

Standardised Connections and the Economic Benefits of Fault Current Limiters on Distribution Networks

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ABSTRACT

This paper discusses the advantages of standardised connections of fault current limiters (FCL) on the 11kV distribution network and the economic benefits of these installations against traditional network solutions. This paper is based on learning to date from Western Power Distribution's (WPD) Tier-2 Low Carbon Networks (LCN) Fund [1] project, FlexDGrid, and other FCL installations.

INTRODUCTION

In order to meet UK and global targets for carbon emission reductions associated with energy production, the installation and connection of distributed generation (DG) onto distribution networks has significantly increased. As these DG units connect to the distribution network, they contribute fault level to the network, along with providing low carbon energy.

In some instances, fault level can be so high that it is above the rating of switchgear and cables. When this occurs, action must be taken to ensure the fault level is kept within these ratings, normally requiring the network to be run split, adding impedance into the network, or replacing the existing equipment with a higher rated equivalent. A new developing alternative to overcome excessive fault level is to install an FCL in the network.

This paper describes the methods taken to standardise the network connection of FCLs onto the 11kV distribution network, irrespective of limiting technology, including the switchgear and protection philosophy utilised. Investigation into the advantages of standardised connections of FCLs and their economic benefits over traditional solutions, to distribution network fault level issues, will be presented, along with the additional engineering benefits.

BACKGROUND

Fault level on distribution networks can often be high, close to the ratings of network connected equipment – commonly cables and switchgear. This is due to historic reasons such as location to large centralised generating plant, or the interconnection of EHV networks or low impedance transformers. A high fault level is often a good indicator of the strength of the distribution network, where there is low impedance between source and load.

These factors contribute towards desirable system voltage profiles and low magnitudes of voltage dips when system disturbances occur. They also have a beneficial influence on the speed of operation of protective devices under fault conditions [2]. However, due to network equipment such as switchgear and cables, which have a maximum fault level value they can withstand, the fault level value for each part of a network must be kept within equipment ratings. If the fault level on a system exceeds the ratings of any connected equipment, this can cause catastrophic failures leading to loss of customer power supplies and potential injury to the public and personnel.

In accordance with UK Government policy [3], a significant reduction in carbon emissions due to energy production is required. Therefore, this has led to a considerable increase in the connection of DG (such as renewable and combined heat and power [CHP]) to distribution networks. Often DG connecting to distribution networks is in the form of rotating plant, which provides its individual contribution, often significant, to the system fault level. If the system fault level is already high, then the introduction of DG can trigger the fault level of the system to be greater than the withstand capacity of the network's equipment.

Traditional solutions to manage the increase of fault level to within allowable limits can generally be categorised as splitting of the network, replacing existing transformers with higher impedance units, or replacing existing switchgear with a higher withstand rated equivalent. Splitting the network removes an existing parallel operation that performs the function of increasing the system impedance to reduce the fault level; however, it also significantly reduces the security and reliability of the network. Replacing transformers with higher impedance units results in an increased source impedance, meaning that the downstream fault level is reduced. The installation of switchgear with a higher withstand rating allows the fault level of the distribution network to further increase to the new switchgear's withstand rating.

New alternative solutions, in the form of FCLs, have been developed. The main FCL technologies are a Pre-Saturated Core FCL and a Resistive Superconducting FCL, along with other developing technologies such as Power Electronic devices. When connected to the distribution network, these devices, upon the inception of

a fault, limit the fault level meaning that additional DG can be connected to a system without the need to change or upgrade existing equipment. Four FCLs have been installed on the UK distribution network to date and at least five more are planned by 2017, as part of WPD's LCN Fund Tier-2 Project, FlexDGrid [4]. This is in addition to a number of units installed throughout Europe.

Costs for the traditional solutions are well understood, as they have been routinely deployed for decades on distribution networks. These costs are driven by the procurement and installation of the equipment (transformers or switchgear). However, costs for the procurement and installation of FCLs are less well understood, due to the limited number of previous installations and varying requirements for each site.

TRADITIONAL FAULT LEVEL SOLUTIONS

Three main solutions to manage system fault level are splitting the network, installing high impedance transformers and upgrading switchgear. Each solution successfully manages fault level; however, each solution has significant disadvantages in the form of network performance, cost or safety.

