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FLEXDGRID

HEAT AND POWER FOR BIRMINGHAM

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Contents

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1 Project Title

FLEXGRID - Advanced Fault Level Management in Birmingham.

FLEXGRID was changed to FlexDGrid between the Full Submission Proforma stage and the Project Direction completion, due to licensing issues regarding the original name.

2 Project Background

Summary

FlexDGrid offered an improved solution to the problem of the timely and cost-effective integration of customers' generation and demand within urban High Voltage (HV) electricity networks.

This project sought to explore the potential benefits arising from trials of three complimentary Methods: (Alpha) Enhanced Fault Level Assessment; (Beta) Real-time Management of Fault Level; and (Gamma) Fault Level Mitigation Technologies. The project location was Birmingham.

This project aimed to deliver a highly transferrable system-level Solution, using real-time knowledge of the Fault Level status of the electricity network and application of Fault Level Mitigation Technologies, to manage multiple generation and demand connections. The learning is transferrable to all Great Britain (GB) networks.

At the time of project initiation the FlexDGrid solution was estimated as having the potential to deliver £1Bn savings across GB through the avoidance of network reinforcement and safeguarding of electricity network assets. This could facilitate 6 GW of generation connections and offset 5.05 $MtCO_2$ / year.

Aim

This project aimed to develop and Trial an Advanced Fault Level Management solution to improve the utilisation of Distribution Network Operator (DNO) 11kV (HV) electricity networks while facilitating the cost-effective and early integration of customers' generation and demand connections.

The FlexDGrid solution would provide DNOs with the capability to defer or avoid costly and prolonged network reinforcement, while improving security of supply.

The Problem to be resolved

Fault Level is a measure of electrical stress when faults occur within networks. It is a growing issue in the connection of Distributed Generation (DG). Conventional solutions to manage Fault Level often entail significant capital costs and long lead times.

BEIS’s (formally DECC) Carbon Plan sets out a strategy for carbon reduction and as a result many local and national policies include Combined Heat and Power (CHP) plants.

The electricity infrastructure in dense urban environments was designed and developed for its former heavy industrial requirements. Whilst we can accommodate the power produced by DG within the existing network, in some locations there are constraints because generation contributes to Fault Level, which may already be at, or close to, its allowable limit. DNOs must ensure that Fault Levels are maintained within equipment ratings: if exceeded, catastrophic failure could occur during a fault. DNO Fault Level calculations are traditionally based on fixed network conditions, involving essential safety margins and resulting in conservative Fault Level assessments.

Conventional Fault Level management solutions involve uprating or replacing transformers and, where large increases are required, replacing switchgear as well. For example, a 78 MVA Primary Substation in Birmingham required two replacement higher loss transformers, costing around £4M and taking three years to complete in order to accommodate DG of less than 3 MW. The upgrade involved the early retirement of fit-for-use assets and increased network losses by 745,000 kWh per annum (319 tCO_2).

In order to meet carbon reduction targets in Birmingham's Central Business District (CBD), the conventional Fault Level solution would involve switchgear and cable replacement at an estimated cost of £48.4M. This would involve significant public infrastructure disruption due to necessary road excavations with elevated risks of power outages. There would also be an increase in FL on customers' HV equipment. Neither of these costs are included in the estimated cost above.

3 Scope and Objectives

The objective of FlexDGrid was to develop and trial an advanced Fault Level management solution to improve the utilisation of DNO 11kV (HV) electricity networks while facilitating the cost-effective and early integration of customers' generation and demand connections. The methods deployed for FlexDGrid would provide learning and practical material to provide DNOs with the capability to defer or avoid costly and prolonged network reinforcement, while improving security of supply.

The project originally identified four main objectives as detailed in the Full Submission Pro-forma and listed below:

(i) Defer/avoid capital investment for customers and DNOs;
(ii) Avoid long connection lead times for low carbon generation;
(iii) Increase network efficiency and reduce Customer Interruptions (CIs) and Customer Minutes Lost (CMLs); and
(iv) Secure long term sustainable and affordable electricity prices with assisted living benefits from Combined Heat and Power (CHP).

4 Success Criteria

Table 4-1 below lists the Successful Delivery Reward Criteria encompassing the main deliverables for FlexDGrid.

Table 4-1: SDRCs for FlexDGrid

FSP	Project Direction	Description	Evidence	Status
9.1	SDRC 1	Develop an enhanced Fault Level assessment process	• Using the Birmingham HV electricity network to trial the Enhanced Fault Level Assessment process. • A workshop with other DNOs to discuss the Enhanced Fault Level Assessment process. • A publication on the Enhanced Fault Level Assessment process to be shared with other DNOs.	✓
9.2	SDRC 4	Simulation and application of the Enhanced Fault Level Assessment process to demonstrate what can be achieved with customers' connections.	• A developed and tested Enhanced Fault Level Assessment process with endorsement from WPD planning and design engineers. • Quicker response to customers' connections applications. • Characterisation of the substations to determine the suitability of potential Fault Level Mitigation Technologies. • Open source Fault Level Mitigation Technology models. • Quantification of additional capacity that will be unlocked to accommodate future customers' connections.	✓
9.3	SDRC 2	Confirmation of project detailed design	• Confirmation and justification of the five substation sites selected for Fault Level mitigation and ten substation sites selected for Fault Level monitoring. • Availability of detailed design documents to other DNOs.	✓
9.4	SDRC 11	Development of novel commercial frameworks with generation and demand customers	• Novel commercial frameworks are readily available for use in customers' connection applications within the project trials. • Produce a `Connections Options' document and dissemination to other DNOs, customers and other interested parties.	✓
9.5	SDRC 7	Installation and open-loop (non-network controlling) tests of Fault Level monitoring equipment.	• Installation of equipment in ten Primary Substation sites. • Open-loop (non-network controlling) test results being disseminated.	✓
9.6	SDRC 8	Installation and open-loop (non-network controlling) tests of Fault Level mitigation equipment.	• Installation of equipment in five (***changed to three as part of a formal Change Request***) Primary Substation sites. • Dissemination of open-loop (non-network controlling) test results and system-level learning.	✓
9.7	SDRC 9	Closed-loop (network controlling) tests of Fault Level monitoring and mitigation equipment.	• Dissemination of closed-loop (network controlling) test results and system-level learning.	✓

