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Evaluating the Impact of Superconducting Fault Current Limiters on Distribution Network Protection Schemes

Jennifer Kincaid	Ibrahim Abdulhadi	Abdullah S Emhemed	Graeme M Burt
University of Strathclyde	University of Strathclyde	University of Strathclyde	University of Strathclyde
jennifer.kincaid@strath.ac.uk	iabdulhadi@eee.strath.ac.uk	abdullah.emhemed@strath.ac.uk	g.burt@eee.strath.ac.uk

***Abstract*- Rising fault levels are becoming increasingly problematic in the UK distribution network, with large sections of the network operating near to its designed fault level capability. With the increase in penetration of distributed generation that is expected in the coming years, this situation is becoming more pressing. Traditional methods of dealing with the issue may not be appropriate – upgrading plant is expensive and disruptive, while network reconfiguration can compromise security of supply. Superconducting Fault Current Limiters (SFCLs) are emerging as a potential solution, with installations now taking place in several locations worldwide.**

The integration of an SFCL into a network involves a number of challenges, particularly concerning the coordination of protection systems. The operation of existing protection schemes may be compromised due to the increased resistance in the network during a fault (in the case of a resistive SFCL). Furthermore, the reduction in fault levels, although desirable, can have a detrimental impact on protection operating times.

This paper will consider an existing medium voltage network in the UK, which incorporates distributed generation capacity. The performance of IDMT overcurrent and distance protection schemes will be examined when an SFCL is installed in this network. In particular, the increased operating time of overcurrent relays will be discussed along with grading implications. The impact on distance protection reach will also be examined. A variety of network operational scenarios including SFCL placement and fault conditions will be considered and compared. Recommendations will be made in terms of protection settings and SFCL placement in order to mitigate the aforementioned issues.

***Index Terms*-- distributed generation, power systems protection, SFCL**

I. INTRODUCTION

Fault levels are a growing concern for Distribution Network Operators (DNOs). A UK DNO have stated that a “significant proportion” of substations on their network have circuit breakers operating at 95% of their duty rating, and this will be typical for the whole UK network [1].

There are a number of reasons for increasing fault levels. Traditionally, load growth has been the key factor. Higher load demand not only leads to increased generation on the grid, which is a major fault level contributor, but also greater interconnectivity: parallel conducting paths decrease the impedance seen by the fault, and also more sources are available to feed it [2]. More recent trends are compounding the problem. A surge in distributed generation, particularly renewables and low carbon technology, is a significant contributor at distribution-level medium voltages, as well as the higher transmission voltages that are typical for past generation connections. It has been shown that a “significant number” of substations will not be able to take the new generation that is likely to be installed in the future [3].

When fault levels are too high, there are a number of issues. Plant connected to the network must have far greater electrodynamic and thermal stability. To accomplish this, the plant is heavier, bigger and more costly [4]. Even if the DNO can afford the expense of replacing, for example, transformers, generators and circuit breakers, there may not be space available to do so, particularly in urban areas. Most crucially of all, circuit breakers need to have sufficient rating to break any fault current that may occur. DNOs do not have the option to simply refuse connection to new loads and generation, as they have a duty to connect on request [5].

Due to the reduction in fault currents that they provide, SFCLs can be used to avoid expensive network reinforcement or less stable network configurations which would otherwise have been needed to cope with rising fault levels [3]. Installations are now taking place worldwide [6, 7]. While the reduction of fault current has obvious benefits, this and the sudden introduction of a resistance into the network, may have detrimental effects.

In order to investigate this, a model of an SFCL was created in PSCAD. Another model was then created of an existing area of the UK distribution network where the operator is considering installing an SFCL. These models were then used together in simulations to investigate realistic integration issues and their mitigation, focusing on the effect on the operation of existing protection schemes.

The main contribution of this paper is to outline the effects that the installation of an SFCL has on existing distribution network protection schemes. This highlights integration issues in a real network application.

