fuel savings. This paper discusses the current state of interconnected generation in the aviation industry and key technological advances that could facilitate feasible interconnection options. The paper demonstrates that interconnected systems can breach certification rules under fault conditions. Through modeling and simulation, it investigates the airworthiness-requirements compliance of potential impedance solutions to this issue and quantifies the potential impact on system weight. It concludes by identifying fast fault clearing protection as being a key enabling technology that facilitates the use of light-weight and standards-compliant architectures.

1. Introduction

The More-Electric concept for aircraft has been a technological shift in the aviation industry that progressively replaces mechanical, pneumatic and hydraulic systems with their electrical equivalents. Civil-aircraft manufacturers have identified that these 'More-Electric' technologies can help reduce overall weight and life-cycle cost for the aircraft operator, as well as optimize performance [1]. This ever-growing electrification on the other hand increases the necessary on-board power generation and distribution requirements, which in turn increase the overall size and complexity of the electrical system. As a result, a modern civil aircraft may utilize up to four types of voltages, 230 V and 115 AC of fixed or variable frequency, and ±270 V and 28 V DC. The power from the engine-driven generators feeds the main 230/115 V AC Bus before being fed through transformers, auto-transformer-rectifier units (ATRUs) and transformer-rectifier units (TRUs) to power the 115 V AC, ±270 V and 28 V DC buses respectively.

Today, the state-of-the-art in more-electric aircraft is represented by the Boeing 787, as it is the first civil aircraft to have most of its pneumatic systems replaced by electrical equivalents [2][3]. It features a peak emergency generation capability of 1,450 kVA, which is provided by two variable-frequency 250 kVA generators on each of its two engines and two 225 kVA Auxiliary Power Units (APUs) [4].

Further to the move towards electric equivalents, the aviation industry is shifting to electrical power for flight control as well. By removing heavy hydraulic pipework that is prone to leaks [5] and switching to electrical actuators, this brings efficiency benefits and thus fuel savings. So far however, electrical actuation has been limited to secondary flight-control surfaces due to reliability issues and possible jamming risks [6].

With airplane electrical demands ever-increasing and fluctuating aviation-fuel costs, there is a need for novel, lightweight and efficient power systems. New architectures for optimized power extraction form the aircraft engine need to be considered. In the quest for reduced fuel-burn and improved engine operability benefits, on-airframe or on-engine interconnected generation (supporting multi-shaft offtakes and power sharing in particular) could offer fuel efficiency and potentially further increase the reliability of supply to flight-essential loads [7][8].

This paper will briefly review the state of interconnected generation in the current aviation industry. It will present the challenges associated with paralleled architectures and identify the key technological drivers that may provide a more feasible route for the implementation of such architectures. For a functional systems analysis of a DC-interconnected electrical network, software models of two and three DC bus systems will be presented to investigate the impact of architecture and protection solutions with respect to standards compliance and system mass. The paper shows the criticality of the operating speed of a protection system in achieving light-weight standards compliant interconnected architectures.

2. Interconnected Generation

Interconnected generation is relatively rare in the current aviation industry. Most aircraft power systems feature an isolated, radial architecture with redundant cabling, so that despite faults or transients occurring at any point in the network, essential systems are adequately provided with electrical power [2]. It appears that Airbus have not used an interconnected architecture in any of their platforms up to the A340 [10][11], while Boeing seems to favour isolated generation in its two-engine aircraft and interconnected generation in its four-engine platforms, such as the 707, 720, 727 and 747 [12][13].

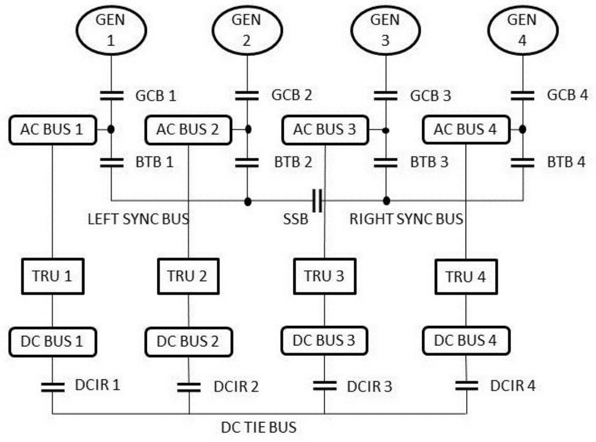


Fig. 1. *Depiction of the B747 interconnected electrical system (adapted from [9])*

In contrast to the variable-frequency, 235 V AC generators (VFG) of the B787, the 747 is equipped with constant-frequency, 115 V AC integrated drive generators (IDGs), allowing for a feasible AC Bus interconnection without the need for heavy, frequency-regulating equipment. Fig. 1 shows a representative schematic of the interconnected electrical system of the 747. The generators are connected to their respective AC buses through individual Generator Circuit Breakers (GCBs). The closure of the Bus Tie Breakers (BTBs) allows the AC buses to be synchronized, thus achieving AC interconnection. In a similar manner, the closure of all four DC Isolation Relays (DCIRs) allows the interconnection of the DC buses. For the majority of the flight profile, the electrical system is in interconnected generation mode, however below 1,500 feet on approach to land, all interconnecting breakers are opened so that the three autopilot systems are powered from independent power supplies [14]. This is to satisfy the higher level of redundancy required by the auto-land system.

Even though the constant-400 Hz IDG has been the predominant civil-aircraft generator technology, new MEA are turning towards the more efficient VFG. Although it too produces three-phase AC power, the frequency varies from 320 Hz to 800 Hz depending on the engine spool speed. The advantages of a VFG include the elimination of the heavy constant-speed gearbox that was used to couple the IDG to the engine, the ability to support electric engine starting, and is also considered to be the most reliable aircraft generator yet [15].

3. Drivers for change

In the proposal of interconnected architectures, together with multi-shaft power offtakes from the gas turbine engines of the aircraft, many authors are claiming that notable improvements in aircraft fuel efficiency could be possible [16-18]. Additionally, recent advancements in fast-acting solid-state protection devices, along with research into engine operability and fuel efficiency benefits may provide key enabling technologies to realize such interconnected architectures. A brief summary of these drivers will be presented in this section.

3.1 Protection Equipment

Interconnected generation reduces the level of electrical isolation and allows a greater portion of the aircraft's systems to be exposed to faults at any one point in the network. As such, fast-acting protection strategies and equipment are therefore required to detect and clear faults before network conditions breach the power quality requirements and potentially effect the operation of critical loads. Advances in the field of Fault Isolation Devices (FIDs) and Solid State Power Controllers (SSPCs) [19-21] may provide a safe and feasible means of interconnection. SSPCs offer very fast protection operation (25-50 μs) and have no moving parts [19][21]. This makes them less susceptible to wear and tear issues and as such, are good candidates for the harsh operating environments of aviation.