9.8	SDRC 10	Analysis of test results, evaluating and quantifying the benefits of the Solution and applicability to GB HV electricity networks.	• Knowledge dissemination:
			  • Network data being made available.
			  • Six-monthly progress reports submitted to Ofgem throughout project.
			  • Eight industry conferences attended and presented by December 2016.
			  • LCNF Annual Conference.
			• Publication of reports.
				✓

9.9	SDRC 3	Hold a workshop, inviting all GB DNOs and other interested parties. At the workshop, the Implementing DNO will provide an overview and expected performance of all three methods.	• Hold a workshop with other GB DNOs by 31 October 2013. • Written responses to the consultation from each GB DNO submitted with the report required under A) Methodology of Method Gamma of 3. CONDITION PRECEDENT.	✓
N/A	SDRC 5	Delivery and Authority approval of report as required under B) Value for money of 3. CONDITION PRECEDENT before issuing Invitation to Tender for Fault Level mitigation technologies 31 December 2013	• Delivery of a report to the Authority under B) Value for money of 3. CONDITION PRECEDENT. • Authority approval that the competitive procurement process will be undertaken in a way that will deliver best value for money.	✓
N/A	SDRC 6	Delivery and Authority approval of report as required under A) Methodology of Method Gamma of 3. CONDITION PRECEDENT before signing contracts for Fault Level mitigation technologies. 31 December 2013	• Delivery of a report to the Authority covering points (i) to (vi) under A) Methodology of Method Gamma of 3. CONDITION PRECEDENT. • Authority approval that there is sufficient evidence that GB DNOs consider that proceeding to Method Gamma would provide the learning outlined in the Full Submission pro-forma.	✓

5 Executive Summary

The FlexDGrid Low Carbon Networks Fund project aimed to develop and trial an Advanced Fault Level Management Solution to improve the utilisation of Distribution Network Operators' (DNO) 11kV (HV) electricity networks while facilitating the cost-effective and early integration of customers' generation and demand connections. The FlexDGrid project was awarded funding through Ofgem's Low Carbon Networks Second Tier funding mechanism and commenced on the 7th January 2013.

The Carbon Plan aims to deliver carbon emission cuts of 34% on 1990 levels by 2020. This national target is devolved, in part, through local government carbon emission reduction targets as set out in their strategy planning documents. The Carbon Plan sets out ways to generate 30% of the UK's electricity from renewable sources by 2020 in order to meet the legally binding European Union (EU) target to source 15% of the UK's energy renewable sources by 2020. The UK Government has identified Distributed Generation (DG) as a major low carbon energy enabler and an important part of the future electricity generation mix.

Fault Level is a measure of electrical stress when faults occur within networks. It is a growing issue in the connection of DG, especially in urban networks, as the majority of DG increases the system Fault Level. Conventional solutions to manage Fault Level often entail significant capital costs and long lead times.

In order to address the Fault Level Management Problem, three methods were trialled and evaluated within the Central Business District (CBD) of Birmingham. These Methods are:

Method Alpha (α)	-	Enhanced Fault Level Assessment;
Method Beta (β)	-	Real-time Fault Level Management; and
Method Gamma (γ)	-	Fault Level Mitigation Technologies.

These three methods aimed to defer or avoid significant capital investment and create a wider choice of connection options for customers who can accept a flexible connection to the network. These benefits will be provided to customers through advanced and modified generation connection agreements. Each method on its own will help customers to connect DG more flexibly.

The project has facilitated the development of a new, Enhanced Fault Level Assessment, methodology to determine the 11kV network Fault Level as well as understanding the key parametric sensitivities affecting the accuracy of the assessment results. Modelling 15 substations in Birmingham, which is the network connecting over 350,000 customers, has improved the assumptions of the Fault Level network modelling process and therefore increased the level of security of the system for existing customers and also new load and generation connections. The new process has improved our system analysis techniques to ensure that the level of capital reinforcement for new connections is minimised.

Through the development and implementation of Method Beta, 11kV Fault Level Monitors were designed, tested and installed at 10 different primary substations. These FLMs provide real time Make and Break Fault Levels at regular intervals, which were used to develop two important outputs enabling the project's objectives to be met.

The first output involved utilising the Fault Levels generated to enable a greater understanding of the general load infeed MVA/MVA values at specific sites. As has been the case since power system analysis modelling was first undertaken, any general load connected at a specific network locations was treated the same whether it was domestic or large industrial connections. Utilising the data from the FLMs and feeding it back in to the EFLA models enabled load specific infeeds to be generated, ranging between 1 and 5MVA/MVA. This is the first of a kind and is a significant outcome from the project and can specifically support the avoidance of capital investment.