II. NETWORK MODEL

For the simulations, a resistive SFCL model was used. This was integrated into a network model of a real section of the UK network. The resistance characteristic of the model involved a rise of resistance according to I^2t, once the current

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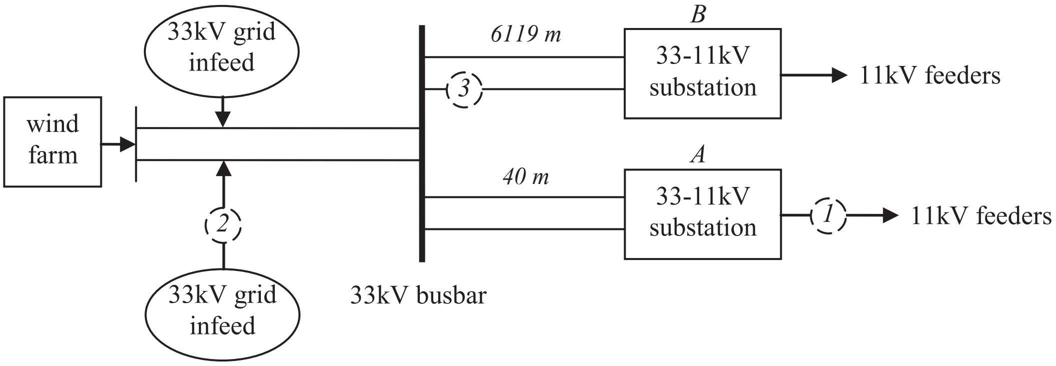

Fig. 1. Single line diagram of the simulation network model, indicating SFCL test locations

through the device rose above a threshold value. A maximum value of resistance was then reached, which reduces back to zero after the fault is cleared. This gave an approximation of the resistance characteristic of a real resistive SFCL, although it does not take into account the temperature of the device.

The network that was modelled has two grid infeeds and a wind farm, connected to two 33-11kV substations, as shown in Fig. 1.

Substation A has three 10MVA transformers, supplying eight 11kV feeders. The 11kV fault current at this substation is 17.37kA RMS, and the load is 26.85MW with a power factor of 0.99. Substation B has two 19MVA transformers, supplying seven 11kV feeders. The 11kV fault current at this substation is 14.98kA RMS, and the load is 19.3MW, again with a power factor of 0.99. The fault current at the main 33kV busbar is 14.18kA RMS.

The wind farm is rated at 90MVA, and was modelled as an induction machine. The torque applied to this machine was determined by wind and turbine models available in PSCAD, with characteristics based on the wind conditions and turbines used at the actual wind farm site.

III. EFFECT OF SFCL ON OVERCURRENT RELAYS

A. SFCL installed on 11kV feeder

The part of the network with the highest fault levels, relative to the nominal load level, is the 11kV feeders from the two substations. For faults at the near end of the feeder, these have a fault current of 13kA RMS. It was therefore decided to investigate the impact of having an SFCL installed at this location.

These feeders are typically protected by IDMT overcurrent relays with IET standard inverse characteristics, and are likely to have an operating time of around 1s for faults at that location [8]. The currents going into the feeder were measured using a 400:1 CT, with the secondary measurements going into an overcurrent relay with a pickup current of 1.2 and a time multiplier setting of 0.42.

TABLE I
FAULT CURRENTS AND OVERCURRENT RELAY OPERATING TIMES FOR SFCL INSTALLATION ON 11KV FEEDER

	RMS fault current	Operating time
Without SFCL	13kA	0.97425s
With SFCL	8.4kA	1.09575s
Percentage Change	-35.5%	+11.1%

In order to see the effects of SFCL operation on the operating times of these relays, a study was carried out with the SFCL device installed on one such feeder, from Substation A. This limited the fault current by around 35%, which caused an 11% increase for the operation of the overcurrent relay, as seen in Table I. However, the operating time still remained approximately one second, and so the effect of the device may not be considered too disruptive to the protection operation.

B. SFCL installed on 33kV grid infeed

Another potential location for the device is on one of the two 33kV grid infeeds, which are the main sources of fault current for a fault at any location in this area of the network. Therefore, installing an SFCL here could potentially reduce fault current levels across a wider area than an installation at any other location possibly could.

Again, the 33kV network is typically protected by IDMT overcurrent relays with IET standard inverse characteristics, but with faster operating times than those seen at 11kV. The currents supplied by the infeeds were measured using an 800:1 CT, with the secondary measurements going into a relay with a pickup current of 0.7 and a time multiplier setting of 0.4.