Splitting the Network

A common arrangement at a primary substation is to have two transformers and an 11kV switchboard, incorporating a bus-section circuit breaker, which enables the two transformers to be connected in parallel or not. For the instance where there is a fault level issue at a substation and the bus-section is closed (transformers connected in parallel), a solution is to open that bus-section circuit breaker; if the transformers and upstream network have the same impedance, this significantly increases the system impedance and reduces the fault level (up to 50% reduction). This action does significantly reduce the security of supply to customers as half of the substation's customers will now lose supply in the event of a transformer fault, where previously no customers would have been affected. In addition, splitting the network may result in uneven load distribution across the transformers and limit the ability to offer customers "firm" connections downstream of the primary substation.

High Impedance Transformers

By increasing the impedance of the system, the fault level can be reduced. This is typically achieved through the removal of existing transformers with higher impedance units. Equation 1 explains that increasing impedance from Z to Z' has the effect of reducing the current from I to I' . Typically, the reduction from I to I' is 15%, meaning that the change of transformers for higher impedance units facilitates a reduction in fault level of 15%.

$$I = \frac{V}{Z} \quad I' = \frac{V}{Z'} \quad (1)$$

An issue with this solution is that the existing transformers being removed are often wholly suitable for the network conditions in terms of health and power transfer availability, meaning an expensive asset is being made redundant and replacement is for fault level issues alone.

Upgrading Switchgear

A switchboard containing a number of panels of switchgear will have a specific fault current withstand rating. If this equipment is replaced, with equipment with a larger fault current withstand rating, then a significant increase in fault level can be achieved. Typically, legacy switchgear has a withstand rating of 250MVA (13.1kA); if this is replaced with equipment with a withstand rating of 475MVA (25kA), an increase of available fault level capacity released is 90%.

Key issues with upgrading switchgear are that although the main substation equipment has been upgraded to 475MVA, a large proportion of customers' equipment and other assets on the network will remain at 250MVA, where, for a fault, a catastrophic failure could be incurred during operation on this equipment. Another consideration with the upgrading of switchgear is that a significant proportion of cables connected to this new switchgear will need to be replaced to have the required fault current withstand capacity.

FCL OVERVIEWS

Three FCLs will be described that can provide fault level limitation of up to 50% of a distribution network's overall fault level.

Pre-Saturated Core (PSCFCL)

The principle of the pre-saturated core fault current limiter (PSCFCL) is based on the properties of transformer design. In this scenario, the primary winding (AC) of the FCL is placed in series with the network that requires fault level mitigation. The secondary winding is DC, where its sole purpose is to saturate the core of the PSCFCL. Under normal operation, the flux from the DC coil is far greater than that produced by the primary winding and thus the core becomes saturated and the insertion impedance is low. As current increases on the primary winding (such as in a fault situation), the opposing flux increases resulting in the core being taken out of saturation and subsequently the PSCFCL creating a high insertion impedance. The PSCFCL is fail-safe as the DC coil is required to keep the core in saturation in normal operation. Should the DC coil fail (or its controller fail), the core will automatically come out of saturation and the PSCFCL insertion impedance will be high, thus providing fault limitation.

Resistive Superconducting (RSFCL)

The resistive superconducting fault current limiter (RSFCL) uses the inherent properties of a superconductor to provide high insertion impedance during fault situations, to limit the flow of fault current. The RSFCL is designed to be inserted in series with the network. During normal operation the RSFCL operates below the critical temperature in the superconducting region with very low losses. Thus, the RSFCL should be designed to ensure that the superconducting region falls within the continuous current rating of the equipment with which it is being inserted in series. As current increases in the RSFCL, there is a subsequent rise in conductor temperature. When the temperature increases above the critical temperature, the RSFCL begins to operate in the normal operating region to provide high insertion impedance. In the superconducting state, the RSFCL requires constant cooling to ensure that the conductor operates below the critical temperature. Whilst transitioning from superconducting to normal conducting modes, the RSFCL temperature greatly increases and requires the current to be diverted / blocked after around 80 milliseconds (although the precise time is dependent on the design of the superconductor) to ensure the device does not overheat. In all instances the device can be said to be fail-safe, as the superconducting properties will provide high insertion impedance or create an open circuit during a fault event.

Power Electronic (PEFCL)

The power electronic fault current limiter (PEFCL) works on the same basis as a circuit breaker with the main difference being that the device is extremely quick to operate (less than 10ms). Unlike the RSFCL and the PSCFCL, the PEFCL does not insert impedance into the network, instead the fault current path is severed, and therefore the fault reduction is much higher compared with the other FCL devices. In addition, being a switching device the PEFCL can be controlled to reduce fault current at different magnitudes unlike the other devices which have a fixed level of reduction. The losses associated with the PEFCL are dependent on the amount of cooling required for the switching devices. As more current is driven through the PEFCL, the greater the amount of heat losses, which in turn requires more cooling. With the PEFCL comprising a number of different power electronic components, the footprint is generally smaller than other FCLs and the general arrangement can be tailored to suit particular installation requirements. The power electronic switching devices used in the PEFCL are controlled in such a way that failure of one or more components will result in the devices opening. As such, the PEFCL is fail-safe during operation.

