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Fault detection and location in DC systems from initial di/dt measurement

By

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Abstract

The use of DC for primary power distribution has the potential to bring significant design, cost and efficiency benefits to a range of power transmission and distribution applications. The use of active converter technologies within these networks is a key enabler for these benefits to be realised, however their integration can lead to exceptionally demanding electrical fault protection requirements, both in terms of speed and fault discrimination. This paper describes a novel fault detection method which exceeds the capability of many current protection methods in order to meet these requirements. The method utilises fundamental characteristics of the converter filter capacitance's response to electrical system faults to estimate fault location through a measurement of fault path inductance. Crucially, the method has the capability to detect and discriminate fault location within microseconds of the fault occurring, facilitating its rapid removal from the network.

Introduction

There is an increasing interest in the use of DC power distribution throughout the power industry. This interest is largely driven by the increased usage and advance of power electronic technologies which have facilitated more interconnected and efficient use of DC systems. Recent proposed applications for DC range from large scale multiterminal DC systems, such as for offshore grid applications[1-3], to more physically compact network types primarily considered within this paper. In particular, DC power distribution has been proposed for use within microgrid[4-6], shipboard[7-9] and aircraft[10-13] applications in recent years. The islanded nature of these network types makes them prime candidates for the implementation of innovative power system architectures, and therefore opportunity exists for them to take advantage of the potential benefits of DC power distribution.

One area which continues to present a barrier to the more widespread adoption of DC is the lack of effective electrical fault protection systems. As a result of these issues, the development of novel DC protection solutions is an area of significant research interest[4, 14]. The following sections of this paper will consider both the potential advantages and protection issues in detail in order to highlight the continued need and potential benefits, as well as the opportunities, for further innovation in this area.

The paper then goes on to describe the concept of how electrical system faults could be detected and located through an initial *di/dt* measurement, that is a *di/dt* measurement very shortly after the point of fault inception. This means of fault detection is compared to existing techniques and examples are subsequently provided on its implementation. The paper concludes by identifying the key challenges in the practical implementation of an initial *di/dt* fault detection scheme as well as highlighting potential application areas.

Potential advantages of DC systems

To gain an appreciation of why such a radical shift in the means of power distribution is being considered, it is useful to first review the benefits that DC power distribution can bring to these applications. For clarity these potential benefits are listed below and nested within this list is a discussion of why these benefits are particularly relevant for microgrid, shipboard and aircraft applications.

1. It is possible to transmit more DC power through a cable of a given voltage rating than with AC

There are a number of reasons why this is the case. The first relates to the insulation limits of cables. Whilst the power delivered through an AC conductor is determined by the voltage RMS, cable insulation requirements are determined by the peak voltage level. This is not the case for DC conductors which can transmit power at the full voltage limit set by the cable insulation. Due to this higher average voltage level, a DC system can therefore transfer up to $\sqrt{2}$ times the power of an AC system operating at the same AC (peak) voltage[9]. Alternative cabling arrangements, such as dividing the DC voltage into a “two-bus” arrangement with positive and negative voltage rails, can achieve even greater improvements in power transfer. For example, Kaipia et al.[6] claims that up to 16 times more power can be transmitted in DC than AC using the same cables and carefully selecting voltage levels. Furthermore, DC systems are free from skin effect (under steady state conditions) and reactive voltage drop, further improving power transfer.