The SFCL was set to limit the fault current at its position for a fault near to the device by 38%. At 33kV, it is even more critical that overcurrent relays quickly trip circuit breakers in the event of a fault. Before the SFCL was installed, the relay took 0.65s to operate for a fault near to the main 33kV busbar, which had an RMS value of 17.7kA. Of this, 8.6kA came from each of the grid infeeds.

Following installation of the SFCL, the current seen at the busbar for the same fault had been reduced to 13.5kA – a reduction of 24%. This was fed by an unchanged 8.8kA from the grid infeed with no SFCL installed, but a reduced 5.3kA from the SFCL infeed. Consequently, the overcurrent relay for the infeed without the device took the same 0.65s to operate, however the relay for the infeed with the SFCL took

TABLE II
FAULT CURRENTS AND OVERCURRENT RELAY OPERATING TIMES FOR SFCL INSTALLATION ON 33KV GRID INFEED FOR A 33KV FAULT

	Before SFCL Installation	After SFCL Installation	Percentage Change
Fault Current	17.7kA	13.5kA	-24%
Infeed without SFCL	8.6kA	8.6kA	none
Infeed with SFCL	8.6kA	5.3kA	-38%
SFCL infeed's relay operating time	0.65s	0.84s	+29%

0.84s – an increase of 29%. The results are summarised in Table II.

Even though the fault current in the network has been reduced, faults need to be dealt with as quickly as before. However, as discussed, reducing the fault current increases the operating time of the overcurrent relays in the system, and so faults stay on the network for longer. This can be particularly problematic for connected distributed generation, as slower protection operation may lead to exceeding critical fault clearance times which results in machine instability [9]. To mitigate this, the settings of the relays may need to be changed. Five separate fault locations in the network were tested to see how the overcurrent relay responded – the results of this can be seen in Fig. 2.

By adjusting the time multiplier setting on the relay, this disparity can be corrected. In this case, changing the time multiplier from 0.4 to 0.35 gave a characteristic that led to the relay operating at approximately the same speed for the same faults as it had before the SFCL device was installed. This is shown by the improved characteristic in Fig. 2.

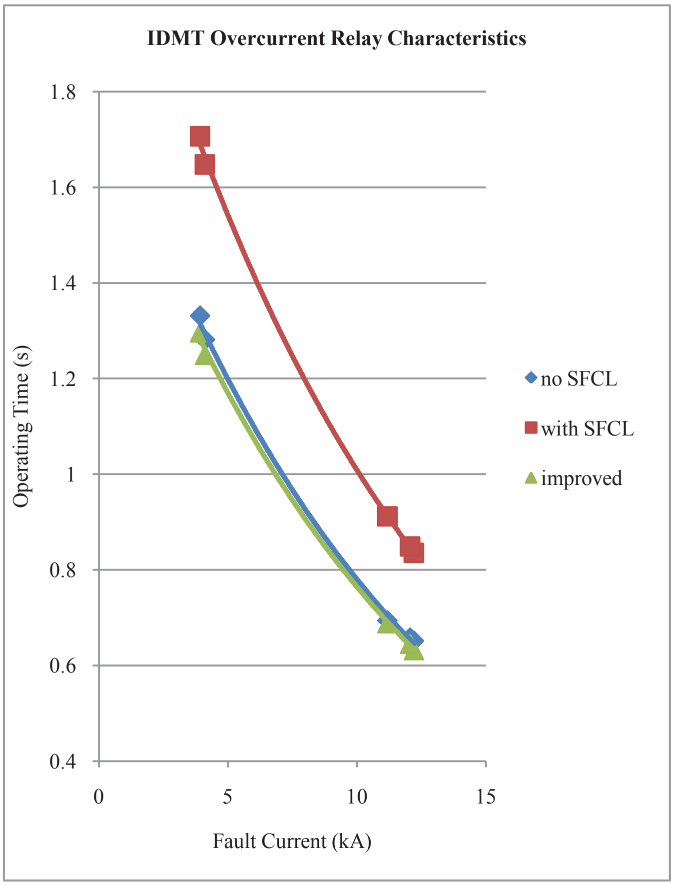

Fig. 2. Operating characteristics of the 33kV grid infeed IDMT overcurrent relay, with and without the SFCL, and with the improved Time Multiplier Setting