Having made the real-time Make and Break Fault Level values readily available through the installation of the 10 FLMs. the second output focused on the development of procedures and systems to both enable customers to engage in alternative connections and for DNO control engineers to dynamically operate the network. One example was the ability to operate the network in parallel configuration, when the FLM data shows the values to be below the acceptable limits. This learning can demonstrate a saving in the region of £145k per MW of generation connection.

Method Gamma set out to install five Fault Level Mitigation Technologies (FLMT) of varying Technology Readiness Levels (TRL) to develop a broad industry understanding of the differing technologies capabilities and suitability through network trials. Planned for installation was one Pre-Saturated Core Fault Current Limiter (FCL), two Resistive Superconducting FCLs and two Power Electronic FCLs, however, due to design and build difficulties in the supply of the two GE Power Electronic FCLs this number was reduced to three. Successfully trialling these three devices enabled over 50MW of generation capacity to be released. It also enabled the 11kV networks to run in parallel continually, whereas previously they operated in split configuration, improving security of supply.

These outputs, of both the installation of the FLMs and FLMTs, supported the reduction in long connection lead times for the connection of low carbon generation, through alternative connections facilitated by the real-time FLM data. The ability to dynamically operate the network based on the FLM real-time data and the installation of the three FLMTs has enabled the increase in the network efficiency through the reduction of CIs and CMLs respectively, where the network can now be operated in parallel. Through the delivered outputs in all three methods, and the combination of methods, additional options and tools have been provided. This enables the deferment and avoidance of capital investments and therefore assists the secure long term sustainable and affordable electricity prices.

6 Details of Work Carried Out

6.1 Substation Selection

The bid stage of FlexDGrid identified 18 primary substations that should be considered for Method Beta and Gamma due to their proximity to Birmingham City Centre and Fault Level information.

Site visits were undertaken as part of the process of selecting suitable sites for the implementation of FCL and FLM technologies to gain an overall understanding of the shortlisted primary substations. A selection process took place following these initial site visits to determine which sites were most suitable for the installation of FLMs and FCLs. The selection process was informed by scoring each primary substation against the following criteria.

- **Availability of Space** - The available space at the site for situating FLM/FCL technology;
- **Network Connection** - How will the technology be connected (are spare circuit breakers available or would a new switchboard be required?);
- **Substation Access** - The access arrangements for the delivery of the technologies;
- **Investment Plans** - Other works planned for the site which may influence the connection of a FLM or FCL; and
- **Auxiliary Supply Capacity** - Capacity of auxiliary systems (such as 110V, 48V and LVAC supplies) for connection of the technologies;

A weighting was assigned to each item above to determine an overall individual score for each substation as listed in Table 6-1 below.

Table 6-1: Substation selection criteria

Criteria	Weighting
Availability of Space	37.5%
Network Connection	27.5%
Substation Access	20.0%
Investment Plans	10.0%
Auxiliary Supply Capacity	5.0%
Overall Score	**100.00%**

Table 6-2 provides the list of substations chosen for installation following application of the scoring criteria.

Table 6-2: Selected substations for FlexDGrid

Substation	FLM	FCL
Kitts Green	✓	✓
Castle Bromwich	✓	✓
Chester Street	✓	✓
Bournville	✓	✓
Sparkbrook*	✓	✓
Hall Green	✓	
Elmdon	✓	
Chad Valley	✓	
Perry Barr*	✓	
Winson Green*	✓	
Bartley Green+	✓	✓
Shirley+	✓	
Nechells West+	✓	

* Substation changed following network upgrade / survey results
+ Substation utilised following the unavailability of originally selected site

As noted above, three substations from the original shortlist had to be substituted with Bartley Green, Shirley and Nechells West due to network upgrades and the results of surveys.

Further details can be found in SDRC 2 – Confirmation of the Project Detailed Design.

6.2 Method Alpha

Overview

Enhanced Fault Level Assessment explored the existing Fault Level calculation and connection assessment methodologies, defined in IEC 60909[1] and DNO internal policies. The Method aimed to facilitate the connection of more customers without compromising the safety of WPD employees and the public. In line with the aims and objectives of Method Alpha, enhanced Fault Level assessment, the following work was carried out:

[1] Short-circuit currents in three-phase a.c. Systems – Calculation of Currents

- Developed the central Birmingham HV electricity network computer model to create a test bed for demonstrating and evaluating the enhanced Fault Level assessment processes;
- Explored Fault Level analysis assumptions and carried out a sensitivity analysis of network modelling parameters;
- Developed tools and methodologies for enhanced Fault Level calculations of HV networks for district engineers who may have limited access to updated network data and professional power system software;
- Developed fit-for-purpose tools and computer models for assessing the impact of FCLs on network Fault Levels in different operating conditions; and
- Reviewed the internal short circuit policy document to update it based on learning from FlexDGrid.

Detailed Model of the HV Network Development

The Birmingham HV electricity network model was developed in order to create the test bed for demonstrating and evaluating the enhanced Fault Level assessment processes. When FlexDGrid started, the existing BaU model for the Birmingham HV network was not updated on a periodic basis and was not directly integrated with the EHV model. In addition, there were a number of different data sources that were used by design and planning engineers to conduct Fault Level assessments. A more detailed electricity network model, such as the model developed in FlexDGrid, would allow better granularity of Fault Level analysis within HV networks.

