Operational Control and Protection Implications of Fault Current Limitation in Distribution Networks

S. M. Blair, N. K. Singh, C. D. Booth and G. M. Burt
University of Strathclyde
steven.blair@eee.strath.ac.uk

***Abstract*—Rising short-circuit fault current levels is one of the problems associated with the increased presence of distributed generation (DG) in electrical networks. A fault level management system involving superconducting fault current limiters (SCFCLs) is a potential solution to this issue. The typical applications of SCFCLs and their advantages over traditional fault current limitation measures are discussed. However, several technical issues remain, relating to: SCFCL post-fault recovery time; network control and protection; and maloperation of the SCFCL due to non-fault transient currents, such as transformer inrush. Initial solutions to these problems, involving a distributed software-based fault level management system, are presented.**

***Index Terms*—Fault current limiter (FCL), fault level management, power system protection, superconducting fault current limiter (SCFCL)**

I. INTRODUCTION

Rising short-circuit fault current levels is a potential barrier to the penetration of distributed generation (DG), including DG using renewable energy sources, within power distribution networks. This work focuses on fault current level management, and combines superconducting fault current limiter (SCFCL) technology, network control and protection functions, and a software management system. Only 7% of existing Active Network Management projects involve fault level management, and 6% address the issue of the implications on protection systems [1].

The resistive-type SCFCL device (which is generally preferred [2]) quickly "quenches" during a fault and inserts a current-limiting resistance into the network. SCFCLs have the potential to significantly reduce some of the costs associated with rising fault current levels (e.g., replacement of switchgear), due to the increasing presence of DG. Marine and aero power systems also present promising opportunities for SCFCLs, but with attendant control and protection challenges.

This paper summaries the typical SCFCL applications described in the literature, and highlights certain disadvantages of traditional fault current limitation techniques. Three main technical issues have been identified that must be resolved before SCFCLs can achieve widespread adoption:

- Certain SCFCL types may take several minutes to recover full superconductivity following an operation.
- The ability of existing protection systems to detect fault conditions and to discriminate and coordinate with other protection systems may be affected or even compromised by fault current limitation.
- Maloperation of SCFCLs may be caused by non-fault related electrical transients, such as transformer inrush current and large motor starts.

It is proposed that a distributed software management system and research-based guidance on the application of SCFCLs, can help mitigate some of these issues.

II. TYPICAL SCFCL APPLICATIONS

The typical applications of SCFCLs in distribution networks are summarised in Fig. 1, and discussed below.

A. DG Connection

DG penetration can be facilitated by connecting DG to the grid via a SCFCL. This limits the new generator's fault level contribution. As illustrated in [2], for low fault level margins, connecting DG to the distribution grid in this way can save an expensive connection to the transmission grid via a transformer.

However, this application was of relatively low concern for US utilities, as reported in an EPRI survey in 2004 [3]. In addition, [4] concludes that, because this location does not limit the grid fault contribution, it is only effective in situations where DG is the main fault current contributor. Deployment of FCLs at 33kV grid incoming feeders was deemed, by simulation, to be significantly more effective than using FCLs at DG connection.

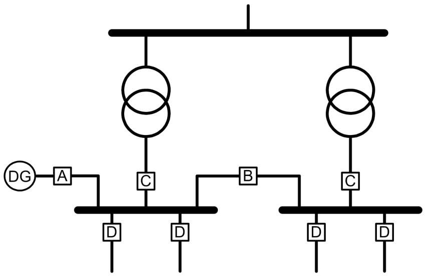

Figure 1. Typical SCFCL locations in a radial distribution system

Furthermore, it is likely that fewer FCLs (albeit of higher rating) are needed for grid incoming feeders.

B. Bus-tie

SCFCLs can permit normally-open bus-ties to be closed (as shown in Fig. 1), where this was previously forbidden due to fault level concerns. This is a popular potential SCFCL location - approximately half of proposed applications are at bus-tie locations [3], [5]. The benefits of being able to close a normally-open bus-tie are [5], [6]:

- Reduction of voltage dips, flicker and harmonics due to lower total source impedance.
- Higher system availability and security of supply due to the parallel connection of the feeding generators and transformers.
- Higher loads possible in sub-systems because of increased interconnection - potential for more efficient use of available generation.
- Ensures even loading of parallel transformers, regardless of the variation of loads on either side of the bus-tie.
- Allows subgrids to be connected directly at a lower voltage level, providing increased reliability without requiring an expensive transformer (e.g., 110kV/380kV) [7].

