SENSITIVITY ANALYSIS OF FAULT LEVEL ASSESSMENTS IN HV NETWORKS

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ABSTRACT

In this paper, the effects of the accuracy of HV network parameters on calculated make and break fault levels are investigated. Fault level calculations, using computer models, are an approximation to the behaviour of the actual distribution network and, due to assumed parameter values, include a level of inaccuracy. The results of the fault level sensitivity analysis studies show that the network parameters which have a greater impact on pre-fault voltage levels need to be modelled more accurately. In addition, the fault level sensitivity to general load fault in-feed assumptions given in engineering recommendations is studied. Based on the sensitivity analysis results, recommendations for modelling the HV networks and architecture of a fault level active management system are proposed.

INTRODUCTION

Growing connections of low-carbon generation to urban distribution networks can increase the fault level of the network, requiring upgrades to electricity network assets. Network upgrades can be prohibitively expensive or entail a long lead time, which can affect the timely connection of distributed generators into the network. The UK aims to have 30% of its electricity provided by renewable sources by 2020 [1]. Birmingham Central Business District (CBD), in the UK, has been identified as an area where a high level of integration of combined heat and power (CHP) plants is expected in HV networks[1] by 2026. As a result of the anticipated level of CHP integration, the fault levels in HV networks could exceed the short circuit ratings of the switchgear. Smart solutions are being demonstrated, as an alternative to traditional network upgrade solutions, in a £17.1m Low Carbon Networks Fund project in the UK, FlexDGrid [2]. FlexDGrid aims to enhance fault level modelling and calculation processes, demonstrating different fault level mitigation technologies in existing primary substations (132kV/11kV) in Birmingham. FlexDGrid will propose the solutions which will defer network reinforcement, unlocking capacity for low carbon technologies (such as CHP plants) to be integrated into HV networks.

As part of the enhanced fault level assessment process within FlexDGrid, the assumptions that underpin fault level calculations were explored and a questionnaire was conducted to understand the consistency of application of fault level calculation standards amongst distribution network operators (DNOs) in the UK [3]. The outputs of these questionnaires supported the need to understand the sensitivity of calculated fault levels to different parameters of an electricity network model, as well as the assumptions considered in standards and engineering recommendations.

Engineering Recommendation (ER) G74 [4] is used by UK DNOs to implement fault level calculations based on the IEC 60909 standard [5]. When implementing ER G74, the pre-fault voltage conditions of the network are determined through a load flow simulation. Fault levels are more sensitive to those parameters which have a greater impact on the calculated pre-fault voltage levels. The operating condition of the generators, tap changer position, network impedance and estimated load demand are among those parameters that may affect the pre-fault voltage levels.

The sensitivity analysis methodology has been implemented on sample HV feeders in Birmingham's CBD. The model parameters are varied within defined ranges and the sensitivity of the calculated fault levels (Making and Breaking) is calculated for each model parameter input to the ER G74 fault level calculation process. The main applications for fault level sensitivity analysis are:

- Identifying the parameters of the network model which need to be measured with precision and estimated with a high level of accuracy;
- Determining the effect of assumptions recommended in ER G74 on calculated fault levels, and identifying any areas of review required in ER G74.

1 The high voltage (HV) network refers to the 11kV network.

- Developing recommendations on network operation schemes and commercial frameworks which result in a reduction in the fault levels on 11 kV networks and facilitate the increased integration of distributed generators; and
- Improving the accuracy of desktop analysis through the adjustment of model parameters which have a high impact on fault level. This application is important for the validation of monitored fault level values.

The remainder of this paper is organized as follows. First, a review of the assumptions and process for fault level calculation using a computer model is presented, along with the assumptions recommended in ER G74. Next, the methodology used for fault level sensitivity analysis is presented. Following this, the results of sensitivity analysis are presented and discussed. A possible architecture for an active network management system is discussed and finally, concluding remarks and recommendations are presented.

COMPUTATIONAL ANALYSIS OF FAULT LEVEL

The fault level assessment is usually carried out using a computer model of the electricity network. A key learning point from the UK DNOs survey was that, for HV network fault assessments, only the HV network is modelled in detail and equivalent models are used for downstream (LV) and upstream networks (EHV). The computer models represent a snapshot of the network conditions for the worst case (highest) fault levels.