These inherent characteristics of DC distribution provide a number of potential benefits. First, they can facilitate a reduction in cable sizes, potentially reducing cost (which is particular important for making DC distribution economic within the microgrid domain[6]), as well as reducing weight and volume of associated conductors[9, 15]. The indirect efficiency savings achieved by reducing the weight of the electrical system can be of significant benefit to ship and aircraft applications. For example, American Airlines claims that removing 1 pound (≈0.45kg) from each of the aircraft in its fleet will save more than 11000 US gallons (≈3.78 litres per gallon) in fuel per year[16], which, based on 2011's average jet fuel costs of $3.05 per gallon[17], equates to an annual cost saving of $33500 per pound of weight removed from the airframe. Whilst this only provides a high level approximation, it highlights that even small weight saving can result in significant reductions in operating costs in the long term and so incentivises design changes to reduce the weight of an aircraft's electrical system. Doerry[18] also provides an example of this from the marine sector, stating that for a small ship (such as surface combatants or offshore supply vessels) to carry an additional 1 ton (≈1000kg) of payload, the overall weight of ship must increase by approximately 9 tons to support it. This ratio reduces to 1 ton of payload to an additional 1.2 tons of ship for larger vessels. This again serves to highlight that the power system can have a much wider impact on the overall system design.

These characteristics also enable conductors to be better utilised where network voltage is fixed or limited by design constraints of the application. For example, in aviation the reduced pressure at altitude lowers the breakdown voltage of the surrounding air, increasing the risk of partial discharge[19]. Therefore within this sector, there is a reluctance to increase voltage in order to avoid this issue. Another example from within the shipping industry is the need for specially trained crew when the operating voltage is greater than 1000V[20, 21]. Although a practical rather than technical constraint, this can have cost and operability implications. This a particular issue for small but power dense ships, such as offshore supply vessels, and has in part lead to low voltage system designs despite the potentially significant on board power requirements[22, 23]. In both cases, a DC network solution would provide more power for the available voltage.

2. Using DC distribution can reduce the number required power conversion stages between source and load

Within marine and aerospace sectors, the development of more-electric and all-electric design concepts, and the novel technologies associated with their realisation, is driving the requirement for greater electrification of secondary systems[24]. Increasingly, this creates a requirement for converter fed generation and load systems [9-11, 25-27]. Similarly within microgrids, distributed resources, such as small-scale generation, back-up energy storage, and some industrial and sensitive electronic loads increasingly rely on the use of power converters[4, 28].

Utilising DC, it is possible to reduce the number of these power converters used in a network. For systems that generate at variable frequency, two conversion stages (rectification and inversion) are required to distribute power on a standard AC bus. This could be reduced to one rectification stage if DC distribution was used. There are also many novel loads which have unique voltage and frequency requirements. For an AC system, two conversion stages are usually required to get the power in the desired form. This again can be reduced to one with DC distribution. Removal of these nugatory rectification and inversion stages could reduce the number of power converters, and subsequent conversion losses, by up to 50%[9, 28]. Additionally, many energy storage devices such as batteries, naturally output DC. This makes it easier to connect to a DC bus rather than AC as no inversion stage is required.

These factors have a potentially significant impact on the cost, complexity, volume and weight of future network designs. George[28] shows a clear example of this, highlighting that for a data centre containing 1000 servers (that use DC power), $3.5 million could be saved annually on power supply costs based on the reduced conversion losses and associated cooling requirements when utilising DC distribution. Efficiency savings of this order may be the difference between the commercial viability of a project as well as reducing its carbon footprint and therefore provide a high incentive for moving to DC.

Similar cost data for aerospace and marine sectors was not found within the public domain, however the increasing power requirements and reliance on power electronics anticipated within future platforms would suggest that significant efficiency savings could be made. Perhaps more important is the indirect efficiency savings achieved by reducing the weight of the electrical system through the removal of redundant components, the potential advantages of which are highlighted above.

3. DC distribution better facilitates the paralleling of multiple non-synchronous sources

There are multiple points to consider here, many of which are equally relevant to AC systems. The following discusses these and highlights where specific benefits can be gained in the utilisation of DC distribution.