The specific advantages of installing a SCFCL at the bus-tie location are:

- Few protection changes are needed.
- The FCL only has to be rated for the maximum fault from either of the two transformers (or the maximum bus-tie transfer), which may be economically advantageous.
- A switchable bus-tie connector is a useful method for mitigating SCFCL recovery time. The bus-tie switch can be opened following a SCFCL operation. This will temporarily reduce the security of supply and power quality, but should be acceptable for a short time. With careful grading, this could increase the system impedance sufficiently to reduce the fault level to circuit breaker-rated levels.

Electric ship propulsion systems, with relatively low voltages (5 to 15kV), are a likely candidate for SCFCLs [2], [8], [9]. Reference [8] proposes a bus-tie SCFCL application, to offer improved reliability for supply to the electric motors (plus the other benefits listed above). Space and weight savings due to lower-rated circuit breakers (CBs) are another important benefit of fault current limitation in marine (and aero) systems.

C. Incoming Grid Feeder

As described above, [4] indicates that this location is highly effective at reducing the fault current level (in radial urban networks), because - even for high DG penetration - the main fault level contribution is from the grid.

Note that networks with SCFCLs on incoming or outgoing feeders may also include (non-superconducting) bus-ties, to achieve the same benefits described in Section II-B. In addition, although this may require more SCFCLs than a single bus-tie device, it may be satisfactory to bypass one SCFCL for maintenance. The other incoming feeder SCFCL(s) can remain active.

D. Outgoing Feeder

This SCFCL location can be used to reduce the fault level for a particular distribution branch. This may require more SCFCLs (but of lower rating) than the bus-tie position. Although it may be more efficient to consolidate the necessary cryogenic system into one large device, several smaller SCFCLs should offer better reliability and redundancy. In this location, the SCFCL helps prevent voltage collapse at the busbar - the voltage remains at ~0.9pu during the fault, and recovers quickly, post-fault [10].

III. Traditional Alternatives to SCFCLs

The merits and demerits of traditional fault current limitation techniques, compared to SCFCLs, are summarised below.

Increase system impedance: Air-cooled reactors or transformer reactance will, however, lead to undesirable power losses (hence increasing operational costs [11]) and power quality issues, which is highly undesired in today's networks [4]. However, reactors may be easier to install and operate, and may be cheaper than SCFCLs [12].

Splitting busbars: This technique changes the network topology to a configuration with a lower fault current level, through reducing the number of parallel impedances. It reduces grid flexibility and the security of supply, and separates current sources from current loads. It can also be expensive to implement, if the bus splitter arrangement does not already exist.

Upgrade switchgear: Retrofitting a substation to handle the increased fault level. This can be very costly, depending on the number of CBs and their rated voltage. The new CBs may also be considerably larger. In some cases switchgear may not be available at the necessary rating, e.g., over 80kA at HV [13]. In addition, this solution does not reduce the fault current level and the associated issues and risks [11].

Sequential CB tripping: This protection scheme involves opening an upstream CB (relatively far from the fault) that is rated to handle the fault current. A downstream CB (nearest the fault), which has a much lower rating and is cheaper, is then opened as there is reduced, or zero, current flow. Finally, the upstream CB is reclosed. This adds delay to the fault clearance which may stress equipment and compromise system stability. Opening an upstream breaker causes disruption to a wider area of the network (including non-faulted areas) than a downstream breaker, local to the fault. A reliable communication system is also required.

Increasing operating voltage levels: This may cause the short-circuit power margins to be exceeded for some devices, so in many cases this option is unsatisfactory [11].