3.2 Fuel Efficiency Gains Through Multi-shaft Offtakes

In terms of fuel consumption, it is most beneficial for a jet engine to be operated as close to the surge line as possible [22]. However, operation too close or beyond this limit leads to the reversal of airflow through the engine and the catastrophic failure of the compressor. Under ground-idle or low-thrust conditions, engine designs extracting all electrical power from the high-pressure (HP) shaft require careful engine-stability control and are therefore operated at higher idle speeds [23]. Multi-shaft engine architectures which extract electrical power from the low-pressure (LP) or intermediate-pressure (IP) shaft allow for lower idle speeds, thus reducing fuel consumption [24].

In addition to reducing fuel burn, multi-shaft offtakes are thought to offer engine operability benefits, either by regulating the power offtake throughout the various stages of the flight cycle, therefore reducing the surge margin held for electrical transients [25][26], or by aiding in functions such as electric engine starting [27][28]. The benefits offered by multi-shaft offtakes however need to be traded off against the weight penalty additional equipment incur for the implementation of these solutions.

3.3 Growing Use of DC

Higher-voltage DC distribution is of growing interest within MEA [1] and More-Electric Engine systems [29] for several reasons. As utilizing DC eliminates the need for frequency and phase synchronization, the paralleling of non-synchronous power sources is better facilitated. DC power distribution also provides a reduction in cable size and weight compared with AC distribution [30]. Research has shown that in comparison to an AC architecture, a DC architecture may, firstly by allowing the generators to operate at more efficient operating points [31] and secondly, by reducing the number of power conversion stages between source and load [30], provide a more efficient electrical network [32][33]. Based on these potential benefits offered by DC distribution, the primary platform studied in this paper will be a DC interconnected electrical architecture.

4. Review of Relevant Literature

To date, the academic literature has mainly focused on the benefits of interconnected generation and generator/power control strategies and schemes. However, the systems-level impact that interconnected generation may have during abnormal operation conditions is not well documented.

Michalko in [34] proposes a multi-shaft off-take method in which the engine shaft-driven generators of the engine are paralleled onto a common DC bus. Although this might be the simplest multi-shaft off-take arrangement, its most significant drawback is that a fault on the DC bus will result in the loss of supply from both generators. As a means to provide greater flexibility on the control of the extracted power-mix, Yue et al propose the paralleling of all generators onto a common DC bus, shown in Fig. 2 [35]. Even though bus tie contactors or other protection equipment may provide some fault isolation capabilities, yet again a fault on the common bus will disrupt all generation sources across the entire network.

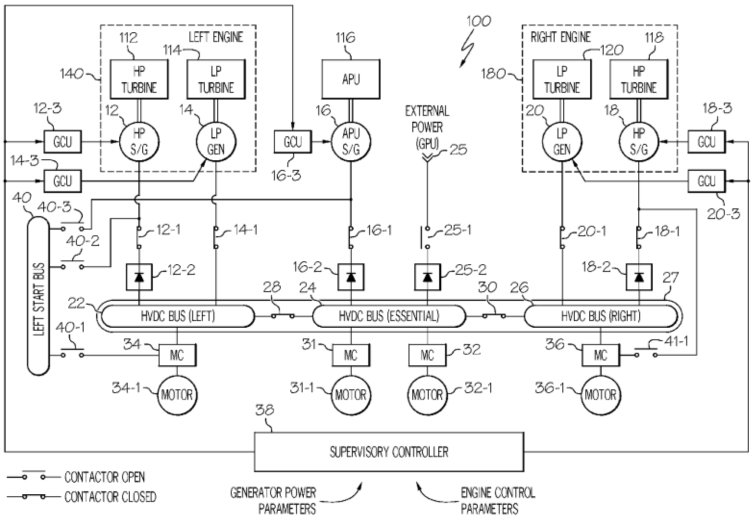


Fig. 2. *Paralleled HVDC Bus electrical power system [35]*

Other off-take methods seeking to achieve power transfer between shafts, such as [36] and [37], although they differ in their implementation approach, assume normal engine operating conditions and do not consider the effect of an on-engine electrical fault. Overall, relevant patents seem to offer significant gains in terms of engine operability and fuel-burn reduction, however they do not address the certification implications regarding protection methods and the interconnection of power sources.

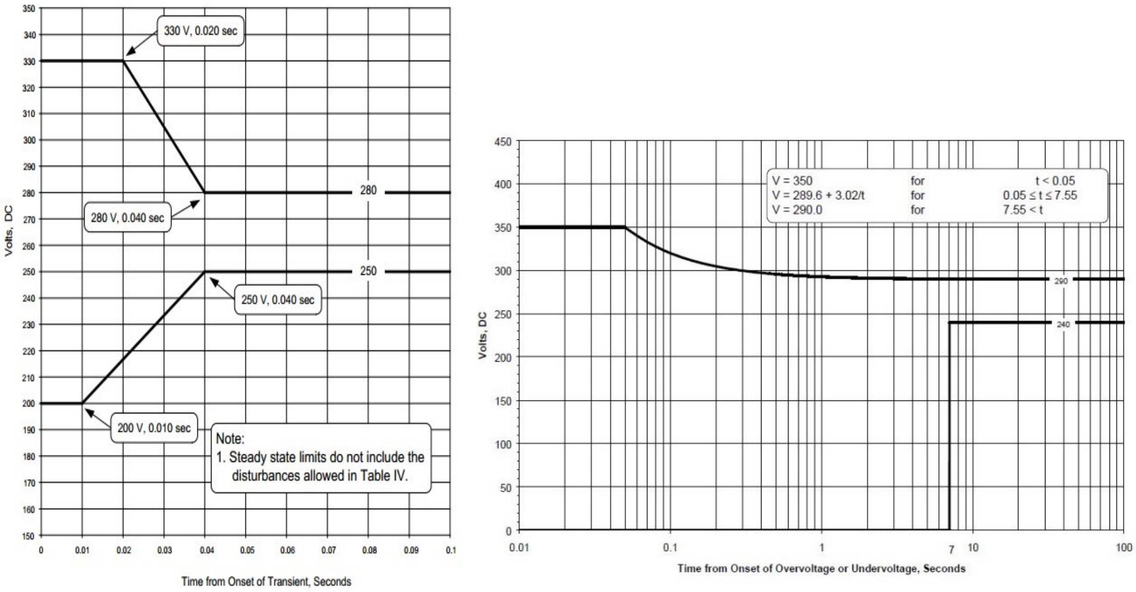
Research into novel distribution systems [38] and control strategies [39] address the MIL-STD-704F power quality requirements, explained at a later section in the paper, however they do so at a component level under normal operating conditions. Although [39] does consider three different fault types, the loss of generator current control, the loss of a generator and current mismatch between generation and load, these are not indicative of all abnormal operating conditions as defined in the power quality requirements. Reference [40] reviews four ‘fault-tolerant’ distribution system topologies for MEA, with two of them implementing a paralleled generation approach to some extent, as all generated power is either connected and supplied through the ‘primary power distribution system’ or via source/load switch matrices. However, in all but one of the topologies reviewed, a fault in the distribution system may interrupt the power supply to the entire network. Reference [41] proposes a distributed system architecture with two parallel power conversion systems, implemented using bidirectional power converters and load grouping, depending on whether the loads require constant- or variable-frequency AC power. Although there is mention of the power quality requirements in this research, it is carried out from the perspective of input current harmonics and THD.