Device Costs

As the FCL market is still in its infancy the exact cost of devices is not readily available. However, Ofgem has awarded Western Power Distribution, through the LCN Fund, £5.83m for five FCLs [4], making the average cost of a single FCL currently £1.17m.

STANDARDISED CONNECTIONS OF FCLS

In order for a device on a distribution network to be adopted by asset owners for operation, there must be a standardised and agreed process of connection. Through the work carried out as part of WPD's LCN Fund Tier-2 Project, FlexDGrid, this work has been appreciably advanced. This is in the form of the design for the integration of five FCL technologies onto the 11kV distribution network in Birmingham, England. The five FCL devices consist of one PSCFCL, two RSFCLs and two PEFCLs. In order to provide a standardised connection, the two main considerations are the switchgear requirements and the protection philosophy to be employed.

Protection Requirements

Similar to other critical plant installed on the distribution network, it is necessary to protect the FCL using independent 'Main' and 'Back-up' schemes.

For all devices described above, the voltage and current on each side of the specific FCL device should be equal under normal, non-fault, operation. However under an internal fault condition, the voltage and current on each side could be hugely different. Therefore the most suitable type of main protection for each FCL is differential (unit) protection, whether it is voltage or current, dependant on the specific system requirements.

A requirement of the differential protection is to ensure that an offset of the protection is provided to enable the FCL to instigate the limitation of fault current under operation. However, as this is less than 10ms for all devices concerned, it is unlikely to be an issue in practice.

As mentioned above, a standard overcurrent and earth fault protection scheme is required to act as back-up for the instance of a non-operation of the differential protection.

Both these protection requirements are standard throughout 11kV network design and as such significantly reduce the potential complexity and cost of protecting an FCL.

Switchgear Requirements

The requirement of the switchgear, for the installation of an FCL, is to ensure that as a minimum it matches the current carrying and fault current withstand capacity of the existing switchgear at the site concerned and has the required measurement equipment to facilitate the necessary protection philosophy.

DNOs and asset owners generally have standard switchgear (circuit breakers) that is utilised on their networks, typically produced by two or more manufacturers, and have standard equipment arrangements for scenarios such as transformer incomers and network feeders. As part of FlexDGrid, an aim was to take the design of an FCL from a unique, bespoke, installation to a standardised approach, as far as practicable. As such, following the identification of the protection requirements, a standard switchgear arrangement was required. In order to facilitate the provision of either voltage or current differential protection, voltage transformers (VT) and appropriate current transformers (CT) are required. Utilising Western Power Distribution's suite of standard 11kV switchgear configurations, it was identified that a standard 11kV transformer incomer circuit breaker had these protection facilities as standard. The advantage of an 11kV transformer incomer is that its rating can be prescribed to match that of the busbar ratings, as required for all FCL installation in order to ensure that the FCL is not the limiting factor on the current carrying capacity of the existing switchgear arrangement.

The use of a standard piece of equipment (the transformer incomer with VTs and CTs is common to most if not all distribution network operators) means that a cost for the installation and connection of the FCL can be well understood and projected forward for the use of an FCL as a standard network asset.

COMPARISON OF SOLUTIONS

Using an average cost of £1.17m for an FCL and taking further data from the allowances associated with the FlexDGrid, an average installation cost of each FCL is £237.4k; this figure includes required switchgear, protection and civil requirements, along with the labour to facilitate the construction. This means that for the installation of a single FCL the complete cost is £1.41m.

In order to allow a comparison of benefit in terms of released fault level headroom by a chosen solution, a calculation of fault level reduction for an FCL is required. A typical requirement is to allow an additional amount of generation to connect to the distribution network that is 10% of a substation's firm load capacity, i.e. a substation with a load firm capacity of 80MVA would need to be able to accept an additional 8MW of generation. It is to

be noted that this is, for every case, with the system operating in parallel, irrespective of whether it was prior to the installation of an FCL.