A methodology for modelling HV networks in PSS/E (power system analysis software) was developed and demonstrated during the first six months of FlexDGrid. The process and data sources used in the modelling methodology are shown in Figure 6-1. EMU, a geographical asset management system, was identified as the most up-to-date data source within WPD representing the geographical connection of the network assets. EMU was used to identify the network connectivity and the size and type of conductors installed in different parts of the 11kV network. A detailed description of the methodology used for integrating the Extra High Voltage (EHV) and HV network models was published in SDRC-4 (Simulating and applying enhanced Fault Level assessment processes).

Based on the knowledge gained and methodology developed during the first six months, a user-friendly Excel-based tool was developed to automate the modelling process by converting EMU data to a PSS/E model. The automation tool together with the methodology was used to develop the HV networks of 14 primary substations located in the Birmingham area.

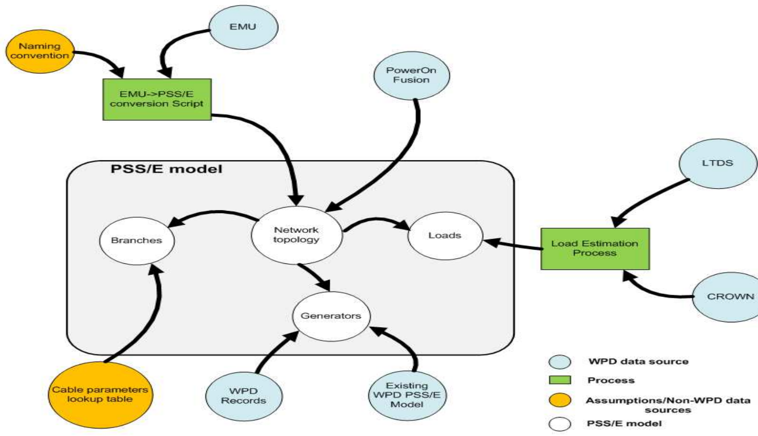

Figure 6-1: 11kV network modelling methodology

Sensitivity analysis of Fault Level assessments in HV networks

A sensitivity analysis was carried out to enhance understanding of the Fault Level calculation process, based on the recommendation in SDRC-1 and responding to a query posed by the DNO community. This analysis demonstrated the sensitivity of calculated Fault Level values (peak make and RMS Break) based on different parameters used in the Engineering Recommendation (ER) G74 Fault Level calculation process. The following work was carried out:

- A sample PSS/E model of a network, representing part of Birmingham's 11kV network, was considered;
- The parameters of the sample model were varied within the range given in Table 6-3 within an assumed time to create different operation condition scenarios; and
- The corresponding Fault Levels of each scenario were calculated. The results were then compared with calculated Fault Levels from the original model to understand the impact of the each network parameter on the network Fault Level.

All Fault Level analysis was carried out based on ER G74 using a PSS/E-compatible Python script[2], developed by WPD, for Fault Level calculations. The detailed results of this analysis was published SDRC-4.

Table 6-3: Model parameters and range of variations used for sensitivity analysis

Parameter	Variation range
Generation power factor (PF)	Unity, 0.95 leading, 0.95 lagging, Voltage control mode (Vset = 1 pu)
Tap position at Primary Substation	Voltage at 11 kV busbar changes between 0.95 per unit to 1.03 per unit
Demand	- 10% to + 10%
General load fault in-feed	0 to 2 MVA per MVA of load
Cable length	- 5% to + 5%

[2] Python is a programming language which allows complex calculations to be implemented and automated: www.python.org

Developing Fault Level Guidance tool

As part of enhancing the Fault Level assessment process an "HV Fault Level guidance tool" was developed. The objectives of this tool were to:

(i) Provide a Fault Level assessment platform for WPD planning engineers who may not have access to power system analysis software for connection studies as part of the G59 generation application process.

(ii) Reduce the time and effort that is spent on data gathering and network modelling for connection studies.

The following work was undertaken to develop the "HV Fault Level guidance tool":

(i) **Developed interface and functional specifications of the tool:** Carried out meetings with HV planners and also Primary System Design (PSD) engineers from all DNOs to identify input/output and functional requirements for the tool.

(ii) **Calculated equivalent 11kV network impedance:** Developed a methodology to calculate the equivalent impedance between a secondary substations and the corresponding upstream primary substation. The methodology was scripted in python and run on the 14 HV network models developed in FlexDGrid (see section 0).

(iii) **Calculated the existing Fault Level:** The Fault Level at 11kV busbars at primary substations and all the relevant secondary substations were calculated using G74 methodology and PSS/E network models. The "HV Fault Level guidance tool" was populated with this information.

(iv) **Developed Excel-base Fault Level calculation:** Make and break Fault Level calculations for a generator connected via an equivalent circuit was formulated in Excel. This formulation was in line with recommendations in ER G74.

(v) **Validated the performance:** The calculations within "HV Fault Level guidance tool" were validated by comparison with PSS/E Fault Level calculation.

(vi) **Developed an updating process:** A procedure for updating and maintaining the tools was proposed along with recommendations that when the updating process should be undertaken.

Development of FCL desktop model

The FCL technologies trialled within FlexDGrid were live assets and their impact had to be considered in Business as Usual (BaU) Fault Level assessments. FCLs usually have a non-linear and complex transient behaviour during a fault. Constructing a desktop transient model to study their impact on the network's Fault Levels was challenging as:

- Detailed parameters of the device were not available due to the technology maturity level;
- Transient models could not be constructed using conventional power system analysis tools; and
- Complex technical knowledge for transient modelling and analysis of the devices was required.