In comparison to faults within AC systems, DC system faults can present very demanding protection challenges with regards to fault current magnitude and propagation speed [42][43]. To mitigate these issues, converter designs have evolved to provide more fault ride-through capabilities and current limiting to suppress fault magnitude [44-46]. However, the use of current limiting could disrupt the coordination of network protection devices as many fault locations could present similar fault current. To overcome this problem protection devices are often time-graded, thus operating at a slower protection speed, leaving the electrical network exposed to fault conditions for a larger time period [44, 47-49]. In turn, this would further disrupt power supply and power quality to flight-critical loads throughout the network.

Overall in the current literature, the protection challenges and requirements of an interconnected network at a systems-level have received little attention.

5. Implementation Challenges of Aircraft Interconnected Systems

The aircraft electrical system is required to provide acceptable power “during all operations of the power system”. These operations are defined in Military Standard 704F (MIL-STD-704F) [50] and other standards, and govern elements such as voltage magnitude and transients, harmonics, frequency for AC and DC systems. Fig. 3 illustrates the restrictions on the DC voltage profiles during a transient under normal operation and under fault conditions. These standards do not draw a notable distinction between isolated radial architectures and interconnected architectures other than specifying some restrictions on the disruption of power to critical loads. As such, the authors assume that the electrical system of the B747 adheres to the faulted system power quality requirements (as specified in Mil-704F) or similar, under fault conditions, even when interconnected.



a *b*

Fig. 3. *Restrictions on the DC voltage profiles during a transient under normal operation and under fault conditions*
a Normal voltage transient envelope for 270 V DC systems [50]
b Overvoltage and undervoltage limits for 270 V DC systems [50]

However, modern MEA are generating much more electrical power and at a higher voltage level than traditional aircraft. This electrical energy is used to power a wider variety of systems than ever before, from safety-critical systems to in-flight entertainment consoles. The A380 for instance uses electrical actuation on all control surfaces as a supplement to the hydraulic system [51]. On this basis, the authors feel it appropriate to consider whether adherence to the faulted condition power quality requirements would be still be sufficient for the greater number of higher-power flight-critical electrical loads on-board an interconnected MEA architecture. More specifically, effective 'buffers' should be implemented such that non-faulted parts of the network only experience a 'normal transient' event when the fault occurs elsewhere on the network, therefore allowing the electrical system to continue to operate under interconnected mode without an unacceptable loss in the performance of critical loads.

Therefore, in order for flight-critical electrical loads to satisfactorily be provided with acceptable power "during all operations" [50], there must be adequate impedance between the various buses otherwise a single electrical fault will cause the whole network voltage to collapse, breaching power quality standards. This paper will consider the use of an inductive impedance buffer. Whilst a simplistic solution, it will enable clearer analysis of the system dynamics and identification of key performance parameters. This underpinning knowledge can then be readily applied to more complex solutions. This aspect is discussed with reference to some potential innovative technologies in the conclusions of the paper.

It is expected that the size of this bus-decoupling impedance will be driven by the speed at which the fault can be detected and cleared. Indeed the following analysis will show that faster fault-clearing times can significantly reduce the extent of the propagation of voltage transients throughout the electrical network, requiring less impedance to stabilize the bus voltage within the normal limits. However, it is recognized that available technologies may constrain the possibilities of operation in this aspect.

To date, aircraft systems make use of contactors and electromechanical relays for higher power DC bus fault interruption, as the available solid-state circuit breakers are not suitable for higher power and voltage application within MEA [52]. Whilst this potentially limits the potential minimum fault clearance time possible in an interconnected system, the analysis conducted does not factor in these constraints in order to consider a wide range of system behavior. Such practical aspects are instead considered in the paper conclusions.

This paper will investigate whether impedance solutions, complete with appropriate fault protection systems can maintain the bus voltage within the set limits and try to estimate the weight penalty incurred for two-bus voltage-compliant interconnected systems. For a more complete study, three-bus interconnected systems will also be analyzed, indicative of more-electric engine systems. As the main rationale of the analysis is to assess voltage compliance during fault conditions, only solid short circuit faults are considered. Whilst other higher impedance or intermittent faults will also be considered as a future work, the impact of these on voltage compliance is expected to be less significant than for short circuit faults.

6. Simulation Analysis

6.1 DC Network Model

To investigate the effectiveness of potential solutions and their certification implications for the feasible realization of voltage-compliant DC interconnected networks, a two-generator, 270 V DC paralleled distribution network has been created. A representative single-line diagram of the 300 kVA model is shown in Fig. 4. Key model parameters are summarized in Table 1. A three-generator model of the same rated power will be presented later in the paper.

The models of interconnected DC architectures developed for this investigation were created at a functional level of fidelity in accordance with guidance provided in [53] using the Matlab/Simulink software package. These functional models neglect switching level transients in order to minimize computational burden and facilitate time-efficient extensive simulations, but still capture the power system and controller dynamics and at a sufficient fidelity.