The first is that the paralleling of any sources provides the opportunity to increase the efficiency of power generation through optimised power sharing between the sources based on their individual operating characteristic. This principle has been applied for a number of years on grid based applications to control the output of power stations through the use of economic dispatch[29], and can be applied within AC and DC systems. However the paralleling of generators onto a DC bus is easier than for an AC bus, as the requirement for tight frequency regulation of the supply is removed[30]. This can enable faster connection of sources to a network, potentially providing better dynamic performance. For microgrids, this may allow the greater use of renewable sources under intermittent conditions, whereas within ships and aircraft, it may facilitate more efficient power sharing between multiple generators[12, 23, 31].

The second point relates to the use of non-synchronous generation sources, which are more likely to be smaller scale distributed energy resources and prime movers. The advantages of decoupling the generator frequency from that of the main distribution system are that it allows the prime movers to be operated at the most efficient speeds[7, 9], or indeed any speed (which is of benefit to intermittent sources such as renewables). Generators could also, at least in certain applications, be operated at very high speed to increase power density[32]. Therefore the use of non-synchronous generation sources offer potential for both increased power density and efficiency. Again these advantages can be captured for both AC and DC systems, although additional conversion stages may be required to achieve a fixed AC output, the drawbacks of which are discussed above.

From the above points it is clear that several significant design and operability benefits exist through the adoption of DC distribution, particularly where multiple sources and power electronic interfaces are connected to the network. However until now a number of factors have held back the use of DC distribution. Historically this was an issue of voltage transformation and available transmission distance[33], limiting the application of DC to very low voltage or certain niche applications. Despite advances in technology having overcome these issues, the limited application of DC to date means that, unlike AC electrical systems, a profound understanding of DC electrical systems is yet to be established within the power industry. This creates an entry barrier to developing DC systems. This is evident from (and compounded by) the lack of appropriate standards in this area, particularly those related to the protection of DC networks, meaning that targets for which a system should be design to are more difficult to establish[28].

Protection challenges for DC systems

The key research challenges which exist in the protection of multiterminal DC networks relate to both fundamental issues associated with the protection of DC networks coupled with those that have developed as a result of the adoption of new network and converter designs.

In a faulted DC system, no natural zero crossings exist in the fault current waveform in which the circuit can be broken. As such, larger, heavier and more costly circuit breakers must be employed to break DC current[15], which often increases the cost and physical burden of the associated network protection systems.

The nature of more modern converter interfaced DC networks are such that electrical fault conditions can develop extremely rapidly, creating extremely high fault currents and severe transient voltage conditions. The extent to which these extreme fault characteristics develop is partly dependent on the type of power converter employed. However they are particularly evident within network which utilise standard voltage source converters (VSC), with the capacitors used as filters on the DC terminals of the VSC being a source of significant fault current[8]. A further issue with these types of networks are that VSCs are typically less robust than thyristor based converter topologies[5, 8] and therefore protection must operate more quickly to prevent converter damage during network fault conditions. Salomonsson et al[5] provide an example of this within a microgrid where protection operating time should be in the order of 2ms to prevent converter diode damage.

Beyond these transient mitigation issues, challenges also exist with the accurate detection and discrimination of faults within DC networks. Previous studies from the authors have shown that severe limitations exist with the application of protection methods available within literature in meeting these faster operating requirements, in particular those which employ non-unit protection techniques[34, 35]. This creates a need for innovative methods to overcome the speed and discrimination challenges, which is the rational for the development of the novel method proposed within the following section.

Initial di/dt fault detection concept

The initial *di/dt* fault detection concept method utilises fundamental characteristics of the converter filter capacitance's response to electrical system faults to estimate fault location and coordinate the network protection response. To illustrate how this is achieved, consider the equivalent network diagram shown in Figure 1.