Moreover, network operators conventionally consider static short-circuit analysis as part of their network planning and connection studies rather than more complex transient studies. The conventional calculation considers fault currents at two post-fault times; first peak (Make) and fault clearance (Break). Therefore a fit-for-purpose computer model for FCLs need only include their behaviour at specific snapshots of the fault period e.g. making and breaking fault times. The following methodology was used to develop a static computer model of FCL:

Stage 1 – FCL manufacturers were requested to provide the impedance of their devices at pre-fault and post-fault conditions for different network scenarios. This data was used to create the FCL impedance look-up tables corresponding to making and breaking Fault Level calculations.

Stage 2 – The conventional short-circuit calculation process was modified to include the FCL impact on the calculated Fault Levels. The process for modelling an FCL impact in short-circuit calculations is shown in Figure 6-2 and described as follows:

- Model the FCL as a branch in the case study. The impedance of this branch is the pre-fault impedance of the FCL;
- Run short-circuit analysis to calculate the prospective fault currents (make and break) passing through the FCL branch. Prospective fault current is the fault current before insertion of the FCL device;
- Determine the impedance of the FCL at make and break times using the prospective make and break fault currents together with the FCL impedance look-up table;
- Create two separate desktop case studies, one for make and one for break Fault Level calculations, where in each case the impedance of the FCL branch is updated accordingly; and
- Run short-circuit analysis to determine make and break Fault Levels with the FCL inserted in the network.

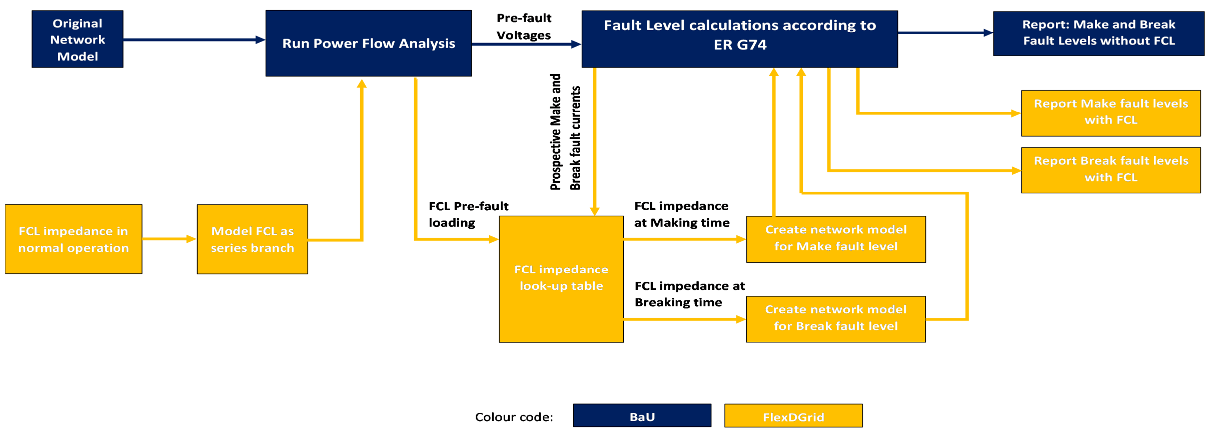

Figure 6-2: FCL Static Modelling Methodology for Short-circuit Calculation

FL calculation policy

As part of Method Alpha, the WPD policy (Standard Technique) for switchgear short circuit duty calculation was reviewed and some clarification points were added to the document. The updated document is now live and used by WPD engineers whilst also being made available on the ENACT Portal to enable direct access by all other DNOs. The updated points are as follows:

- A terminology section including the definition of various terms together with relevant illustrations to provide clarifications about the parameters which are referred to in the main body;
- A standard fault breaking time which should be considered for calculation of Fault Levels at different voltage levels where the actual protection response time is unknown;
- The typical transient and sub-transient parameters of synchronous generators where the manufacturers data is not available; and
- The fault contribution of the converter-connected generators such as Photo-Voltaic.

6.3 Method Beta Overview

Overview

Method Beta aimed to increase understanding and management of Fault Levels thought the installation of real-time Fault Level measurement devices, specifically those developed under the WPD LCNF Tier-1 project “Implementation of an Active Fault Level Management Scheme”, at ten Primary Substation sites. This enabled accurate Fault Level data to be gathered for various network running arrangements, providing verification of the Fault Level assessed in Method Alpha. This allowed the 11kV network configurations and the status of DG plant to be monitored on a more granular level. It was predicted that up to 10% capacity could be released through this Method. Uncertainties in data, and the previous lack of real-time Fault Level monitoring capability, led to conservative safety margins (up to 15%) in the current assessment of electricity Fault Levels.

FLM Procurement

Following a procurement exercise the Fault Level Measurement (FLM) device selected was built by S&C Electric. The device was based on the one installed under the WPD Tier-1 project with changes to add additional monitoring and communications.

FLM Design

Due to the operational principles of the FLM, and to reduce the risk to customers, it was decided that all connections to the network would utilise current generation circuit breakers with numerical protection. Six connection options were developed, providing multiple configuration options.

For each of the ten substation sites selected, the most appropriate connection option was determined and then approved by our internal design team. Following this initial approval, detailed design packages for electrical and civil works required to connect the FLM were completed.