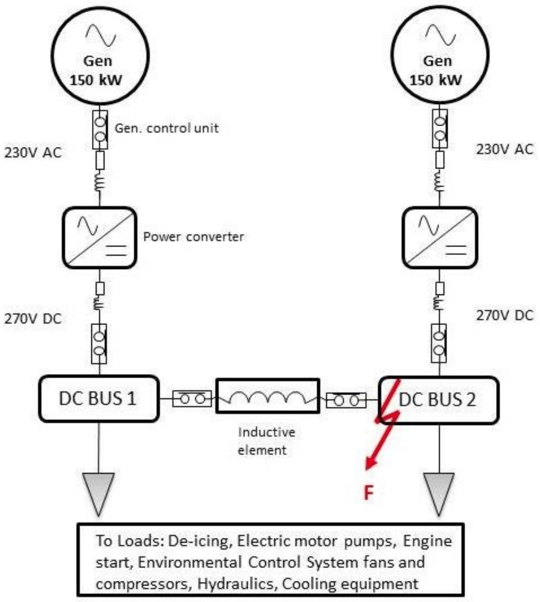


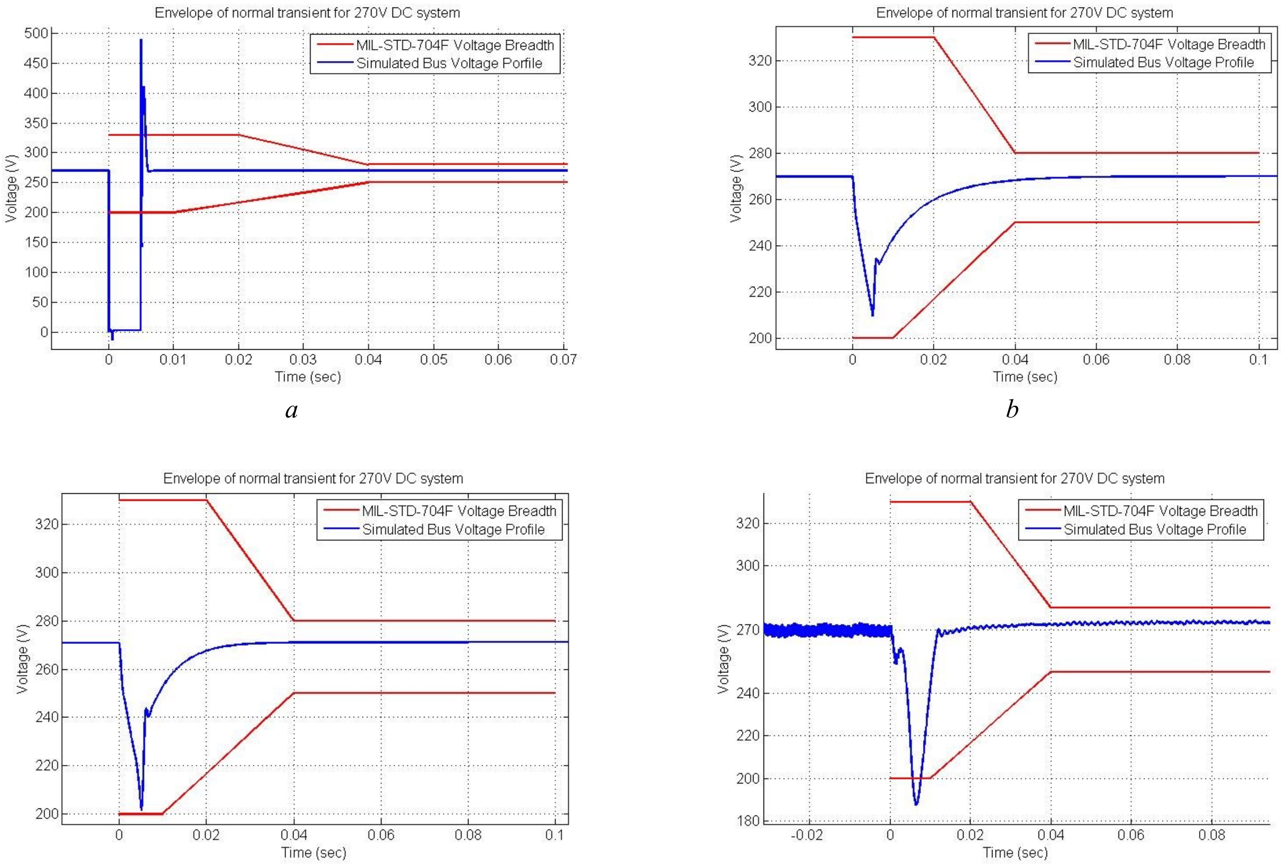
Fig. 4. *Representative single-line diagram of twin-bus interconnected generation Simulink model*

Table 1 Network parameters of paralleled distribution model

Rated power	300 kVA
Operating voltage	270 V DC
2-Generator nom. current	555A
3-Generator nom. current	370A
Feeder resistance	0.801mΩ/m
Feeder inductance	0.65 µH/m

The generation systems are comprised of 4-pole permanent magnet machines, interfaced with controlled rectifiers operating with drooped voltage control which in turn are connected to lumped loads via DC buses. The per-meter feeder resistance and inductance have been adapted from [54] to a quarter of the length of the B787-8, i.e. 14.2 m. Serving as a decoupling mechanism, an inductor is used to interconnect the DC buses. The rating of the inductor will vary for different simulation scenarios, as will be explained later in the paper. Solid short-circuit faults are introduced under full-load, balanced conditions on DC Bus 2 to investigate the behavior of the interconnected system under fault conditions and the impact a varied fault-clearing time has on the voltage profile of DC Bus 1.

To set a baseline, Fig. 5a depicts the voltage measured on the non-faulted DC Bus 1 during a short-circuit fault on DC Bus 2, with a negligible inter-bus impedance connection. The fault is applied at t=0 sec. and cleared after 5 ms, realizing a 5 ms protection operation speed. This protection speed will be varied for different simulation scenarios. During this transient event, the simulated voltage (blue line) collapses to



a   *b*

c   *d*

Fig. 5. *Voltage profiles of the non-faulted bus during various fault scenarios for2 and 3 bus architectures*
a Voltage profile of non-faulted bus with negligible inter-bus inductance for a 5 ms fault-clearing time
b Voltage profile of non-faulted bus with 3 mH inter-bus impedance connection for a 5 ms fault-clearing time
c Voltage profile of non-faulted bus with 3.5 mH inter-bus impedance connection for a 5 ms fault-clearing time
d Voltage profile of non-faulted bus with 3 mH inter-bus impedance connection for a 5 ms fault-clearing time

near-zero during the fault and then overshoots the compliant voltage breadth (red lines) once the fault has been cleared. Clearly, the voltage profile of the non-faulted bus exceeds the bounds of the normal voltage envelope defined in MIL-STD-704F.

It is therefore apparent that in order to decouple the transient responses of the interconnected DC buses to some extent, an effective inter-bus impedance is required. In this approach, although the voltage of the faulted bus will collapse, the non-faulted bus should then only experience a standards-compliant voltage transient. The following simulation cases will investigate this for two and three DC bus architectures.

6.2 Simulation Analysis of Two Bus Network

To observe the impact on the transient response of the non-faulted bus, an inductive inter-bus impedance connection was employed and a wide range of inductance values were considered. From this analysis, it was possible to identify suitable inductor ratings which could enable standards-compliant interconnection options for a range of simulated fault clearance times. In comparison to the baseline profile of Fig. 5a, the voltage profile of the non-faulted bus using a 3 mH inductor for a fault-clearing time of 5 ms is illustrated in Fig. 5b. Clearly, the voltage profile is within the defined limits. Aggregated data regarding inductor ratings for different fault-clearing times will be presented at a later section in the paper.