IEC 60609 is widely utilised for fault level calculations by DNO and Transmission network operators companies. Engineering Recommendation (ER) G74 is used by UK DNOs to implement the IEC 60909 standard for desktop fault level calculations. One of the differences between ER G74 and IEC 60609 is the pre-fault voltage conditions assumed for fault level calculation. IEC 60609 recommends a conservative approach using ‘C factor’ multipliers, which create artificially high network voltage levels for fault current calculation, whereas ER G74 utilises the calculated pre-fault voltage levels from a power flow analysis.

The pre-fault voltage levels are affected by the model parameters of the network. Every component of the computer model has associated bands of accuracy. The degree to which the components’ values can vary affects the pre-fault voltage levels and consequently the calculated fault levels. In this paper the following network parameters and assumptions which can have a high impact on voltage levels and fault levels are considered:

- Generators’ operating power factor
- Circuit impedance
- Tap changer position
- General load fault in-feed
- Demand

Network model parameters

Generator power factor

The power factor at which a generator operates has an impact on the fault current contribution of that generator. The internal voltage and the impedance (sub-transient/transient) of a generator determine the fault current contribution from the generator. The generator’s internal voltage, however, has a vector relationship with the pre-fault voltage at the connection point and the pre-fault generator output current. Figure 1 shows a Thevenin model of a single generator connected to the network. In Figure 1, V_s is the internal voltage, X_s is the synchronous impedance, V_T is the voltage at the generator’s connection point to the network and I_G is the output current of the generator. The vector relationships between these variables, when the generator operates in different power factors, are shown in Figure 2. The magnitude of the generator’s internal voltage is greater than the voltage at the connection point when a generator operates in lagging and unity power factor, whereas in leading power factor the internal voltage is lower than the network’s voltage.

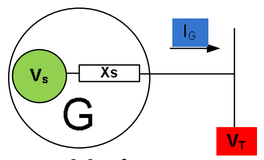

Figure 1: Thevenin model of a generator connected to the network

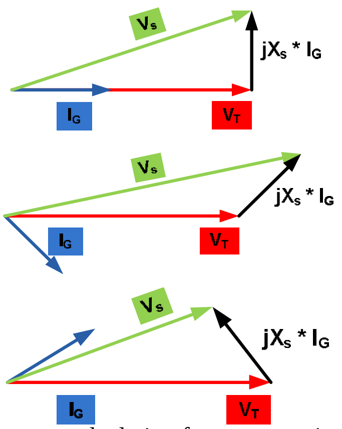

Figure 2: The vector calculation for generator internal voltage when it operates at (from top to bottom) Unity power factor, Lagging power factor, and Leading power factor

It should be noted that the generator operation power factor can affect the network voltage (V_T), however, network voltage depends on the operating conditions of all network components. Therefore, in a real system, different operating power factors versus different network voltages can be envisaged.

Figure 3 shows the variation in initial rms fault current contribution for a 1 p.u. rated output generator when it operates at different network voltage levels and power factors.

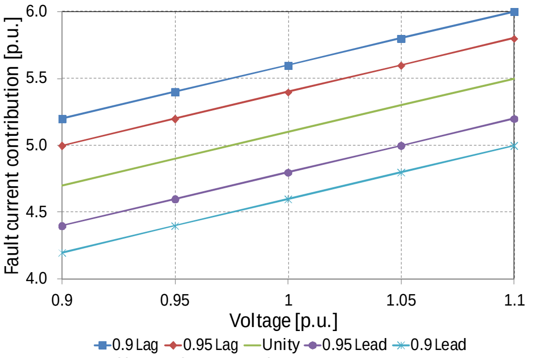

Figure 3: The effect of power factor on generator initial rms fault in-feed (The sub-transient reactance of the generator is assumed to be 0.20 pu)

Circuit impedance

The circuit length or impedance of a network model has sources of uncertainty, resulting in levels of inaccuracy. This inaccuracy can stem from:

- Ageing effects of conductor on the actual circuit length and the conductor electrical parameters (e.g. resistance and reactance);
- Inaccurate estimated lengths of conductor for each circuit section (line sag and the terrain slopes in the trajectory of cables may be neglected);
- Assumed types of conductors, which may be incorrect (when conductor type records for part of a network are missing or conductor databases are not accurately maintained).
- Assumed resistance; whether “cold DC” or “hot AC”.