FLM Testing

A key part of Method Beta was confirming that the FLM device had a measurement error of less than ±5% of the actual in-feed values. In order to determine this, witnessed tests were carried out at S&C's High Power Laboratory at their manufacturing facility in Chicago, USA which was capable of providing, at the same time, 11kV and in excess of 33.4kA. Further details on the testing can be found in SDRC 7 – Installation and Open-Loop Tests of FLM Equipment.

To ensure the device was suitable across the variety of real world situations, three different configurations were agreed to test the device at a range of X/R ratios and powers. Prior to each test sequence of the FLM a 3-phase bolted fault was placed on the system with the laboratory measurement devices used to provide the actual Fault Level of the test configuration. This was then used as the target value for analysis of the FLM accuracy.

FLM Installation

Method Beta successfully installed Fault Level Measurement devices at ten substations. Below is an example of an installation at one of the ten substations. Full details about the installation at all sites can be found in SDRC 7 - Installation and Open-Loop Tests of FLM Equipment.

Elmdon FLM Installation

The FLM installation at Elmdon was the first of the ten to be completed and commissioned. The substation had a spare breaker available that was of a suitable type for the connection of an FLM directly onto the existing switchboard. The single line diagram of the connection at Elmdon is shown in Figure 6-3.

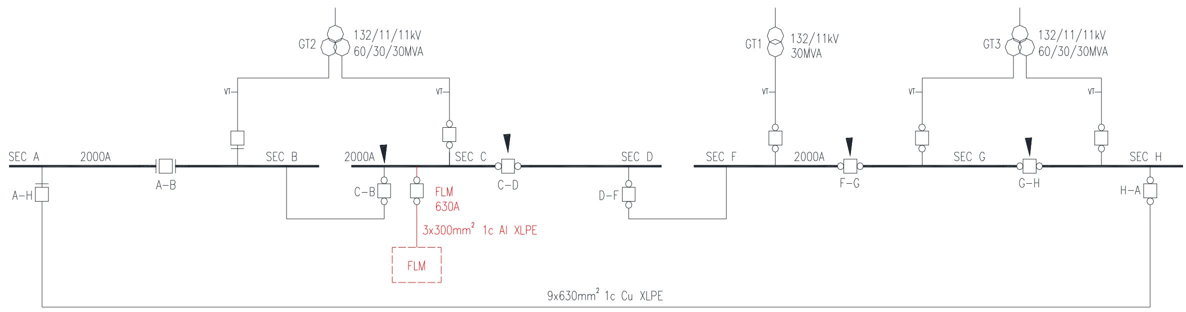

Figure 6-3: Elmdon FLM Schematic

The FLM was positioned within the 132kV compound adjacent to the local distribution substation. A dedicated gate to the FLM compound was placed in the site perimeter fence so personnel did not have to go through the 132kV compound to access the device. Being the first site meant that many lessons were learnt with changes made and verified. These lessons and the refinement in processes were then applied to all sites going forward.

6.4 Method Gamma

Overview

Method Gamma aimed to reduce network Fault Levels through the installation of Fault Level Mitigation Technologies (FLMTs), otherwise known as Fault Current Limiters (FCLs). The design and installation of FCLs builds on learning and technologies developed from earlier Innovation Funding Incentive (IFI), Energy Technologies Institute (ETI) and Low Carbon Networks Fund (LCNF) projects to create a system-level approach. The method involved installing FCLs at five 132/11kV substations in and around the centre of Birmingham to reduce the Fault Level of the surrounding 11kV networks. Three different FCL technologies were chosen to be developed however; this was reduced to two following issues with the GE Power Electronic technology.

Fault Level Reduction

The 11kV network in Birmingham is supplied from a number of 132/11kV substations at strategic locations in and around the city. The direct transformation from 132kV to 11kV results in lower network impedances between the EHV and HV voltage levels due to the absence of an intermediate voltage supply level (such as 33kV). The lower network impedance has resulted in very high Fault Levels on the 11kV network. Operation of the network with Fault Levels exceeding equipment ratings cannot be permitted as the equipment may not be able to sustain / interrupt the resultant current. Due to the high Fault Levels most 11kV busbars at primary substations have to be run in split configuration. Operating the network in split configuration requires manual or automated sequence switching to quickly restore customers in the event of an upstream fault.

The implementation of Method Gamma allowed the 11kV busbars at a primary substation to be connected in parallel by reducing the prospective fault infeed by connecting an FCL across the bus-section or in series with the incoming feeder. The objective for Method Gamma was that the chosen primary substation shall be able to accommodate additional generation, up to 10% of the firm capacity of that primary substation, without exceeding the equipment ratings following installation of an FCL.

FCL Procurement

The Invitation To Tender (ITT) for procuring FCLs was open and competitive, capturing manufacturers of different technologies across the globe. Three different FCL manufacturers were chosen to ensure that FlexDGrid trialled a variety of different technologies.

Site specific pro-forma for the five FCL sites were submitted to the manufacturers to complete at the start of the tender process. The pro-forma detailed the specific functional and Fault Level reduction requirements for each site with the manufacturers left to complete the cost, size and lead-times for each device.

The site specific pro-formas formed the basis of the technical discussions with the manufacturers at the post tender negotiations. The individual submissions were then evaluated based on the following categories: technical, service, delivery and financial. The results from the evaluation are listed in Table 6-4.