6.3 Simulation Analysis of Three Bus Network

Besides the addition of a second, equally-rated inductor, a similar approach was adopted for a three-bus network, shown in Fig. 6. Due to the symmetry of the network, only two fault locations were considered, F1 and F2, however there appeared to be no significant difference in fault response between these fault locations in terms of peak fault current and voltage profile. Fig. 5c illustrates the voltage profile of the non-faulted DC Bus 3 during a fault sustained for 5 ms with 3.5 mH of inter-bus impedance.

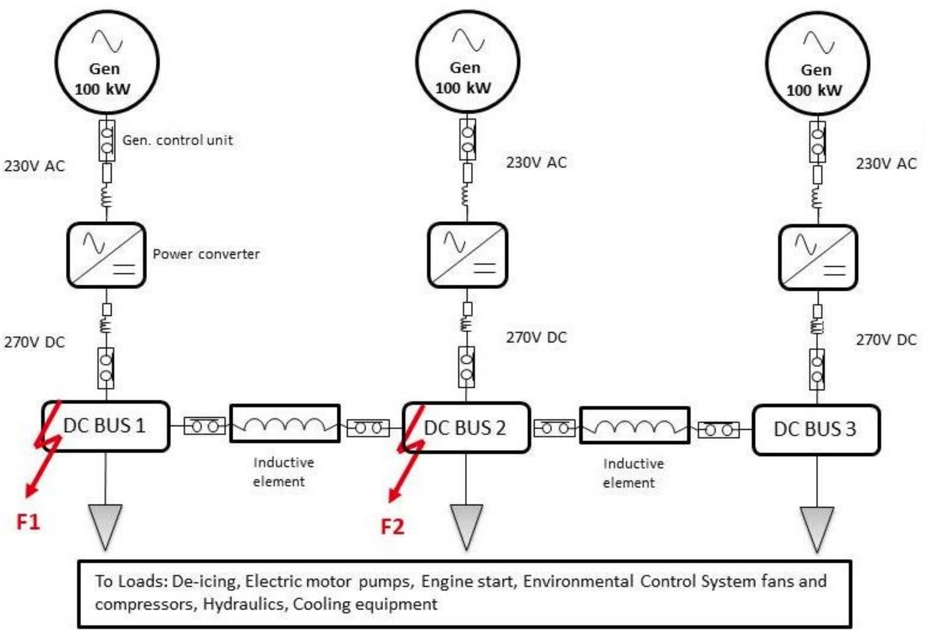


Fig. 6. *Representative single-line diagram of three-bus interconnected generation Simulink model*

Table 2 Inductor Ratings and Through Fault Current

Architecture type	2 Bus Architecture				3 Bus Architecture			
Fault-clearance time (ms)	5	1	0.5	0.1	5	1	0.5	0.1
Inductor (mH)	3	1	0.5	0.1	3.5	1	0.7	0.1
Fault current (A)	389	237	236	237	334	237	182	236

7. Inductor Rating Against Protection Speed

As previously stated, the inductor rating is in direct correlation to the operation speed of the protection system. Faster fault-clearing times are expected to lessen voltage transients propagating throughout the network, thus reducing the required impedance necessary to achieve compliant interconnections. In turn, this reduces the added weight penalty for each interconnected architecture.

Following extensive simulations, aggregated inductor rating data, along with the sensed fault current passing through the interconnecting inductor for two and three DC bus architectures are summarized in Table 2. It is clear from the table that compliance is achievable with smaller inductors if faults are cleared in a shorter time frame.

As system mass is an effective illustrator for the apparent trade-off between inductance sizing and protection operation speed, in order to achieve a uniform comparison, a kg mass per unit mH-A rating was derived by the authors. This figure was derived from a lightweight, high-current, aviation-grade inductor [55] available commercially to be 0.025 kg/mH-A.

The individual inductor weights, shown in Fig. 7, are calculated using the following equation:

$$Weight = k \cdot L \cdot I_{fault} \quad (1)$$

where k equals 0.025 kg/mH-A, L represents the necessary impedance and I_{fault} is the maximum current passing through the inductor during the fault. It should be noted that these weights do not include bus-tie breakers or contactors.

Overall, it is evident that the 3 Bus architecture carries approximately twice the weight penalty of the 2 Bus architecture, which is to be expected as the former requires one more interconnecting inductor than the latter. More specifically, it would appear that for any one architecture, any change in the protection speed is mirrored by the same change in the inductor weight. In the 2 Bus architecture for example, making the protection speed five times faster, from 5 ms to 1 ms, means that the required inductor is approximately 5 times lighter. This demonstrates that fast protection operation speed is crucial to the potential feasibility of interconnected systems.

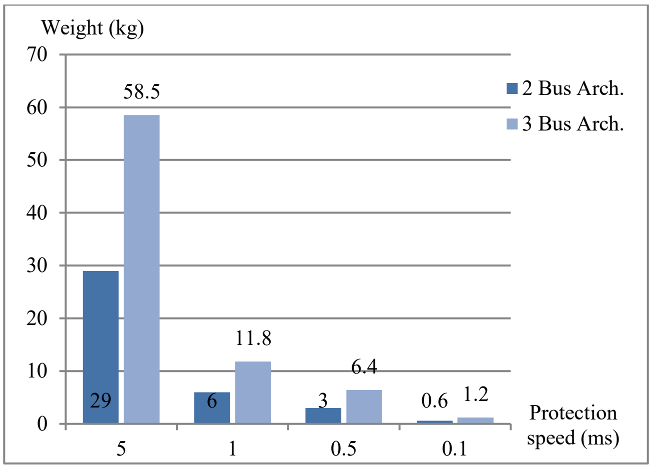


Fig. 7. *Required inductor weight against protection operation speed*

8. Adverse Factors on Inductance Ratings

In previous sections, the identified impedance ratings were derived under full-load, balanced operation conditions. This section will briefly discuss the effects of unbalanced conditions and power quality on the required impedance ratings necessary to achieve compliant interconnection. The adverse effects of adding inductance in-between interconnected buses will also be considered with respect to transient load sharing and protection relay coordination.

8.1 Generator Imbalance

For both architectures, a similar simulation analysis was carried out with one generator operating at 50% of its rated power and the adjacent generator operating at 150%, indicative of an engine/throttle push-back emergency. From this analysis, it was evident that if the fault is applied on the respective DC bus of the under-performing generator, there is no breach of the voltage envelope, however if the fault is on the respective DC bus of the over-performing generator, then the impedance ratings identified previously cannot maintain the non-faulted bus voltage within the defined limits. In the latter case, the interconnecting inductors should be over-rated, as shown in Table 3, further increasing the weight penalty of the architecture.