Tap Changer Positions at primary substation

Transformer tapping is a regular operational exercise to maintain the voltage profile on the network within the acceptable limits. The position of the tap at the upstream substations can alter the voltage profile of the network and consequently the fault current contributions. The actual position of the tap changer, when a fault occurs in the network, may differ significantly from the modelled position. The impedance of the transformer may also change for different tap positions.

General load fault in-feed

The load demand on the network consists of rotating machines which can contribute to fault level. Modelling all the rotating machines is difficult and time consuming. ER G74 states “where measured values are not available, the following indicative allowances can be used for calculating the initial three-phase symmetrical RMS short-circuit current contribution at a 33kV busbar from the asynchronous motors in the general load supplied from that busbar: For load connected to the supply network at (i) low voltage, allow 1.0 MVA per MVA of aggregate low voltage network substation winter demand; (ii) high voltage allow 2.6 MVA per MVA of aggregate winter demand. These contributions relate to a complete loss of supply voltage to the motors.”.. This assumption may need to be revisited due to variations in load composition since 1992 when ER G74 was first published. It is also not clear how the general load fault contribution would differ when alternative voltage levels are considered (for example at 11kV and 6.6kV).

Demand

The calculated voltage profile can be affected by the magnitude of the estimated demand in a network model. For the purpose of network studies in extreme conditions, the maximum or minimum aggregated load is usually estimated and modeled at the distribution (HV/LV) substation. The accuracy of the estimated load may be affected due to lack of information and recorded loadings of distribution substations. In addition, It is important that the demand accurately reflects true demand, not merely “demand - embedded generation”. It is expected that some degree of inaccuracy in calculated voltage profile and fault level stems from the inaccuracy in estimated demand.

METHODOLOGY

An electricity network computer model represents a snapshot of the network operational conditions. If the network model parameters are changed from their original values, the model representation will deviate from the original operational condition. For the purpose of the sensitivity analysis, a PSS/E model of a sample network, representing part of Birmingham’s 11kV network, has been considered, as given in Figure 4. Feeder A and Feeder B represent a long feeder and a short feeder respectively. These feeders are supplied by an upstream 132/11kV primary transformer. Four generators with a total capacity of 4.6 MVA and stochastic connection points are assumed in the sample model. All generators are operating at 0.415kV (at unity power factor) and are connected to the 11kV network with 11/0.415kV transformers. The total demand supplied through feeder A and feeder B is 4.74 MVA and 1.56 MVA respectively.

The parameters of the sample model have been varied within an assumed range to create different network conditions scenarios. The corresponding fault current contributions to the 11kV busbar at the primary substation, point M1 in Figure 4, are calculated for each scenario. The results are then compared with calculated fault contributions from the original model to understand the impact of each network parameter on the fault level. The variation ranges of the network parameters are as follows:

Generation power factor (PF): Unity, 0.95 leading, 0.95 lagging
Circuit impedance: 5% to + 5% from original value
Tap position at Primary Substation: Voltage at 11 kV busbar changes between 0.95 per unit to 1.03 per unit
General load fault in-feed: 0 to 2 MVA per MVA of load
Demand: 10% to + 10% from original value

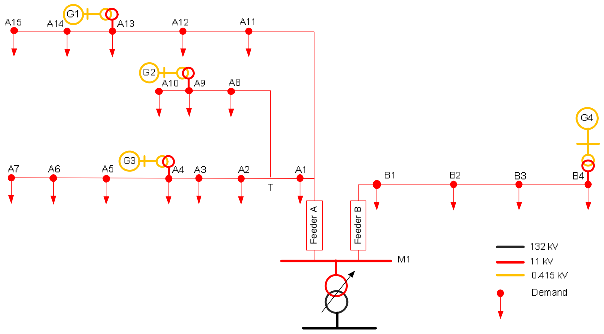

Figure 4: The sample model representing a short and a long feeder

Part of the general load consists of asynchronous machines which contribute to the fault level (both Peak Make and, potentially, rms Break). According to ER G74, the initial rms fault contribution from the general load connected to the low voltage network is around 1 MVA per 1 MVA of load when aggregated at 33kV. In a computer model, the fault contribution from general load is usually modelled with an equivalent generator at the 33kV or 11kV points where the aggregate load is connected. For the purposes of this study, 1 MVA per MVA of load has been applied at 11kV using an X/R ratio of 2.76.