Fuses: Fuses can act quickly to limit fault current. The main disadvantages are that fuses are single-use and are time-consuming to replace, following operation (during which the supply is compromised). Current commutating fuses (which route current through a parallel reactor during a fault) can maintain supply post-fault; further faults are limited by the parallel reactor, but downstream voltage levels may be reduced.

I_s-limiters: The fault current is quickly routed through a shunt fuse, by detonating a small explosive charge. This is particularly useful at HV, as a cost-effective and faster-operating (less than 1ms) alternative to a CB. Over 2,500 devices are in operation throughout the world. However, the device is single-use, and there are safety concerns if it fails to operate [14].

IV. SCFCL TECHNICAL ISSUES

A. Post-Fault Recovery Time

When a resistive-type SCFCL "quenches" during a fault, the superconductor exceeds its critical temperature threshold (T_c) due to the energy dissipated darning the fault. To re-enter the superconducting state, a cryogenic system must cool the superconductor below the critical temperature. This recovery period may take up to several minutes [2]. This can be a significant problem because the SCFCL is inoperable during this period; either the prospective fault current level will exceed device ratings, or the SCFCL and part of the downstream network must be disconnected. Note that some varieties of SCFCL, such as the DC-biased iron-core and diode-bridge, inherently do not require recovery.

The authors of [15], [16] propose a solution based on the physics of the superconductor. If the current exceeds the critical current (I_c), but the temperature remains below T_c, the superconductor does not fully enter the normal conducting state. A "flux-flow" resistance is exhibited by the SCFCL during abnormally-high current flow, but is removed during normal current level conditions. The device returns to its superconducting state immediately; no recovery time is necessary. However, a relatively large (and expensive) quantity of superconductor (and the associated cooling system) is needed, and the AC losses will be greater because of the greater volume of superconductor.

This will require careful design of the T_c and I_c parameters for each situation. However, issues may arise regarding multi-shot reclosing, or faults that are not cleared quickly. The temperature may exceed T_c, thus forcing a recovery period.

Another solution is to have a second pre-cooled SCFCL which is switched-in, post-fault, in parallel to the recovering SCFCL [17]. Assuming the switching can occur fast enough (and depending on the reclosing policy), the fault level is not compromised during the recovery period.

For the bus-tie location, reference [6] points out that it is acceptable to remove the SCFCL during recovery. The authors imply that this will only be for a few seconds, but it may be much longer. A recovery time of 60 seconds is deemed acceptable for bus-tie SCFCLs in [7].

A compromise is to use a shunt resistor or reactor instead of a second SCFCL [18], [19]. A fast switch removes the SCFCL from the circuit approximately 50-80ms after the fault inception (leaving only the shunt), to reduce the energy absorbed by the cryogen (and hence reduce the recovery time); the shunt carries most of this burden. However, this leads to losses and voltage issues. A control system could request an upstream transformer to increase its tap ratio, or an energy storage device could be activated to compensate; these options require further consideration. Utilities can specify the impedance of the shunt, and hence the level of fault current limitation [18].

B. Impact on Protection Scheme

During faults, SCFCLs add a non-linear impedance into the system which could negatively affect protection relays or their measurement devices [11].

CIGRE Working Group A3.10 [5] suggests four impacts of SCFCLs on protection: relay settings; selectivity (time co-ordination between overcurrent relays); protection "blinding" (especially for directional protection); and compatibility with downstream fuses. Working Group A3.16 [20] followed on from the work of A3.10, and produced guidelines for the impact of FCLs on protection systems. It is the only comprehensive study on the impact of FCLs on the protection scheme [13]. The framework correlates specific FCL characteristics with typical protection types (overcurrent, distance, directional and differential), and the location of the FCL relative to each protection zone; heuristics identify any protection issues. It does not cover situations involving multiple FCLs locations, FCL failure, or reclosing schemes. Overall, this study is a useful first step. However, effective protection with SCFCLs requires further investigation. Some of the issues are discussed below.

1) Overcurrent Protection: A SCFCL could delay an overcurrent relay trip operation (especially for severe fault current limitation), for a given I-t curve, since the fault current is reduced [21]. The coordination time between upstream and downstream relays (which will have different I-t curves) would also increase. This may increase the stress on equipment during a fault, but may be beneficial because it offers greater flexibility - there is more time to trip the downstream CB before the upstream relay trips.