Table 3 Inductor Ratings for Generator Imbalance Conditions

Architecture type	2 Bus Architecture				3 Bus Architecture			
Fault-clearance time (ms)	5	1	0.5	0.1	5	1	0.5	0.1
Inductor (mH)	8.5	2	1	0.15	10.5	2.5	1.5	0.15

8.2 Power Quality

As a means of introducing a degree of added instability into both simulated power networks, whilst complying with a maximum of 6 V voltage ripple imposed by the standards, a 10 kVA converter fed constant-power load was attached to each DC bus. Due to the introduced voltage fluctuations, the initially identified inductors were unable to stabilize the non-faulted bus voltage inside the bounds of MIL-STD-704F, as shown in Fig. 5d for the 2 Bus architecture for a 5 ms clearing time. Therefore new minimum inductor ratings are required for both architectures, shown in Table 4, and their respective mass shown in Fig. 8. The 1:1 ratio between protection speed and inductor weight identified in a previous section does not hold in this case as, with the addition of voltage fluctuations, larger inductors are required, resulting in a new ratio of 1:0.68-0.85 depending on the specific architecture. This ratio becomes worse in protection speeds of 0.5 ms and 0.1 ms as it appears the inductor weight reduces by a factor of 0.43 and 0.39 for the 3 and 2 Bus architectures respectively.

Table 4 Inductor rating for fluctuating voltage conditions

Architecture type	2 Bus Architecture				3 Bus Architecture			
Fault-clearance time (ms)	5	1	0.5	0.1	5	1	0.5	0.1
Inductor (mH)	3.5	1	0.6	0.3	6.5	2	1	0.5
Fault current (A)	384	314	330	338	208	198	278	260

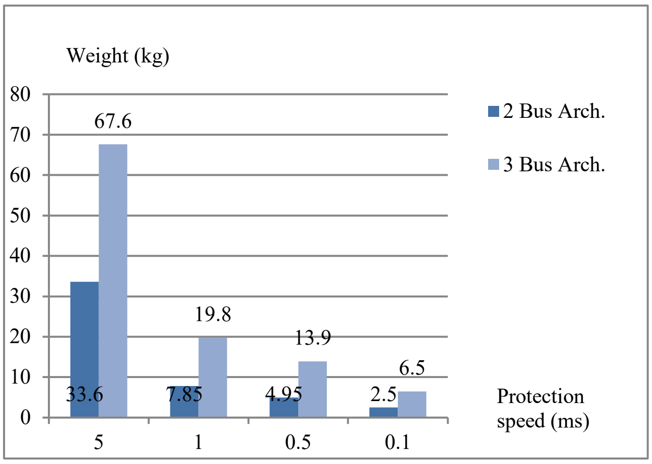


Fig. 8. *Required inductor weight against protection operation speed for fluctuating voltage conditions*

8.3 Potentially Undesired Effects due to Interconnecting Inductance

The addition of inductance between adjacent buses could potentially compromise the stability of the electrical network with regards to the transient load sharing of generators following step changes in load. Although this poses a serious problem in islanded microgrids [56], where poor transient load sharing is exhibited when synchronous generators are paired with inverters, this does not seem to be an issue with more interconnected systems [57], or a wider threat to the stability of the system [58]. Although there are means of control to mitigate for such issues, such as droop-based and master-slave control, a deeper analysis of those is out of the scope of this paper. Fig. 9 shows a comparison of voltage response to a 50kW load step and down on the three bus network both with and without the inclusion of inter-bus inductance. From these results, it can be seen that the response of this particular inductive system is over damped, reducing the peak of the voltage transients but extending the settling time of the system.

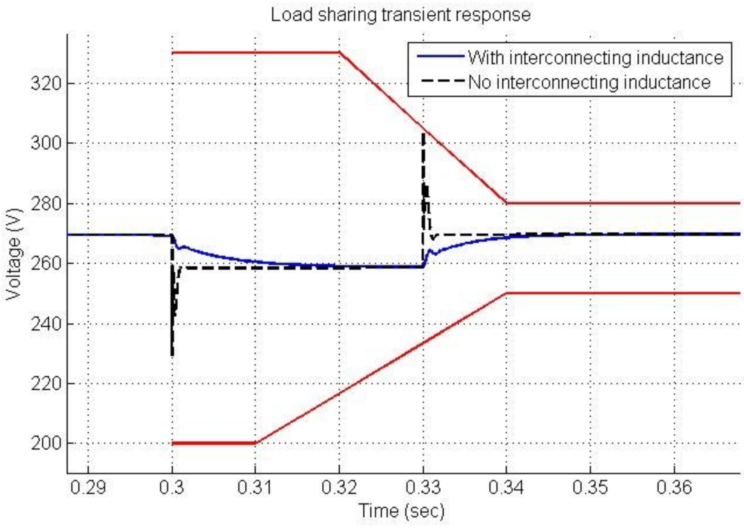


Fig. 9 *Load sharing transient response during a 50 kW step change with interconnecting inductance (blue line)and without (dashed line)*

During a fault, the fault-current magnitude and voltage-disturbance propagation are expected to be greater in an interconnected network than in an isolated system. Therefore the protection system devices and relays must be reconfigured to operate and coordinate accordingly. Although research has shown that high-impedance faults can result in dampened protection operation [59] or protection blinding [60], in the simulations presented earlier, the ratings of the interconnecting solutions proposed are driven by low-impedance short-circuit faults. This along with novel research into high-impedance fault mitigation [61], leads the authors to believe that relay coordination poses no greater problem compared to other protection issues, however a relay-coordination analysis is out of the scope of this paper.

9. Conclusion

This paper briefly reviewed the state of interconnected generation within the current aviation industry and presented the challenges associated with interconnected architectures, as well as key technological drivers that could provide a more feasible route for the implementation of such architectures. It was also demonstrated that closely coupled DC systems could breach power quality requirements under fault conditions.

To mitigate this, inductive impedance connection solutions acting as a DC-bus voltage decoupling mechanism for two and three DC bus architectures were analyzed from a power quality and system mass perspective. From the results presented, the inductive decoupling method was shown to be critical to the standards compliance, suggesting that other active solutions such as solid state current limiting for example [52] may not be sufficient in isolation unless new standards for interconnection are developed which permit very short duration but significant magnitude transients across the wider network, or the faulted system voltage envelopes can be shown to be acceptable for higher power critical loads.

Additionally, the rating/mass of the interconnecting solution was shown to be in direct correlation to the operating speed of the protection system. Although there are no weight or noise thresholds clearly set out in the airworthiness standards concerning the electrical system, it is believed that there can be weight restrictions or budgets at a manufacturer systems-design level and/or that these restrictions may also be customer driven. It is therefore important that any modifications to the electrical system incur the smallest weight penalty possible, thus demonstrating that fast-acting protection and fault clearance technologies are key enablers towards feasibly-implemented interconnected systems. From a technical perspective, this suggests added value in the development of SSPC technologies for future MEA applications, as well as smaller aviation-grade higher-voltage/power inductors necessary for such applications.