RESULTS AND DISCUSSION

The fault level sensitivity analysis shows that different parameters of the network model have different effects on the making and breaking fault currents. Figure 5 summarises the results of the sensitivity analysis and shows the average variations in the fault current contributions from the HV network to busbar M1, the 11kV busbar at the primary substation, against different model parameters of the sample network.

The results of the sensitivity analysis show that the generation power factor has the largest effect on the fault current, the Peak Make and rms Break fault current change by around 7% when the generator's power factor changes from unity to 0.95 lead. In addition, the analysis shows that demand can have the lowest impact, less than 1%, on both breaking and making fault current.

Demand variation affects the network voltage profile and general load fault in-feed. These two have opposite effects on fault levels. Increasing demand may result in lower voltage profiles along the network and consequently a lower fault current. However, the general load fault in-feed (1 MVA fault contribution for every 1 MVA load) increases if demand increases.

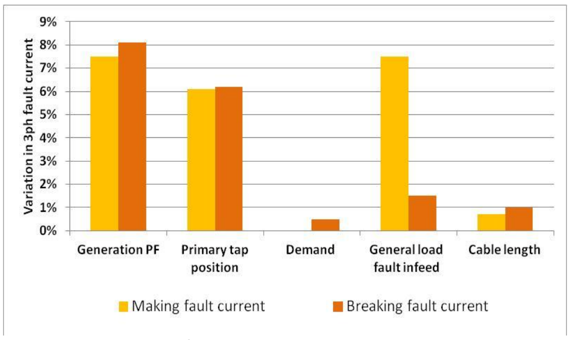

Figure 5: Summary of sensitivity analysis results

ACTIVE FAULT LEVEL NETWORK MANAGEMENT APPLICATION

Fault level monitoring in conjunction with a "connect and manage" scheme is one of the solutions to expedite the connection of flexible customers (for example, distributed generators) and defer network asset upgrades. For the purpose of active fault level management, under a "connect and manage" scheme the flexible customers can be disconnected when the monitored fault level at the upstream substation is close to exceeding the fault level limits. In a more flexible scheme, based on what was learnt from sensitivity analysis, the operating power factor of the generator as well as upstream transformer tap position can be controlled to reduce the fault level rather than disconnecting the customer as the first action.

The architecture of a closed-loop active fault level management system is shown in Figure 6. The fault level monitoring (FLM) technology informs the active network management (ANM) system about the fault level at the primary substation. If the fault level exceeds a pre-set limit, control commands are communicated to the distributed generators to operate in leading power factor.

In addition, as a primary action, by controlling the tap position at the primary substation, the voltage across the 11kV network can be reduced. Voltage regulation at primary substations is also being trialled as a solution to demand control [6], but it has rarely been used in ANM systems for the purposes of the fault level management.

It should be noted that in some networks there is not enough room for voltage control corrective actions because of the voltage limits in the LV network. In addition, voltage stability issues may arise due to operating generators in leading power factor. These issues can be controlled by defining permissible voltage limits at the primary substation and other parts of network. The voltage and currents at different points of the 11kV network will be also monitored to ensure they do not exceed the statutory limits. As an ultimate solution to fault level control the distributed generators can be tripped if using corrective actions (transformer tapping or generation power factor control) may results in any voltage or thermal rating violation.

Further work is in progress within FlexDGrid to develop a commercial framework based on the learning from the sensitivity analysis, active fault level monitoring and other UK DNOs' experience in deploying "connect and manage" schemes.

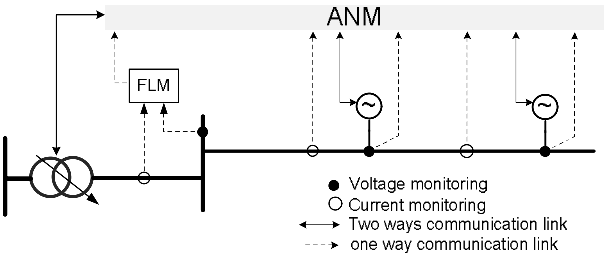

Figure 6: Architecture of an active fault level management system

CONCLUSION AND RECOMMENDATIONS

Fault level calculations, using computer models, are an approximation to the behaviour of the actual distribution network and, due to assumed parameter values, include a level of inaccuracy. The impacts of inaccuracy in network model parameters, on the calculated fault level in HV networks, were studied in this paper. The results showed that generation power factor and tap position of the transformer can have a large effect on voltage profile and, consequently, the calculated fault level. Based on the sensitivity analysis, the following recommendations may be considered.