The bus-tie SCFCL application requires relatively few protection changes [6], [22]. This is because the SCFCL will only impede the fault current contribution from the "healthy" side of the bus. The faulted side will not experience any overcurrent protection delay. SCFCLs with a parallel shunt (particularly an inductive shunt), will experience a delayed current zero-crossing point [22]. This involves larger overall I^2R loses (compared to a SCFCL without a shunt), but may allow more time for protection to operate within the 1st cycle.

FCLs that impede only the DG fault current contribution can minimise changes to overcurrent relay settings, and can reduce stress on the distributed generator [23].

2) Distance Protection: The effects of a SCFCL on distance protection are discussed in [11], [24]. An RTDS was used to model a simple network with a resistive-type SCFCL, which interfaced with a hardware relay. The relay fails to correctly identify the fault distance when the SCFCL is placed after the voltage transformers (VTs), and does not trip (when it should) when the fault is sufficiently far from the VTs.

This can potentially be mitigated by measuring the voltage across (which can itself be used to indicate the presence of the fault) and current through the SCFCL, and hence its impedance. The distance relay can then, in real-time, compensate for the instantaneous impedance increase due to the SCFCL.

3) Other Protection Issues: High fault levels are an emerging issue in marine power systems, particularly with the introduction large-scale Integrated Full Electric Propulsion (IFEP) systems. The requirements for marine electrical protection schemes are even more stringent than for terrestrial systems [8]: systems must be fast-acting; they should only operate for faults in the designated area (unless for backup); they should only operate the minimum number of CBs to clear a fault; there must be a backup protection system; and the protection system should cope with variable fault levels.

Conventional overcurrent relays may not operate for significantly reduced fault current (or could operate spuriously for non-fault transient currents) which may merit a complete redesign of the protection system. Unit protection may mitigate this problem (and may also solve the problem of variable fault levels). In addition, [8] proposes a fast centralised fault-location and protection scheme (using a real-time communication system) which is particularly applicable to networks with SCFCLs. An issue identified in [21] highlights the need for such systems: due to their fast first-peak limitation property, SCFCLs may operate for remote faults (which could normally be handled by downstream relays and CBs).

The failure of a SCFCL device could introduce an unexpected impedance into the system which, apart from causing undesirable losses, could trip undervoltage protection [4].

C. SCFCL Maloperation Due to Non-Fault Related Electrical Transients

High currents that resemble faults, such as transformer magnetising inrush current, could accidentally trigger the operation of a SCFCL. Inrush current can be up to an order of magnitude greater than load currents, and may persist for many cycles (approximately one second for large transformers). This is a problem because - unlike traditional relays which can recognise inrush through 2$^{\text{nd}}$ harmonic currents, and block operation - the operation of a SCFCL cannot be readily blocked during inrush. The superconducting material will automatically react to inrush in the same way as it would to a fault. This action is undesirable because it is an unnecessary use of the SCFCL, which must subsequently recover.

It is necessary to evaluate the extent of this issue and, where appropriate, provide solutions. Initial simulations, using PSCAD with an urban radial distribution system model, have confirmed that inrush current can reach an order of magnitude greater than normal current, as stated in the literature, at some of the typical SCFCL locations. However, this ratio depends on the load (assuming the load is connected during transformer energisation); for small loads the peak inrush is high, relative to the steady-state value. There is potential for a control system to manage the energisation of transformers to avoid maloperation of SCFCLs; the SCFCLs could be bypassed during energisation, or transformer energisation could be controlled in some way. However, the network must be adequately protected during this period.

The worst-case scenario for SCFCL maloperation occurs when the grid is reconnected after loss-of-mains, because potentially a large number of transformers must be re-energised. However, if local DG is available to supply the loads and islanding is permitted, the inrush is significantly reduced, because the transformers are already energised when the grid is reconnected. This has been confirmed by simulation.