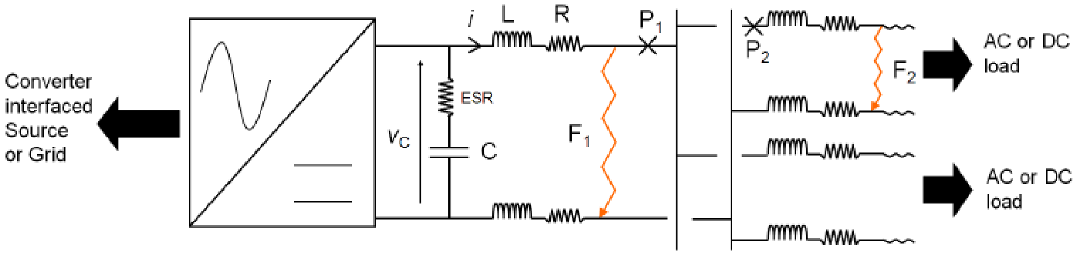

Figure 1
Equivalent circuit for a faulted microgrid network containing a converter interface, filter capacitance and line impedance[35]

When a fault occurs on the DC network, capacitor C at the converter output begins to discharge and contribute to the fault. This discharge current does not increase instantaneously but instead its initial rate of change is dependent on the voltage between capacitance and fault and the fault path inductance. As time approaches zero (time of fault occurrence), this derivative is equal to

$$\frac{di(t \to 0)}{dt} \to \frac{v_{C_F}(0) - i_L(0)R}{L}. \tag{1}$$

With knowledge of inductance per unit length of the line (H/m), and assuming initial line voltage drop is negligible, distance from the capacitor to the fault location can be calculated from equation (1). Provided that *di/dt* can be measured sufficiently close to time zero, then the inductance *L* can be accurately determined.

Figure 2 shows an example of this characteristic behaviour through the simulation of the example microgrid network shown in Figure 1. Faults F_1 and F_2 have been placed at locations 5 metres and 30 metres respectively from the converter, with fault resistances of 1mΩ (short circuit) and 500mΩ (arcing fault) simulated at each location. Full details of this network are presented within[35].

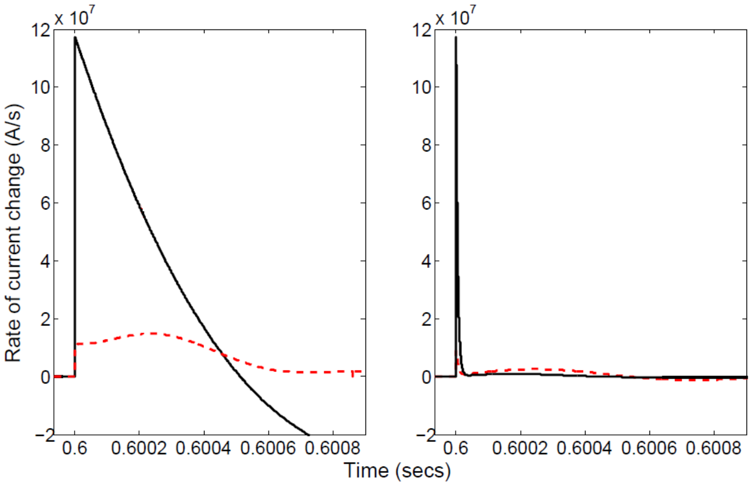

Figure 2

Example microgrid network *di/dt* response for 1mΩ (left) and 500mΩ (right) faults at F_1 (solid) and F_2 (dotted)[35]

Figure 2 illustrates that the initial rate of change is dependent on the location of the fault and is similar for both fault resistance cases. This highlights the potential to utilise such a measurement to very quickly detect both low and high impedance fault types within DC networks. It should however be noted that the high *di/dt* decays very rapidly for higher impedance faults and this will impact on the measurement speed requirements to obtain an accurate fault location. Prior to an example of how this measurement could be utilised as part of a wider protection scheme, the following section compares this approach to existing protection techniques.

Existing techniques and differentiating factors

There are two main distinguishing features in this method compared to techniques presented currently within literature. The first is the use of an inductance measurement for fault location rather than impedance, as is commonly used for distance protection used in transmission systems. This means that the method is insensitive to fault resistance, which is particularly beneficial in the detection of high resistance faults such as arcs. Furthermore, the method only uses the initial (first few µs) rather than sustained *di/dt* characteristic for fault detection, unlike derivative current schemes presently employed. To clarify these differences the following subsections describe the current application of these two protection techniques.