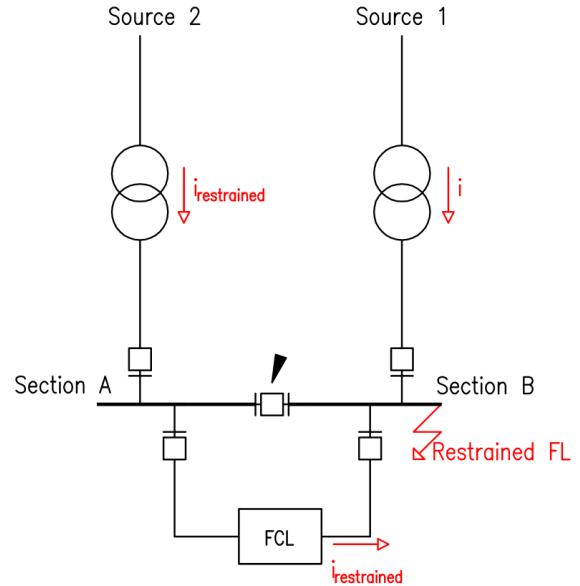


Figure 1: Typical FCL Installation

Using the network identified in Figure 1 the calculation methodology for fault level reduction is [5]:

$$FL_{MAX} = FL_{S1} + FL_{S2} \quad (2)$$

$$FL_{GEN} = K \times (P_{FIRM} \times 0.1) \quad (3)$$

$$FL_{REST} = FL_{SGRATING} - FL_{GEN} \quad (4)$$

$$FL_{REDFLOW} = \left(1 - \left[\frac{FL_{REST} - FL_{S1}}{FL_{S2}}\right]\right) \times 100\% \quad (5)$$

$$FL_{REDTOTAL} = \left(1 - \left[\frac{FL_{REST}}{FL_{MAX}}\right]\right) \times 100\% \quad (6)$$

$FL_{REDTOTAL}$ in Equation 6 is the total reduction in fault level at the substation. For the five selected sites as part of FlexDGrid this value, as an average, is 30%.

FCL versus Splitting the Network

Splitting the network has no capital cost impact to the network as the action is to open a previously closed bus-section circuit breaker. Therefore the cost of an FCL installation is £1.41m greater than this solution.

Operating costs in the form of charges for interrupting customers' supplies (CI) and the number of minutes a customer is without supply (CML), should be considered as they can be considerable: in the region of £44k for three minutes. This is based on the FlexDGrid project area, which on average has 18,000 customers per

substation, therefore affecting 9,000 customers in this instance. In addition, splitting the network is likely to result in uneven loading on the 11kV busbars which could limit firm capacity and accelerate transformer ageing. Also, the DNO would not be able to offer a firm connection (automatic N-1) to downstream customers.

FCL versus Higher Impedance Transformers

Replacing existing transformers at a 132/11kV substation with higher impedance units typically facilitates 15% fault level headroom and costs £1.87m [6]. The installation of an FCL whilst providing an initial financial saving of £460k also facilitates an additional 15% of fault level headroom (30% in total). This value for a substation with a firm capacity of 78MVA could mean an additional 4.2MW of generation [7]. This equates to a saving of 574T of CO_{2e} if the generation is a CHP unit [4].

Other factors to consider are that the replacement of transformers necessitates the removal of otherwise healthy and suitable assets to remedy the existing fault level issues, and the substantial risks associated with outages for removing and replacing transformers.

FCL versus Upgrading Switchgear

In order to replace legacy switchgear with new, higher withstand rated switchgear (additional 225MVA), at an average primary substation (city centre location) the cost is in the region of £870k [4], based on a 19-feeder substation. This value is associated only with the replacement of the equipment located within the substation. In order to minimise any safety-related issues with overstressing, in terms of fault level, there is a need to not only replace the switchgear connected to the primary substation, but also remote to it, along with a length of cable per feeder to ensure that its rating is satisfactorily matched to the new switchgear. On average, the downstream reinforcement work would cost in excess of £8.5m per substation [4].

The cost saving through installing an FCL rather than upgrading the switchgear is around £8m, which is significant. Notwithstanding cost comparison to that of an FCL installation, carrying out the switchgear replacement is not financially viable.

CONCLUSION

Traditional solutions are well understood and the cost of these solutions is unlikely to reduce, due to the technologies and methodologies being well established. However, FCL technologies are still significantly developing and the cost of FCLs is likely to reduce by 12% over the next five years [8], meaning that they will become even more cost competitive. The cost of previous FCL installations have been far in excess of the costs discussed in this paper, where previous FCL installation projects have been in the region of £4m, including

product development [9]. Some savings are in relation to the maturity of the FCL market; however, a significant proportion of the savings has transpired from the standardisation of the connection and protection of FCL connections.

The work presented is a considerable step towards the installation of FCLs being considered a feasible and cost-effective solution to the problem of fault level issues on a distribution network. Further work is required to fully demonstrate the connection and protection methodologies proposed and for FCL manufacturers to continue work on reducing the cost of FCL devices whilst increasing the performance of the technology.

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