V. PROPOSAL FOR A DISTRIBUTED FAULT LEVEL MANAGEMENT SYSTEM

Fault current levels must not exceed equipment ratings. It is proposed that a distributed SCFCL management system can help achieve this, and additionally mitigate some of the issues associated with SCFCLs - particularly control and protection issues.

One of the advantages of a SCFCL is that it automatically reacts to faults. There is very little to control (except for a degree of control involved with managing the cryogenic system, to maintain a particular temperature). Local circuit breakers or isolators may exist, but these may be controlled by a local relay, rather than a controller embedded in the SCFCL. There may also be local current or voltage measurements. The latter can be used to identify if the SCFCL has operated; a voltage greater than zero (or a threshold close to zero) across the SCFCL implies that the SCFCL has developed an impedance.

In the initial design, each SCFCL (or, more generally, any Distributed Energy Resource) will be controlled by a local system. The entire system will be governed by a centralised management device, which manages the system according to overarching goals. Several SCFCLs may be managed (such as controlling bypasses) by the central controller, connected via a communications infrastructure. Adaptability to changes in the electrical topology, and a safety-critical nature are important to the design.

Several standards exist for supporting communications in electrical power systems: IEC 61850, the Common Information Model (CIM), IEC 60870, etc. For example, IEC 61850 specifies high-speed communication services and a distributed functional architecture. The CIM provides a standard, semantic model for describing components in a power system, and exchanging messages between them. The principles underpinning these paradigms can be adopted.

The system may also be extended to include conventional active network management techniques, such as: automated islanding, load shedding, voltage support, energy storage, FACTS, etc.

VI. CONCLUSIONS AND FURTHER WORK

At this stage, there is no universally applicable approach to each application of SCFCLs. Each situation must be analysed individually. Very many publications exist on the topic, superconductor materials have been extensively developed, and several prototype SCFCLs have been tested. Yet, no dramatic changes in the basic approach, at the systems level, have occurred since research began in the late 1970s. The resistive-type SCFCL, with a resistive or reactive bypass, (as proposed in 1978 [19]) appears to be the best overall option - being inherently fail-safe is crucial in most applications. As described, many technical issues (and practical issues, such as cost) remain. In particular, the impact on the protection system, the superconductor recovery time, and the risk of maloperation during non-fault transients are significant challenges.

The issue of transformer magnetising inrush current causing spurious SCFCL operation must be better understood. Further simulations are to be conducted by the authors using a SCFCL model to determine, comprehensively, if maloperation can occur. In addition, the effect of multi-shot reclosing schemes will be explored.

A fault level management system is proposed to help mitigate the technical barriers to SCFCL application. Some initial control and protection strategies have been suggested, such as managing SCFCL bypasses (particularly for inrush current immunity), the potential for centralised protection schemes, and adaptive distance protection.

ACKNOWLEDGEMENTS

This work was carried out within the Rolls-Royce University Technology Centre at the University of Strathclyde. The authors gratefully acknowledge the funding and support offered by Rolls-Royce.

REFERENCES

[1] R. MacDonald, G. Ault, and R. Currie, “Deployment of active network management technologies in the UK and their impact on the planning and design of distribution networks,” in *SmartGrids for Distribution, 2008. IET-CIRED. CIRED Seminar*, pp. 1–4, 2008.

[2] M. Noe and M. Steurer, “High-temperature superconductor fault current limiters: concepts, applications, and development status,” *Superconductor Science and Technology*, vol. 20, no. 3, pp. R15–R29, 2007.

[3] S. Eckroad, “Fault current limiters - utility needs and perspectives,” Tech. Rep. 1008696 and 1008694, EPRI, 2004.

[4] N. K. Singh, G. M. Burt, C. C. Brozio, D. Roberts, C. G. Bright, and M. Husband, “Managing urban network fault level - a role for a resistive superconducting fault current limiter?,” CIRED (Unpublished), 2009.

[5] H. Schmitt, “Fault current limiters in electrical medium and high voltage systems,” Tech. Rep. 239, CIGRE WG A3.10, 2003.

[6] L. Ye and A. Campbell, “Behavior investigations of superconducting fault current limiters in power systems,” *Applied Superconductivity, IEEE Transactions on*, vol. 16, no. 2, pp. 662–665, 2006.