Rate of current rise fault detection.

Rate of current rise (ROCR) fault protection operates on the principle that under fault conditions current will rise more rapidly than under normal operating conditions[36]. This method is not too far removed from overcurrent protection however its main advantage is that faults can be detected earlier as the fault is detected while current is rising rather than at its peak, so full fault current does not need to develop to allow detection and discrimination. Early detection and isolation is advantageous as it can help minimise the disruption to the rest of the network and reduce stress on circuit breaking equipment. Figure 3 illustrates the various levels of ROCR which a network may experience.

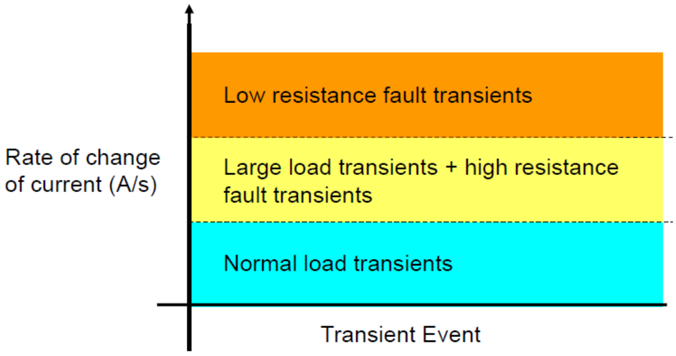

Figure 3
Fault detection regions for traditional *di/dt* based protection systems

Figure 3 shows that there are two distinct regions where load transients and fault transients would normally lie in terms of ROCR. However there are also two overlapping areas where distinguishing between large load transients and high resistance faults becomes difficult. Partly for this reason ROCR is not usually used in isolation, and is normally accompanied by a current magnitude measurement to avoid spurious tripping[37].

Distance protection.

Distance (also known as impedance) protection works on the principle that the impedance of a transmission line is proportional to the length of the line, and so by measuring the impedance, the length of a line can be derived[38]. Distance protection is implemented by measuring voltage and current at a point on the network and from that the impedance of the line downstream of that point can be calculated. If a fault occurs on the network it effectively shortens the length of the line from the point of measurement to the point of fault and so will change the impedance measured. The impedance characteristic is illustrated in figure 4.

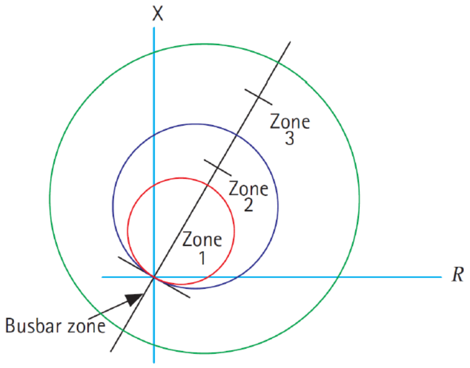

Figure 4
Mho Characteristic with zones of protection[38]

Figure 4 shows three zones of protection covered by the relay physically located at the crossing between the X and R axis. These zones are in part used due to the uncertainty in both measurement and line parameters, which makes it impossible to protect an exact length of line. Instead overlapping zones are used and enables each part of the line to be protected. Faults in Zone 1 are tripped instantaneously, and Zones 2 and 3 with increasing time delays respectively.

Distance protection is commonly employed on long lengths of line (such as transmission lines) but it is not as common in smaller systems as the desired levels of discrimination are difficult to achieve. However the following section does build upon the principles of distance protection, therefore understanding of this fault detection method can facilitate the development of more relevant techniques tailored to the requirements of compact networks.