1. It is recommended that a detailed model of the HV network is used for generation connection studies. This allows pre-fault voltage conditions to be calculated more accurately, resulting in more accurate calculated fault levels. Using equivalent network models is likely to result in a higher calculated fault level;

2. In order to calculate fault currents as accurately as possible, it is recommended that a generator's model represents the actual power factor at which it is set to operate. Nonetheless, for worst case fault level calculation, it is recommended that generators are modeled in unity power factor;

3. The tap position at Primary Substations has a large effect on the calculated fault currents. It is recommended that care should be taken to model the tap at the position which results in a network voltage profile representing the system condition in real-life; and

4. General load has a effect on the making fault current. It is recommended that large synchronous and asynchronous motors (or large concentrations of such motors) are modelled if possible. It is also recommended that work is carried out to understand the load mix and appliances used by low voltage connected customers. The ER G74 recommendation on general load fault in-feed may need to be reviewed.

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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%.

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

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 uprated 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.

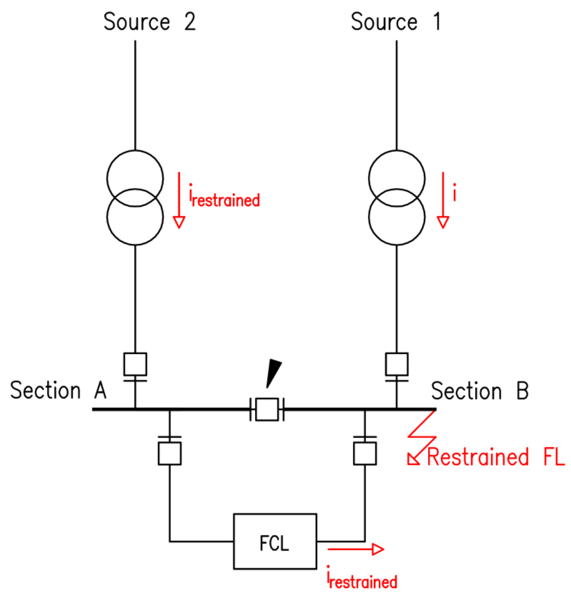

Figure 1: Typical FCL Installation

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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USE OF REAL-TIME FAULT LEVEL VALUES TO GENERATE AN MVA PER MVA INFEED TEMPLATE FOR 11KV DISTRIBUTION NETWORKS

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ABSTRACT

This paper discusses the process of generating and the advantages of utilising real-time fault level values to produce MVA per MVA general load fault infeed templates for 11kV distribution network modelling. This paper is based on learning to date from Western Power Distribution's (WPD) Tier-2 Low Carbon Networks (LCN) Fund [1] project, FlexDGrid.

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.

A key element of determining the connection point and accessibility of the network for new DG to be connected is power system analysis modelling. Fault level for the connection of all new DG is a key consideration and therefore must be modelled accurately. The accuracy of the distribution networks' model is paramount in determining the change in fault level borne by the connection of additional DG in the system. DG is modelled accurately, through the provision of generator specific details in relation to sub-transient, transient and steady-state condition; however, the general load contribution to fault level is commonly modelled through one of two pre-evaluated contributions as determined in G74 [2].

This paper describes the process taken to generate site specific 11kV MVA per MVA general load fault level infeed values. This work is designed to provide greater granularity and accuracy of 11kV fault level data to more accurately assess the network for operational and safety requirements. The aim of the learning is to investigate the use of real-time fault level values to generate an MVA per MVA infeed template for 11kV distribution networks.

BACKGROUND

Fault level is generally considered to be an indicator as to the system strength of a network. Traditionally this has led to the desire for a large system fault level, which can safely operate protection and supress the effect of system harmonics. However, as the level of DG connecting to a distribution network increases, at all voltage levels but particularly at 11kV, fault level issues, where the connection of the DG increases the system fault level, become a significant barrier to connection.