[7] W. Hassenzahl, D. Hazelton, B. Johnson, P. Komarek, M. Noe, and C. Reis, “Electric power applications of superconductivity,” *Proceedings of the IEEE*, vol. 92, no. 10, pp. 1655–1674, 2004.

[8] C. Booth, I. Elders, J. Schuddebeurs, J. McDonald, and S. Loddick, “Power system protection for more and full electric marine systems,” *Proceedings of IMarEST - Part B - Journal of Marine Design and Operations*, vol. 2008, pp. 37–45, July 2008.

[9] A. Neumann, “Application of fault current limiters,” Tech. Rep. 07/1652, BERR, 2007.

[10] L. Ye, M. Majoros, T. Coombs, and A. Campbell, “System studies of the superconducting fault current limiter in electrical distribution grids,” *Applied Superconductivity, IEEE Transactions on*, vol. 17, no. 2, pp. 2339–2342, 2007.

[11] R. Adapa, “Fault current management guidebook - updated,” Tech. Rep. 1012419, EPRI, 2006.

[12] L. Kovalsky, X. Yuan, K. Tekletsadik, A. Keri, J. Bock, and F. Breuer, “Applications of superconducting fault current limiters in electric power transmission systems,” *Applied Superconductivity, IEEE Transactions on*, vol. 15, no. 2, pp. 2130–2133, 2005.

[13] S. Eckroad, “Survey of fault current limiter (FCL) technologies - update,” Tech. Rep. 1016389, EPRI, 2008.

[14] P. B. Ltd, “Development of a safety case for the use of current limiting devices to manage short circuit currents on electrical distribution networks,” Tech. Rep. 04/1066, DTI, 2004.

[15] H. Shimizu, K. Mutsuura, Y. Yokomizu, and T. Matsumura, “Inrush-current-limiting with high tc superconductor,” *Applied Superconductivity, IEEE Transactions on*, vol. 15, no. 2, pp. 2071–2073, 2005.

[16] H. Shimizu, Y. Yokomizu, T. Matsumura, and N. Murayama, “Proposal of flux flow resistance type fault current limiter using bi2223 high tc superconducting bulk,” *Applied Superconductivity, IEEE Transactions on*, vol. 12, no. 1, pp. 876–879, 2002.

[17] W. Paul and M. Chen, “Superconducting control for surge currents,” *Spectrum, IEEE*, vol. 35, no. 5, pp. 49–54, 1998.

[18] H. Neumueller, H. Kraemer, W. Schmidt, S. Kalsi, D. Folts, A. Malozemoff, and A. Otto, “Economically viable fault current limiters using YBCO coated conductors,” in *Power Engineering Society General Meeting, 2007. IEEE*, pp. 1–5, 2007.

[19] K. E. Gray and D. E. Fowler, “A superconducting fault-current limiter,” *Journal of Applied Physics*, vol. 49, pp. 2546–2550, Apr. 1978.

[20] H. Schmitt, “Guideline on the impacts of fault current limiting devices on protection systems,” Tech. Rep. 339, CIGRE WG A3.16, 2008.

[21] B. W. Lee, J. Sim, K. B. Park, and I. S. Oh, “Practical application issues of superconducting fault current limiters for electric power systems,” *Applied Superconductivity, IEEE Transactions on*, vol. 18, pp. 620–623, June 2008.

[22] E. O. Usabiaga, F. G. Garcia, L. Garcia-Tabares, J. Peral, J. Rodriguez, P. M. Cid, and X. Granados, “Superconducting hybrid fault current limiter: Manufacturing, modelling and simulations,” 2001.

[23] G. Tang and M. R. Iravani, “Application of a fault current limiter to minimize distributed generation impact on coordinated relay protection,” 2005.

[24] J. Langston, M. Steurer, S. Woodruff, T. Baldwin, and J. Tang, “A generic real-time computer simulation model for superconducting fault current limiters and its application in system protection studies,” *Applied Superconductivity, IEEE Transactions on*, vol. 15, no. 2, pp. 2090–2093, 2005.