TABLE III
FAULT CURRENTS AND OVERCURRENT RELAY OPERATING TIMES FOR SFCL INSTALLATION ON A 33KV GRID INFEED AND AN 11KV FAULT

	Before SFCL installation	After SFCL installation	Percentage Change
Fault Current	14.7kA	13.3kA	-9.9%
Infeed without SFCL	2.6kA	3.1kA	+17%
Infeed with SFCL	2.6kA	2.0kA	-24%
Feeder's relay operating time	0.953s	0.972	+2%

As mentioned previously, placing the SFCL at the infeed allows it to reduce the magnitude of fault currents for faults in a larger area of the network. For a fault at the near end of one of the 11kV feeders at Substation A, the SFCL at the infeed reduces the fault current by 9.9% – from 14.7kA RMS to 13.3kA – with a 2% increase in operating time of the overcurrent relay on the feeder (as shown in Table III). This is due to the SFCL reducing the fault current contribution from the grid infeed with the SFCL by 24%. However, the current contribution from the infeed without the SFCL rose by 17% - from 2.6kA RMS to 3.1kA RMS.

IV. EFFECT ON THE SFCL OF NON-FAULT TRANSIENTS

During the 33kV overcurrent study, the issue of non-fault transients triggering the operation of the SFCL was raised. The fault current seen at the SFCLs position for the 11kV fault discussed above is of comparable magnitude to the start-up current of the wind farm. Consequently, if the SFCL is set to trigger for the 11kV fault, then it will also trigger for the start-up current of the wind farm.

If the SFCL falsely triggered during the wind farm start-up, the resistance of the SFCL would result in a voltage drop of 1kV across the device. Although this would be within the required voltage limits, it would still have knock-on effects downstream and could potentially result in undervoltages at the far end of network lines. It is likely that the wind farm will use soft or staggered start methods in order to reduce this initial current, in which case the issue may not be so problematic. Another possibility would be to remove the SFCL during the wind farm start-up, but this would make the network susceptible to the non-limited fault currents. If network plant can only cope with the limited current, then this could cause serious safety issues.

Alternatively, SFCLs have been installed in some networks specifically to limit non-fault transients [2]. If an SFCL were installed at the wind farm feeder, reducing the start-up current by 36% (from 4.84kA RMS to 3.1kA RMS), it would reduce the voltage drop seen during the wind farm's start up, and reduce the current surge seen by the rest of the network. However, the SFCL would have little impact on the fault current in the network. The initial peak of the fault current on the 33kV side only would be reduced by around 20%, but there would be no effect at all at 11kV or on the fault current to be cleared by the circuit breakers. This is because the fault contribution from the wind farm model was mainly sub-transient.

V. EFFECT OF SFCL ON DISTANCE RELAYS

A. Mho Characteristic Distance Protection

The simulations of distance protection were done using the mho characteristic, with the SFCL installed in position 3 as shown in Figure 1, which is on a 6119m length of 33kV cabling. The positive sequence impedance of the line that was used was 0.0656 + j0.0984 Ω/km [10]. This gave the relay setting impedance for 80% reach of the line as 0.3211 + j0.4817 Ω. The fault applied to the network was a three phase to ground fault.

Before the SFCL was incorporated into the network, the distance relay had an impedance reach of 88% of the line, which includes CT errors, hence protecting the line for faults up to 5400m. With the SFCL installed, the relay had only 58% reach, which corresponds to faults up to 3550m. This means that there is nearly a kilometre of the line where, if a fault were to occur, the relay would not immediately trip. This would make it dependent on backup protection, which is subject to an undesirable time delay.

As discussed previously, the SFCL works by inserting a resistance into the network. However, this also affects the impedance seen by the relay, causing it to incorrectly evaluate whether or not the fault has occurred within its area of protection. This is because the relay impedance setting is based on the impedance of the network without the SFCL device.