Network fault levels are most commonly modelled using a power system analysis tool, examples of which are PSS/E, IPSA and DigSilent. Whilst generators are accurately modelled using their specific electrical properties, due to the vast and varying types of load connection on network substations a generic approach to modelling has been considered. Guidance is given in such documentation as G74 as to the values to be used to model the load connected to a substation, however, this is generally split by the voltage level at which it is connected.

As the availability to gather more sophisticated network data, such as real-time fault level values [3] and more specific load type characteristics the opportunity to further understand the contribution to fault level of general network load increases.

TRADITIONAL MODELLING METHODOLOGY

Network models are used by Distribution Network Operators (DNO) for system planning purposes and to analyse the impact of changes in network configuration and new connections. The information gathered can then be used to determine suitable network reinforcement requirements and operational restrictions. Over time, the accuracy and detail contained within the models has improved and increased, enabling additional confidence in the results produced and reducing required safety margins. In the UK, DNO models for the 11kV High Voltage (HV) network are traditionally maintained and run separately from the Extra High Voltage (EHV) network models. This is due to the complexity and size of the complete 11kV network having a potentially negative impact when running EHV system studies, due to increased computational time and potential for errors. In the majority of cases, this has led to the 11kV and Low Voltage (LV) models being created in a different software package to the EHV models.

In order to represent the HV and LV networks in the EHV models, an equivalent load and generator are created using information from the HV network model. These are placed on the Primary substation busbar that acts as the infinite source in the HV models. Typically, any large generation connected to the Primary substation via a dedicated feeder is also independently modelled.

Using the EHV network models, system fault levels are calculated based on the recommendations of G74. Section 9.5.1 of G74 states; for low voltage networks allow 1.0 MVA per MVA of aggregate low voltage network substation winter demand and for high voltage connected load 2.6 MVA. To complete network fault studies these values are applied to the whole substation load irrespective of load type.

FlexDGrid Method Alpha

As part of the Enhanced Fault Level Assessment (EFLA) process developed within FlexDGrid's Method Alpha, 11kV network models for each primary substation, within the project area, were created for inclusion within the existing EHV model. This allows for greater accuracy when assessing the impact on the 11kV network and the loads connected to it when modelling fault levels.

Each substation model accumulated network data from all available sources including installation and maintenance records, to ensure that the models were as close as reasonably practicable to the actual network conditions. The size of each LV load connected to the network was then estimated by either the installed transformer rating or the agreed supply capacity. A distribution factor was then applied to each one so that the total substation load was equal to the winter maximum demand, as per current WPD planning philosophy.

FAULT LEVEL MONITORING

FlexDGrid Method Beta

The aim of FlexDGrid's Method Beta was to install ten Active Fault Level Monitor (AFLM) devices throughout the project area. The AFLM is designed to place a non-customer affecting disturbance on the 11kV network with monitoring hardware within the device recording waveform disturbances of both the current and voltage [3]. During the open loop testing of the AFLM throughout 2015, a decision was made to operate all the devices every six hours to enable the device to provide a representative spread of fault level data for differing system load conditions.

Monitored Data

Using the recorded disturbances, the AFLM calculates the 10ms peak fault level and the 90ms RMS fault level at its point of connection. All the AFLM devices installed as part of Method Beta were connected to a section of the Primary 11kV busbar within the substation, producing results for the 11kV Primary substation fault level.

The fault level results along with the steady state current and voltage at the time of the AFLM operation are collected and processed. As part of this processing, the network topology is determined and results categorised accordingly. All the data is then amalgamated and averaged over various time periods in order to understand, at this stage, the general trend in MVA per MVA at each 11kV Primary substation over time.

MVA PER MVA CALCULATION

To calculate the 11kV MVA per MVA general load infeed value at each substation the EFLA network model was utilised. Steady state data collected by the AFLM was inserted into the network model and used to manipulate the model to replicate the general site condition over the specific time period being considered. This was completed by then fixing transformer set point voltages and scaling all 11kV loads using the distribution factors utilised during the development of the EFLA model.

Using the enhanced model, a G74 Fault Level calculation for the AFLM point of connection was carried out. With each calculation, the MVA per MVA general load infeed value for the 11kV load was refined until the calculated fault level closely matched the AFLM recorded value.