10. Acknowledgments

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11. References

[1] The Boeing Company, “787 No Bleed Systems”, AERO magazine, issue 28, quarter 4, 2007, available online at http://www.boeing.com

[2] I. Moir and A. Seabridge, “Aircraft Systems: mechanical, electrical, and avionics subsystems integration”, 3rd ed. John Wiley & Sons Ltd, 2008, ISBN 978-0-470-05996-8

[3] M. Sinnett, “787 No-Bleed Systems: Saving fuel and enhancing operational efficiencies”, *Boeing Aero Magazine*, no. 28, pp. 6–11, Dec. 2007

[4] K.J. Karimi, “Future Aircraft Power Systems – Integration Challenges”, presentation, The Boeing Company, 2007, https://www.ece.cmu.edu/~electriconf/2008/PDFs/Karimi.pdf, November 2015

[5] J. A. Rosero, J. A. Ortega, E. Aldabas, and L. Romeral, “Moving towards a More-Electric aircraft,” Aerospace and Electronic Systems Magazine, IEEE, vol. 22, no. 3, pp. 3 –9, Mar. 2007, doi:10.1109/MAES.2007.340500

[6] A. Garcia, J. Cusido, J. A. Rosero, J. A. Ortega, and L. Romeral, “Reliable electro-mechanical actuators in aircraft,” IEEE Aerospace and Electronic Systems Magazine, vol. 23, no. 8, pp. 19 –25, Aug. 2008, doi:10.1109/MAES.2008.4607895

[7] J.M Kern, H.L.N. Wiegman, “Integrated electrical power extraction for aircraft engines”, U.S. Patent US7468561 B2 Dec. 2008

[8] L. Gaines, P. Auer, G. Lane, J. Wissinger, “More-Electric aircraft starter-generator multi-speed transmission system”, U.S. Patent US20070151258 A1 Jul. 2007

[9] G. Mackenzie-Leigh, P. Norman, S. Galloway, G. Burt, E. Orr, “Defining requirements for the implementation of interconnected generation in future civil aircraft”, presented at SAE 2013 AeroTech Congress, September 2013, doi: 10.4271/2013-01-2125

[10] Airbus Training, “Airbus A340 simulator flight crew operating manual.” Smart Cockpit, http://www.smartcockpit.com/docs/FCOM_A340-Electrical.pdf

[11] Airbus, “Airbus A340 Flight Deck and Systems Briefing for Pilots”, January 2000, http://www.smartcockpit.com/aircraft-ressources/A340_Flight_Deck_and_Systems_Briefing_For_Pilots.html,April 2014

[12] C. Tenning, “Unplanned Characteristics of the 747-400 Electrical Power Generation System”, http://www.angelfire.com/ct3/ctenning/ electrical_essays/747dash400elec/747dash400elec.html, 22 April 2014

[13] Federal Aviation Administration, “Master Minimum Equipment List: B-707 and B-720”, November 1990

[14] The Boeing Company, “Boeing 747 Flight Crew Operations Manual (Chapter 6: Electrical)”, Smart Cockpit, April 2006, http://www.smartcockpit.com/docs/Electrical_(B747-400).pdf, 23 April 2014

[15] A. Abdel-Hafez, “Power Generation and Distribution System for a More-Electric Aircraft - A Review”, InTech, 2012, ISBN 978-953-51-0150-5

[16] E. Papandreas, “Multi spool gas turbine system”, U.S. Patent US8220245 B1, Jul. 2012

[17] D.B. Sidelkovskiy, “Multi-shaft gas turbine engine”, Patent WO2014137452 A1, Sept. 2014

[18] R.J. Hope, “Multi-shaft power extraction from gas turbine engine”, U.S. Patent US20130247539 A1, Sept. 2013

[19] D. Izquierdo, A. Barrado, C. Raga, M. Sanz, and A. M. Roldan, “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, doi:10.1109/TAES.2011.5937248

[20] M. A. Rezaei and A. Huang, “Ultra fast protection of radial and looped electric power grid using a novel solid-state protection device,” presented at 2012 IEEE Energy Conversion Congress and Exposition (ECCE), 2012, pp. 610–614, doi:10.1109/ECCE.2012.6342765

[21] W. Liu and A. Q. Huang, “A novel high current solid state power controller,” presented at 31st Annual Conference of IEEE Industrial Electronics Society, IECON 2005, p. 5, doi:10.1109/IECON.2005.1569094

[22] Zarati, Khaled and Duplaa, Sébastien and Carbonneau, Xavier and Tantot, Nicolas “Engine performance and surge margins optimization by means of nozzles variability”, 22nd ISABE Conference, Oct. 2015

[23] D. Rensch, “Turbofan engine with at least one apparatus for driving at least one generator”, U.S. Patent 20100000226 A107, Jan. 2010

[24] The Boeing Company, “787 Propulsion System”, AERO magazine, quarter 3, 2012, available online at http://www.boeing.com

[25] J. Derouineau, “Engine power extraction control system,” US patent: US7285871, Oct 2007

[26] J.M. Kern, H.L.N. Wiegman, “Integrated electrical power extraction for aircraft engines”, U.S. Patent US7468561 B223, Dec. 2008

[27] A.O. Colin, A. Lebrun, G. Barjon, “Device for producing electrical power in a two-spool gas turbine engine”, U.S. Patent US7973422, Jul. 2011

[28] M.J. Provost “The More Electric Aero-engine: a general overview from an engine manufacturer”, presented at International Conference on Power Electronics, Machines and Drives, pp.246-251, doi:10.1049/cp:20020122, 2002

[29] M. Hirst, A. McLoughlin, P.J. Norman, S.J. Galloway, “Demonstrating the more electric engine: a step towards the power optimized aircraft”, published in IET Electric Power Applications, vol. 5, no. 1, pp. 3-13, February 2011, doi: 10.1049/iet-epa.2009.0285

[30] C. Hodge, D. Mattick, “The Electric Warship II”, Trans IMarE, vol. 108, part 2, pp. 109-125, 1997

[31] S. Fletcher, “Protection of Physically Compact Multiterminal DC Power Systems”, PhD thesis, University of Strathclyde, May 2013

[32] J. Haire, “F-22 Program Delivers Power System Breakthrough”, U.S. Air Force News Release, July 2000

[33] A. Abdel-Hafez, “Power Generation and Distribution System for a More Electric Aircraft - A Review”, InTech, 2012, ISBN 978-953-51-0150-5

[34] R. G. Michalko, “Electric power distribution system and method with active load control,” US patent: US7400065, Jul. 2008