Protection scheme introduction

The proposed fault detection method is primarily designed for DC distribution networks where generators, energy storage devices and loads (both AC and DC) are interfaced through power electronic converters to the network. As the capacitor fault response provides the mechanism for fault location rather than the response of source or load itself, the converter interface is essential. The following presents an initial proposal into how the fault detection method could be utilised within an example network.

Referring to the busbar network presented in Figure 1, the desired protection system response to the two fault locations would be for the local protection devices to operate to isolate faults on their branch. This would mean P_1 would act to isolate F_1 and P_2 would act to isolate F_2. For faults occurring on other branches in the network, the non-faulted branches should remain connected. In the example network, there is no means of isolating faults on the DC busbar and these faults can only be cleared through the disconnection of all sources of fault current. To achieve the desired discrimination for branch faults, an initial *di/dt* measurement could be set on each of the converter output capacitors (or just on the main source converter if the parallel branches contain no converters of their own) and, operating in isolation from each other, these would trip on a certain threshold. In this case, if protection is to operate for faults on a branch up to the busbar, the threshold would be set to trip breakers when the inductance measured is less than the inductance of the conductor connecting the capacitor to the busbar. For faults beyond the protected zone it is assumed that protection elsewhere in the network will act to isolate the fault.

For this relatively simple primary protection scheme, the process of operation would be:

1. Determine loop inductance up to the busbar L_{CABLE}
2. Set relay to trip when $V_C/(di/dt) < L_{CABLE}$
3. Continuously measure *di/dt* and send trip signal to circuit breakers when the threshold is exceeded.

Note that continuous measurements of *di/dt* would be taken as it would not be possible to guarantee any measurement could be taken at the exact fault occurrence time.

Ideally this scheme would provide protection of the full branch up to the busbar, however because of measurement and parameter uncertainties this cannot be easily achieved. As is the case with more traditional distance schemes, it is likely that the method would only primarily protect a certain portion of the line to avoid any overreach on to or beyond the busbar[38]. This and other operating challenges are discussed in more detail in the following section.

Operating challenges

There are two overriding challenges which need to be understood and overcome in order for initial *di/dt* measurements to feasibly become part of an effective protection system. The first is the understanding of how the time of *di/dt* measurement following the fault influences the accuracy of fault location. Following the initial fault related peak, the natural *di/dt* response decays exponentially over time and the rate of this decay is proportional to the damping within the network. This means that a delay in measurement could see a smaller *di/dt* measured than appeared initially and hence the location of a fault appearing more distant, possibly leading to non-detection of the fault condition.

The second key area is to quantify the degree of uncertainty in any measurement of fault location. This could be made up by a number of factors, such as uncertainty in the line parameters and measurement error. One further consideration for the type of scheme described in the previous section is the consistency of line inductance when exposed to mutual inductive effects from other parts of the network.

These challenges are being addressed as part of ongoing work and will be the subject of future publications.

Conclusions

The integration of active converter technologies is key to the development DC distribution systems however their introduction also creates a number of network protection challenges.

Given some of the shortfalls of current techniques to meet these challenges, continued innovation in the protection of these networks is required in order to fully realise the benefits DC distribution can offer. To help tackle this issue, this paper has described a novel fault detection method based on the initial *di/dt* response of a converter's filter output. By utilising the transient behaviour of the network to discriminate fault location, it is possible to detect faults far faster. In turn, this enables the operation of protection at lower current levels, potentially reducing the stress on network and circuit breaking components, the likelihood of post fault voltage transients and therefore helping to improve long term asset health. A patent application has been made related to this fault detection method[39].

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References

1. J. Yang, J. Fletcher, and J. O'Reilly, "Multiterminal dc wind farm collection grid internal fault analysis and protection design," Power Delivery, IEEE Trans., vol. 25, no. 4, pp. 2308 –2318, Oct. 2010.

2. C. Meyer, M. Hoing, A. Peterson, and R. De Doncker, "Control and design of dc grids for offshore wind farms," Industry Applications, IEEE Transactions on, vol. 43, no. 6, pp. 1475 –1482, nov.-dec. 2007.