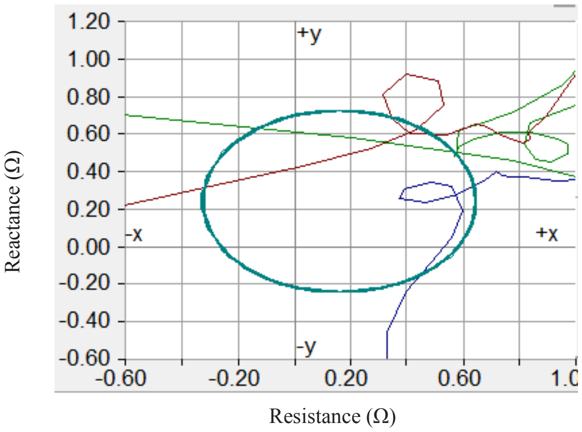

Fig. 3. Mho characteristic relay with a fault occurring at 58% of the line length, with the SFCL installed.

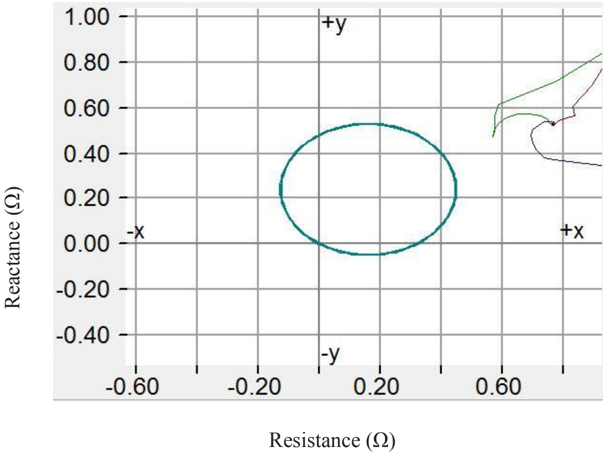

Fig. 4. Mho characteristic relay with a fault occurring at 88% of the line length, with the SFCL installed. The fault impedance is outwith the characteristic's trip area.

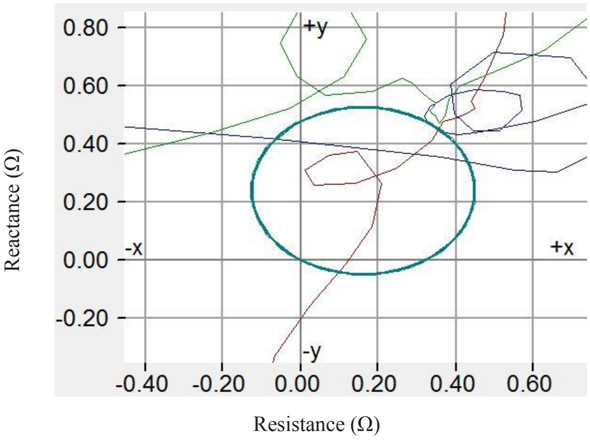

Fig. 5. Mho characteristic relay with a fault occurring at 88% of the line length, with the SFCL installed and the Time Multiplier Setting adjusted. The fault impedance is within the characteristic's trip area.

Fig. 3. and Fig. 4. show the mho characteristics of the distance relays, with the phase currents seen during the fault. It can be seen that at 88% the phase currents are far from being within the trip characteristic. The increased resistive component seen by the distance relay has moved the locus further along the resistive x axis.

For this 6119m length of line, the fault current at the far end of the line from the relay is still of sufficient magnitude to cause the SFCL to reach the same resistive value as for a fault at the near end. Consequently, by expanding the mho characteristic to compensate for this, the effect of the SFCL can be mitigated. The reach of the relay was increased to 90%, hence compensating the increase in resistance of 0.4Ω. The altered characteristic can be seen in Fig. 5.

For a longer line, the effect of the SFCL on the distance is less pronounced. Had this line been 5 times longer, then with the SFCL installed and no adjustments made to the standard characteristic, the distance relay would still have had a reach of 81% - which again is acceptable for zone 1 protection. For a very long line, where there is a considerable difference between the fault currents at the near and far ends, the mho characteristic will be harder to correct. This is because the resistance of the SFCL will vary for different possible fault positions.