[35] E. Yue, J. Derouineau, W. T. Pearson, “Paralleled HVDC bus electrical power system architecture, US patent: US7936086m, May 2011

[36] P. M. Hield, J. M. Cundy, R. A. Midgley, A. C. Newton, A. L. Rowe, “Shaft power transfer in gas turbine engines with machines operable as generators or motors,” US patent: US5694765, Dec. 1997

[37] C. D. Eick, L. T. Gaines, M. J. Laidlaw, D. M. Benson, L. A. Portolese, B. L. Flaherty, W. T. Pearson, “More electric aircraft power transfer systems and methods,” US patent: 7552582, Jun 2009

[38] A. Trentin, P. Zanchetta, P. Wheeler, J. Clare, “Power conversion for a novel AC/DC aircraft electrical distribution system”, IET Electrical Systems in Transportation, Vol. 4, Iss. 2, pp. 29–37, 2014. doi: 10.1049/iet-est.2013.0005 [1] ‘Author Guide - IET Research Journals’, http://digital-library.theiet.org/journals/author-guide, accessed 27 November 2014

[39] K. Muehlbauer, D. Gerling, “Two-Generator-Concepts for Electric Power Generation in More Electric Aircraft Engine”, XIX International Conference on Electrical Machines - ICEM 2010, Rome

[40] A. Abdel-Hafez, “Power Generation and Distribution System for a More Electric Aircraft - A Review”, Recent Advances in Aircraft Technology, Dr. Ramesh Agarwal (Ed.), InTech, 2012, ISBN: 978-953-51-0150-5

[41] J. Chang, A. Wang, “New VF-Power System Architecture and Evaluation for Future Aircraft”, IEEE Transactions on Aerospace and Electronic Systems, vol. 42, no. 2, April 2006

[42] D. Salomonsson, L. Soder, and A. Sannino, "Protection of Low-Voltage DC Microgrids," IEEE Trans. Power Del., vol.24, no.3, pp.1045-1053, July 2009

[43] S.D.A. Fletcher, P.J. Norman, S.J. Galloway, P. Crolla, G.M. Burt, "Optimizing the Roles of Unit and Non-unit Protection Methods Within DC Microgrids," IEEE Trans. Smart Grid, vol.3, no.4, pp.2079-2087, Dec. 2012

[44] Elserougi, A.A.; Abdel-Khalik, A.S.; Massoud, A.M.; Ahmed, S., "A New Protection Scheme for HVDC Converters Against DC-Side Faults With Current Suppression Capability," IEEE Trans. Power Del., vol.29, no.4, pp.1569-1577, Aug. 2014

[45] Cairoli, P.; Dougal, R.A., "New Horizons in DC Shipboard Power Systems: New fault protection strategies are essential to the adoption of dc power systems", Electrification Magazine, IEEE , vol.1, no.2, pp.38-45, Dec. 2013

[46] Schmerda, R.; Cuzner, R.; Clark, R.; Nowak, D.; Bunzel, S., "Shipboard Solid-State 46Protection: Overview and Applications," Electrification Magazine, IEEE , vol.1, no.1, pp.32-39, Sept. 2013

[47] ‘Baran, M.E.; Mahajan, N.R., "Overcurrent Protection on Voltage-Source-Converter-Based Multiterminal DC Distribution Systems," IEEE Trans. Power Del., vol.22, no.1, pp.406-412 Jan. 2007

[48] Ke Jia; Christopher, E.; Thomas, D.; Sumner, M.; Tianshu Bi, "Advanced DC zonal marine power system protection," IET Generation, Transmission & Distribution, vol.8, no.2, pp.301-309, February 2014

[49] Jovcic, D.; Taherbaneh, M.; Taisne, J.-P.; Nguefeu, S., "Offshore DC Grids as an Interconnection of Radial Systems: Protection and Control Aspects," IEEE Trans. Smart Grid, vol.6, no.2, pp.903-910, March 2015.

[50] US Government, “MIL-STD-704F”, September 2014

[51] D. van den Bossche, “The A380 flight control electrohydrostatic actuators, achievements and lessons learnt”, 25th International Congress of the Aeronautical Sciences, ICAS 2006

[52] D. Sheridan, J. Casady, M. Mazzola, R. Schrader, V. Bondarenko, “Silicon Carbide Power Electronics for High-Temperature Power Conversion and Solid-State Circuit Protection in Aircraft Applications”, SAE International, doi:10.4271/2011-01-2625

[53] AE-7M Subcommittee, “Aircraft Electrical Power Systems Modeling and Simulation Definitions,” SAE Aerospace Information Report, AIR6326, August 2015

[54] S. Fletcher, P. Norman, S. Galloway, G. Burt, “Determination of protection system requirements for dc unmanned aerial vehicle electrical power networks for enhanced capability and survivability,” IET Electrical Systems in Transport, vol. 1, no. 4, pp. 137-147, 2011, doi:10.1049/iet-est.2010.0070

[55] Commercial product source, “Low Profile, High Current Power Inductor”, March 2015. http://www.vishay.com/ppg?34183

[56] A. D. Paquette, M.J. Reno, R.G. Harley, D.M. Divan, “Transient Load Sharing between Inverters and Synchronous Generators in Islanded Microgrids”, IEEE Energy Conversion Congress and Exposition, September 2012, doi:10.1109/ECCE.2012.6342533

[57] W. U. N. Fernando, M. Barnes, O. Marjanovic, “Modelling and control of variable frequency multiphase multi-machine ac-dc power conversion systems”, 5th International Conference on Power Electronics, Machines and Drives, April 2010, doi:10.1049/cp.2010.0082

[58] A. Gkountaras, S. Dieckerhoff, T. Sezi, “Real Time Simulation and Stability Evaluation of a Mevium Voltage Hybrid Microgrid”, 7th International Conference on Power Electronics, Machines and Drives, April 2014, doi:10.1049/cp.2014.0490

[59] S. Luo, X. Dong, S. Shi, B. Wang, “A Non-unit Protection Principle Base on Travelling Wave for HVDC Transmission Lines”, 50th International Universities Power Engineering Conference, December 2015, doi:10.1109/UPEC.2015.7339909

[60] P. Rakhra, P.J. Norman, S.J. Galloway, G.M. Burt, “Experimental Validation of Protection Blinding on DC Aircraft Electrical Power Systems with Power-Dense Energy Storage”, 8th IET Conference on Power Electronics, Machines and Drives, April 2016, doi:10.149/cp.2016.0158

[61] K. Lai, M.S. Illindala, M.A. Haj-ahmed, “Comprehensive Protection Strategy for an Islanded Microgrid Using Intelligent Relays”, IEEE Transactions on Industry Applications, vol. 1, is. 99, August 2016, doi:10.1109/TIA.2016.2604203