3. L. Tang and B.-T. Ooi, "Locating and isolating DC faults in multiterminal DC systems," Power Delivery, IEEE Transactions on, vol. 22, no. 3, pp. 1877 –1884, July 2007.

4. R. Cuzner and G. Venkataramanan, "The status of DC micro-grid protection," in Industry Applications Society Annual Meeting, 2008. IAS '08. IEEE, Oct. 2008, pp. 1–8.

5. D. Salomonsson, L. Soder, and A. Sannino, "Protection of low-voltage dc microgrids," Power Delivery, IEEE Transactions on, vol. 24, no. 3, pp. 1045 –1053, July 2009.

6. T. Kaipia, P. Salonen, J. Lassila, and J. Partanen, "Application of low voltage dc-distribution system - a techno-economical study," in 19th Int. Conf. on Electricity Distribution, May 2007.

7. J. G. Ciezki and R. W. Ashton, "Selection and stability issues associated with a navy shipboard dc zonal electric distribution system," Power Delivery, IEEE Transactions on, vol. 15, no. 2, pp. 665 –669, April 2000.

8. M. E. Baran and N. R. Mahajan, "Overcurrent protection on voltagesource- converter-based multiterminal dc distribution systems," Power Delivery, IEEE Transactions on, vol. 22, no. 1, pp. 406 –412, Jan. 2007.

9. C. Hodge and D. Mattick, “The Electric Warship II,” Trans IMarE, vol. 109, no. 2, pp. 127–37, 1997.

10. M. Sinnet, “787 No-Bleed systems: saving fuel and enhancing operational efficiencies,” in Boeing Commercial Aeromagazine, Quarter 4, 2007, pp. 6 – 11.

11. J. Bennett, B. Mecrow, D. Atkinson, C. Maxwell, and M.Benarous, “A fault tolerant electric drive for an aircraft nose wheel steering actuator,” in Power Electronics, Machines and Drives, 2010. 5th IET Conference on, April 2010.

12. S. A. Long and D. R. Trainer, “Ultra-compact intelligent electrical networks,” in 1st SEAS DTC Technical Conference, July 2006.

13. E. Gietl, E. Gholdston, F. Cohen, B. Manners, and R. Delventhal, “The architecture of the electric power system of the international space station and its application as a platform for power technology development,” in Energy Conversion Engineering Conference and Exhibit, 2000. (IECEC) 35th Intersociety, vol. 2, 2000, pp. 855 –864 vol.2.

14. S. Fletcher, P. Norman, S. Galloway, and G. Burt, “Determination of protection system requirements for dc unmanned aerial vehicle electrical power networks for enhanced capability and survivability,” IET Electr. Syst. Transp., vol. 1, no. 4, pp. 137–147, 2011.

15. J. I. Hanania, “A study of some features of ac and dc electric power systems for a space station.” NASA, Sept. 1983, pp. 223–228, document ID: 19860004616,Accession ID: 86N14085.

16. IAPA, “IAPA First Class Newsletter May 2012,” Available at: http://www.iapa.com/.

17. American Airlines, “Fuel Smart,” Available at: http://www.aa.com/i18n/amrcorp/newsroom/fuel-smart.jsp.

18. N. Doerry, “Next Generation Integrated Power Systems (NGIPS) for the Future Fleet - Keynote Presentation,” Elec. Ship Tech. Symposium, 2009, Available at: http://ewh.ieee.org/conf/ests09/.

19. I. Cotton, A. Nelms, and M. Husband, “Higher voltage aircraft power systems,” Aerospace and Electronic Systems Magazine, IEEE, vol. 23, no. 2, pp. 25 –32, Feb. 2008.

20. “Maintenance of electrical switchgear and controlgear for voltages above 1 kV and up to and including 36 kV - Code of practice,” BS 6626:2010, 2010.