DATA ANALYSIS

Substation Load Distribution

The load at each substation was analysed and split into three categories based on available metering data. These were Domestic, Small Commercial and Industrial and Large Commercial and Industrial. The table below shows the percentage breakdown of customer types for each of the ten Primary substations.

Substation	% of Substation Load		
	Domestic	Small Commercial /Industrial	Large Commercial /Industrial
ELMD	7%	7%	86%
CHES	20%	19%	61%
CASB	24%	10%	66%
BOVI	32%	14%	54%
NECW	35%	24%	41%
KITG	52%	14%	33%
HALG	57%	19%	23%
CHAV	60%	24%	16%
SHIR	61%	25%	13%
BARG	66%	12%	22%

Table 1 - 11kV Substation Load Type

MVA per MVA Results

The average MVA per MVA general load infeed result for each 11kV Primary substation based on its percentage of domestic load is shown in Figure 1 below. The results are for fault levels calculated between June 2015 and January 2016.

Figure 1 shows that three primary substations, BARG, HALG and CHAV, generally follow the G74 recommendation of 1.0 MVA/MVA infeed for 11kV connected loads. These substations have a large domestic load with few large commercial or industrial customers connected.

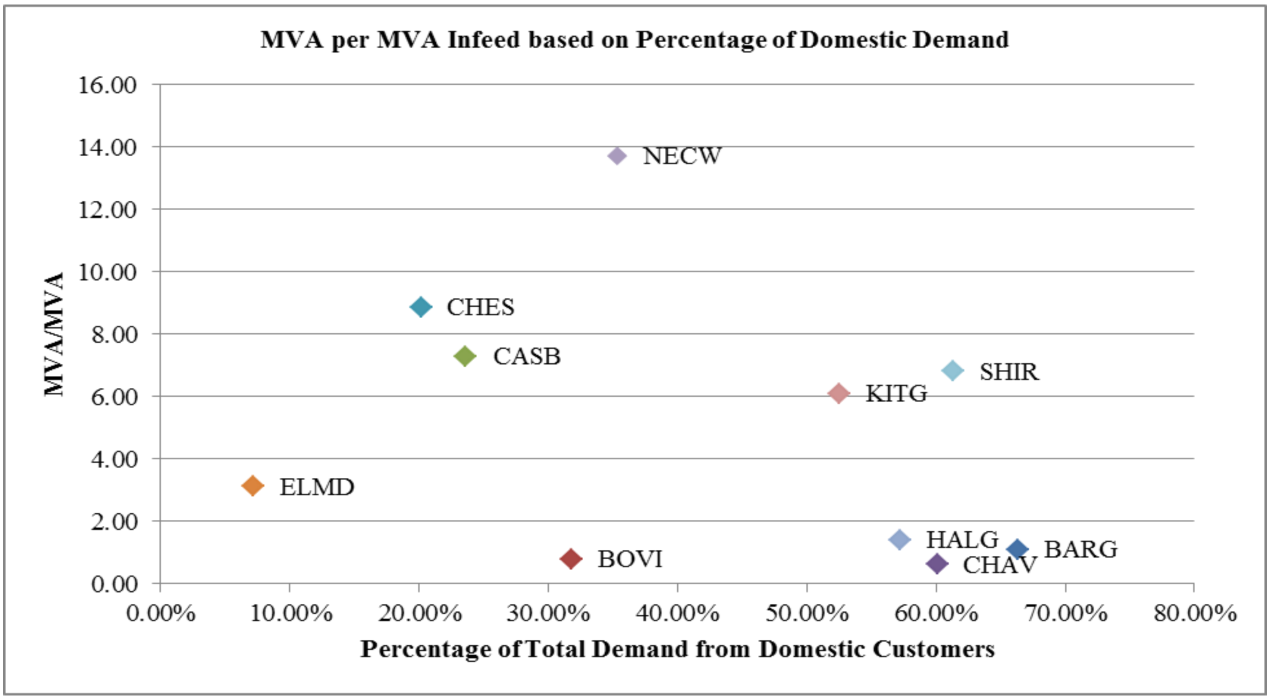

Figure 1: MVA per MVA Load Infeed based on % of Domestic Demand at each Substation

CHES and CASB substations by contrast have a relatively low domestic demand and a high percentage of large commercial and industrial customers connected. The combined average infeed calculated for these substations is 8.08 MVA/MVA. This is considerably above G74 recommended values. KITG substation has a high percentage of both domestic and large commercial and industrial loads. As such the calculated infeed is between the value when a substation is dominated solely by commercial and industrial loads and a domestic dominated load, as described previously, at 6.09 MVA/MVA.