Table 6-4: Summary of the selected sites and associated FCL technology

Substation	Manufacturer	Name	Technology
Kitts Green	GE	Active Fault De-Coupler	Power Electronic
Castle Bromwich	GridON	PSCFCL	Pre-Saturated Core
Chester Street	Nexans	SFCL+	Resistive Superconducting
Bournville	Nexans	SFCL+	Resistive Superconducting
Sparkbrook	GE	Active Fault De-Coupler	Power Electronic

FCL Design

The initial design stage of FlexDGrid involved preparing design packages for each of the ten substation sites. The design packages provided an overview of the substation describing the type and location of existing equipment at the site in addition to details of how the new technologies should be connected. A standard approach was developed for the connection of FCLs detailing the advantages and disadvantages for each option.

FCL Testing

A significant focus was placed on the rigorous testing of the FCLs due to the associated technologies being relatively immature compared to traditional network assets such as transformer and switchgear. As such, each FCL device was subject to both Factory Acceptance Testing (FAT) at the manufacturer’s facilities as well as a Type Test at a third party test laboratory.

Rigorous test procedures were developed to ensure that the FCLs were tested in the appropriate manner. This was challenging because FCLs do not have any international standardised test procedures such as transformers and switchgear. To develop the testing procedures, an analysis of existing international equipment standards was performed and the applicability of their tests to the different FCL technologies was assessed. A selection of tests was then selected and modified to suit the specific FCL technology under test. This was then compiled into the final test procedure.

7 Outcomes of the Project

7.1 Outcomes for Method Alpha

Method Alpha enhanced the Fault Level assessment by improving the granularity of the network models, providing the fault assessment tools for planning engineers and informing the network modelling procedure. The main outcomes of Method Alpha were as follows:

1. The detailed 11kV network models of 15 primary substations and an automated procedure for updating or developing further network models for Fault Level assessments
2. A user-friendly Excel-based tool for FCL impedance which can be used by primary system design engineers for the Fault Level assessments of HV networks of primary substations where FCLs have been installed.

Detailed 11kV network models

The detailed 11kV network model of 15 primary substations integrated in the EHV model provided a test bed for all the Fault Level calculations and enhanced Fault Level assessment process required in FlexDGrid. In summary the developed models included 3,041 secondary substations and 1,878 km HV circuits.

Figure 7-1 and Figure 7-2 show examples of FlexDGrid outcomes enhancing the 11kV network and integration to the existing EHV model. Figure 7-1 represents the BaU network model prior to FlexDGrid. Figure 7-2 represents tangible output of FlexDGrid in terms of delivering an integrated network model that was used to test the enhanced Fault Level assessment processes throughout the project trials.

The detailed models developed in FlexDGrid allowed the following studies to be conducted:

1. **Fault Level assessments for different substation configurations:** A full representation of the HV busbars at primary substations is embodied in the developed models, including front and rear bus bars, as wells as circuit breakers and busbar couplers.
2. **Fault Level assessments for different 11kV network configurations:** All normally open points (NOPs) and interconnections between different HV networks supplied by different Primary Substations are modelled.
3. **Enhanced Fault Level calculations as part of connection studies:** as the complete HV network has been modelled, distributed Generators can be modelled at their actual connection points in the HV network rather than considering an equivalent circuit between the point of connection to the upstream Primary Substation.
4. **Fault current contributions from EHV network:** The developed HV network models are integrated into the EHV PSS/E model. This enables the assessment of any possible changes in HV Fault Levels as a result of changes to the EHV network.

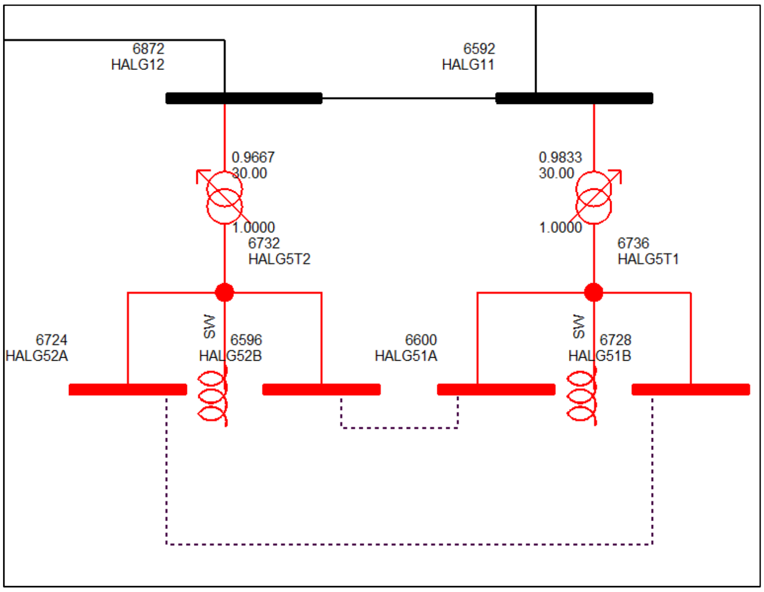

Figure 7-1: representation of the HV network (BaU pre-FlexDGrid) of Hall Green within PSS/E