21. Naval Sea Systems Command Office of Corporate Communications, “Navy advances electrical protection for shipboard sailors. [online],” Available at: http://www.navy.mil/, Story number NNS120126-19, [Accessed: 26.1.12].

22. A. Rice, “Rolls-Royce: Low voltage drive range provides end to end capability for electric propulsion packages,” Available at: http://www.rollsroyce. com/Images/In-depth13tcm92-23311.pdf.

23. P. Andersen and H. Buchloh, “Electrical power supply system, especially for ships (Translation),” European Patent number EP2090508A2, January 2009.

24. N. R. C. Committee on Autonomous Vehicles in Support of Naval Operations, Autonomous Vehicles in Support of Naval Operations. National Academies Press, 2005, ch. 3, ISBN: 0-309-55115-3.

25. J. Rosero, J. 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, March 2007.

26. K. Emadi and M. Ehsani, “Aircraft power systems: technology, state of the art, and future trends,” Aerospace and Electronic Systems Magazine, IEEE, vol. 15, no. 1, pp. 28 –32, Jan 2000.

27. P. Butterworth-Hayes, “All-electric aircraft research speeds up,” in Aerospace America, January 2009, pp. 1–7.

28. K. George, “DC Power Production, Delivery and Utilization: An EPRI White Paper,” Available at: http://www.epri.org [Accessed:2.4.12], June 2006.

29. B. Chowdhury and S. Rahman, “A review of recent advances in economic dispatch,” Power Systems, IEEE Transactions on, vol. 5, no. 4, pp. 1248 – 1259, Nov 1990.

30. M. E. Baran and N. R. Mahajan, “DC Distribution for Industrial Systems: Opportunities and Challenges,” IEEE Trans. Industry Applications, vol. 39, no. 6, pp. 1596–1601, November/December 2003.

31. P. J. Norman, S. J. Galloway, G. M. Burt, D. R. Trainer, and M. Hirst, “Transient analysis of the more-electric engine electrical power distribution network,” in Power Electronics, Machines and Drives, 2008. PEMD 2008. 4th IET Conference on, April 2008, pp. 681 –685.

32. J. G. Vaidya and E. Gregory, “High-Speed Induction Generator for Applications in Aircraft Power Systems,” in SAE Power Systems Conference, November 2004, pp. 1830–1836, document Number: 2004-01-3174.

33. C. L. Sulzberger, “Triumph of ac. 2. the battle of the currents,” Power and Energy Magazine, IEEE, vol. 1, no. 4, pp. 70 – 73, Jul-Aug 2003.

34. S. D. A. Fletcher, P. J. Norman, S. J. Galloway, P. Crolla, and G. M. Burt, "Optimizing the roles of unit and non-unit protection methods within dc microgrids," Smart Grid, IEEE Transactions on, Accepted for publication.

35. S. Fletcher, P. Norman, S. Galloway, and G. Burt, "Analysis of the effectiveness of non-unit protection methods within dc microgrids," in IET Renewable Power Generation, Sept 2011.

36. E. Cinieri, A. Fumi, V. Salvatori, and C. Spalvieri, "A new high-speed digital relay protection of the 3-kvdc electric railway lines," Power Delivery, IEEE Trans., vol. 22, no. 4, pp. 2262 –2270, Oct. 2007.

37. W. Xiaohong, L. qunzhan, and C. Xiaochuan, "The research on main protection for dc feeder line of subway," in Autonomous Decentralized System, 2002. The 2nd International Workshop on, Nov. 2002, pp. 342 – 346.

38. "Network protection and automation guide, chapter 11 distance protection. [online]," Available at: http://www.alstom.com/grid, [Accessed: 2.12.11].

39. S. D. A. Fletcher, P. J. Norman, S. J. Galloway, and J. E. Hill, "Protection System for an Electrical Power Network," UK Patent application GB1102031.0, February 2011.

Biography

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