The four remaining substations are considered anomalous results at this stage. ELMD and BOVI, from the data provided in Table 1, indicate that the fault level infeed for these substations should be similar to that of CHES and CASB, around 8.08MVA/MVA, however, both are significantly lower than this. Further investigation of the loads connected at the primary substations showed that whilst both ELMD and BOVI have large amounts of commercial and industrial load connected, they are likely to be mixed use load connections. NECW should, based on load type data, have a value between that of 6.09 and 8.08 MVA/MVA and SHIR should follow the G74 recommendation of around 1.0 MVA/MVA, however, based on investigation of load types and connection points the amount of commercial and industrial connections at each substation is situated close to the Primary substation, meaning that it is likely to have an increased impact on the system fault level due to minimal impedance between the load and substation.

PRODUCTION OF TEMPLATES

In order to utilise the analysis presented the generation of a template for 11kV MVA per MVA general load infeed is required, therefore enabling the wider utilisation of the general load fault level infeed types based on load make up of a Primary Substation.

From the evidence presented it is clear that for a domestic load percentage greater than 55% the existing fault level infeed value presented in G74, whereby it can be considered that most load is LV connected, for LV connected load of 1.0 MVA/MVA is appropriate.

Similarly it can be shown that where a Primary substation has less than 25% of its load made up of domestic load that neither of the existing values presented in G74 are appropriate. A value closer to that presented of the average between CHES and CASB of around 8.0 MVA/MVA is required.

A key value to be considered is that where a split between domestic and commercial and industrial load is around 50%. This scenario is presented through Primary substation KITG, where the value is around 6.0 MVA/MVA.

UTILISATION AND BENEFITS

The ability to have a significantly increased level of granularity as to the 11kV fault level general load infeed and therefore the overall system 11kV fault level has many applications.

The employment of this enhanced network data can be utilised to more accurately assess the network for future load and generation connections to the network. This benefit centres on the increased level of network security and safety based on the utilisation of this data. Increased safety of the 11kV system can be realised through more accurately understanding the network conditions for current and future network connections to ensure that no fault level limits of equipment such as switchgear and cables are exceeded.

Utilising a robust fault level infeed an 11kV general load template would mean that this information could be utilised for any network of which the load type by percentage on an 11kV Primary substation is known.

LEARNING

Key learning centres on the fact that the largest fault level general load infeed value presented in G74 is 2.6 MVA/MVA, however, the evidence presented shows that for certain load types the fault level infeed is in excess of 8.0 MVA/MVA. More widely it can be considered that greater importance on the load type of a substation, irrespective of voltage, should be given when considering the fault level of that substation.

Finally, the anomalous data presented in the form of four substations is driven by the fact that although a substation has a particular split of load type the AFLM connected to the system only considers a certain element of the network. As the AFLM is connected to a single busbar within the substation and there is no available data to accurately determine the load type of an individual section anomalous data at the monitored sites will continue. Therefore, a methodology to determine the load type per section of a particular substation is required to remove these anomalies and more accurately represent an 11kV general load fault level infeed template.

NEXT STEPS

The data presented considers a six month period, therefore a significant next step is to further understand the patterns of data presented over a longer period of time, specifically to more accurately ascertain the viability of the large commercial and load infeed value of around 8.0 MVA/MVA and the domestic dominated value of around 1.0 MVA/MVA.

The voids presented in the template, due to the load type being split over several sections of Primary substation, are to be more accurately determined. This work will focus on the development of a methodology to determine the load type for the area of network where each AFLM device is connected. This analysis will allow a full template of fault level infeed values to be generated, which from current available data, appears to trend towards a generic hysteresis curve.

Once a full template is produced the final step will be to trial and demonstrate its value on an unmonitored network (where an AFLM is not present) and to retrospectively monitor the real-time general load infeed values.

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