B. Recommendation of SFCL installation

Based on the simulations that were carried out and the configuration of the network, there are two clear locations for SFCL installation, in order for the device to have a positive impact on the network. These locations are on an 11kV feeder from a substation, or at one of the grid infeeds. The 11kV feeder experienced very high fault current which would benefit from seeing substantial limitation, while the grid infeed allows the benefits of the SFCL to be seen over a wider area of the network. These locations would have more of an impact than having the SFCL installed in position 3. Also, having the SFCL installed on the wind farm feeder would have insufficient impact on fault currents in the network.

Installing the SFCL on an 11kV feeder would cause the least disruption, since the effect of the installation on protection schemes would be less pronounced, as shown by the overcurrent relay studies. Depending on the specific protection guidelines used by the DNO, the overcurrent relay settings may not need to be changed at all. Also, since this location had the highest fault currents, the reduction is potentially highest, meaning required plant ratings could be substantially less. There is some potential for conflict with recloser sequences, and so (again, for least disruption) a feeder without overhead lines would probably be preferable. Another potential location, which was not simulated during the studies, would be to have the SFCL installed between a 33-11kV transformers and the 11kV busbar inside one of the substations. This can have a wide reaching impact on the 11kV network downstream of the SFCL. Therefore a comprehensive study of this arrangement is required to quantify this impact. Furthermore, distributed generation installed on the LV network will need to be considered.

Installation of an SFCL would be more disruptive at the 33kV infeed, causing longer delays in operating times of the overcurrent relays. However, the potential benefits of having fault current limitation for the larger area of the network may make it worthwhile. Adjustments to the time multiplier settings, as outlined, could compensate for the delays, but it would likely be required that more complex simulations be carried out to establish how the coordination of protection schemes are affected. Additionally, there are more likely to be non-fault transients which may affect the device operation. Adaptive protection strategies could be employed in order to dynamically adjust and grade the overcurrent time multipliers based on the impact of SFCL on fault levels. Having the SFCL connected or bypassed can be simply reflected by two settings groups that provide standard grading or faster protection operation respectively.

Overall, installation of the device on an 11kV feeder is probably more suitable. In practical terms, it will be easier to arrange for it to be installed in the network. Devices for 11kV in the UK have been more widely developed and so the process for their design, installation and operation are generally more available. The SFCL will also, as discussed, have a substantial impact on the fault current of that feeder. Although at 33kV there could be fault current reduction for all the feeders, this may not be substantial enough to significantly affect the headroom for plant installed in the network. For maximum impact and usefulness, the SFCL should be (if possible) installed on the feeder with the highest fault current, or with plant operating at a high percentage of its rating.

VI. CONCLUSIONS

Superconducting Fault Current Limiters have an important role to play in distribution networks, as fault levels continue to rise due to the trend towards increased distributed generation, and load levels continue to grow. They provide a means of keeping the fault current to a level that the plant installed on the network can deal with, but it is important that their overall impact within a network is understood before they are widely deployed. The main aim of this paper was to understand the effect that the integration of an SFCL will have on existing distribution network protection relays.

A. Impact of the SFCL on IDMT Overcurrent Protection

The simulations carried out using the network and SFCL models showed that, as expected, by limiting the fault current the SFCL caused the operating time of overcurrent relays to increase. The impact was higher at 33kV than at 11kV – when installed on an 11kV feeder the SFCL was not too disruptive to the relay's operation, but when installed at the grid infeed the operating time increased by nearly a third. Further studies showed that the effect of the SFCL on any single relay could be mitigated by reducing the Time Multiplier Setting of the relay. However, this could potentially affect the coordination between overcurrent relays in the network, and so affect the operation of backup protection. Further studies will be needed to establish the extent of the impact that changing the relay settings would have on coordination.

B. Impact of the SFCL on Distance Protection

In addition to establishing how much the overcurrent relays were affected by the presence of the SFCL in the network, the simulations also showed how much distance relays were affected. As expected, the resistance of the SFCL affected the impedance seen by distance relays and so affected their operation. In this network, the impact that this had on the reach of the distance protection was substantial. With the mho characteristic distance relay, the reach reduced from 88% to 59%. It was also shown that the impact of the SFCL on the distance relay's operation decreased as the line length increased.

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