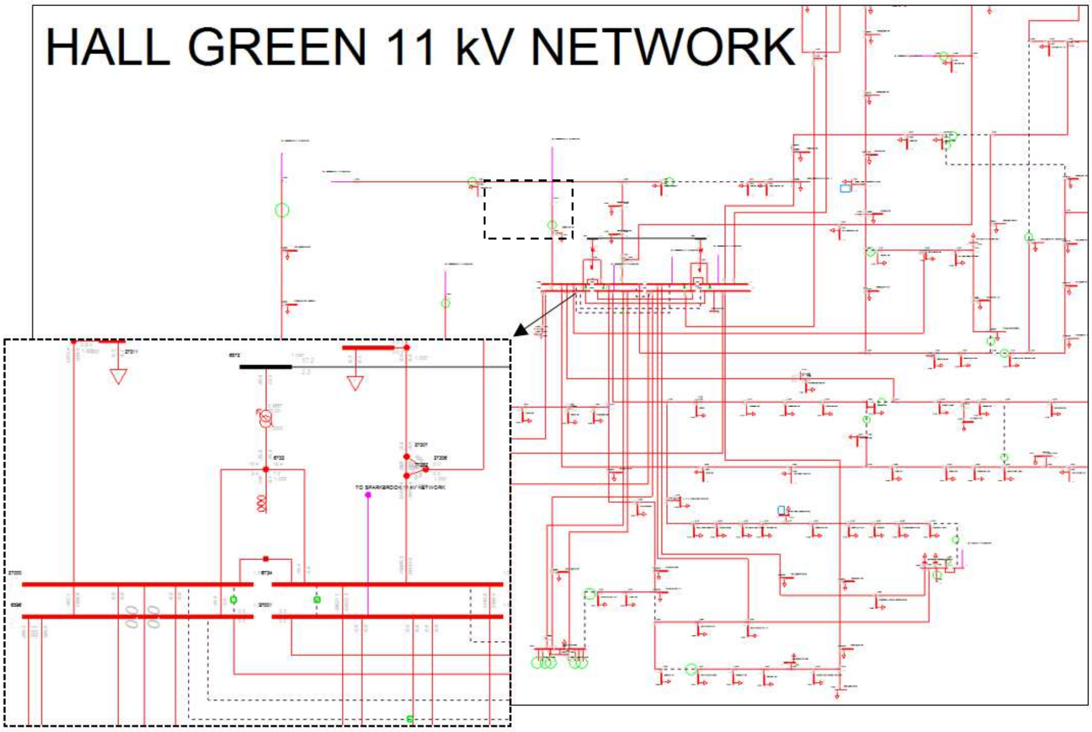

Figure 7-2: representation of the integrated Hall Green HV network model within PSS/E as a result of FlexDGrid

Enhanced Fault Level assessment tools

Network modelling tool

A user-friendly Excel-based tool was developed to automate the modelling process by converting EMU data (Network assets geographical data) to a PSS/E model to create the 11kV network topology. Figure 7-3 shows the user interface of this Excel tool. The exported file is a PSS/E V32 file in RAW format. This tool significantly reduced the time required for developing the 11kV network to be used as part of the wider EFLA activities.

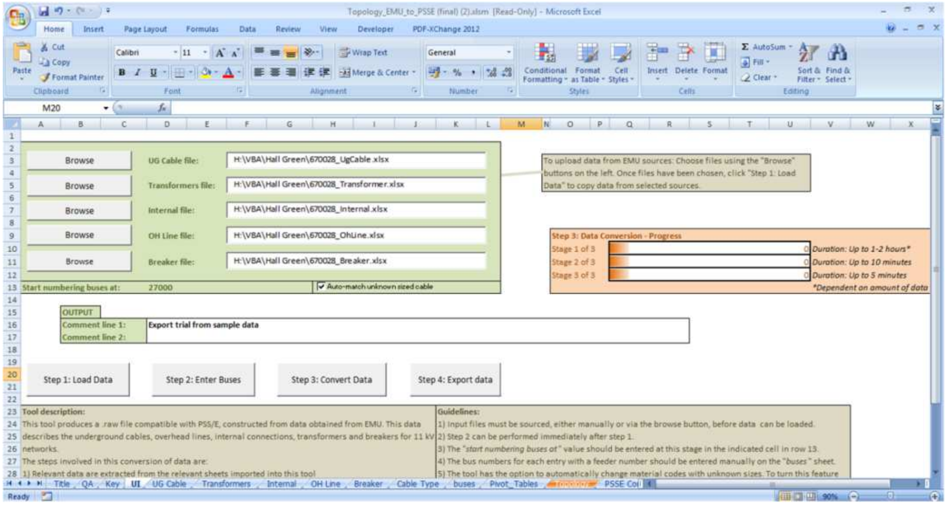

Figure 7-3: the Excel-tool developed to convert EMU data to PSS/E V32 RAW file

Fault Level Guidance Tool

This is an Excel-based tool which can be used by HV planners and DNO engineers to estimate the Fault Levels at HV networks as part of studies required for G59 generation application process. This tool may be used when a power system analysis software and network models are not available. "HV Fault Level guidance tool" contains the following information:

1. Fault Level data at the primary substations and secondary substations.
2. Equipment short circuit ratings at primary substations and secondary substations.
3. Equivalent impedance between the secondary substations and their corresponding primary substation.

The dashboard of the "Fault Level Guidance Tool" is shown in Figure 7-4. A user can specify the point of connection of a generator and enter the generator's electrical parameters in the designated area in the dashboard. Upon filling all input data the results of the Fault Level calculations will be available in the "Dashboard" tab. The results include:

- Making and Breaking fault current contribution of the generator at the connection point and at the upstream primary substation; and
- Making and Breaking Fault Levels at the connection point and at the upstream primary substation after connection of the generator.

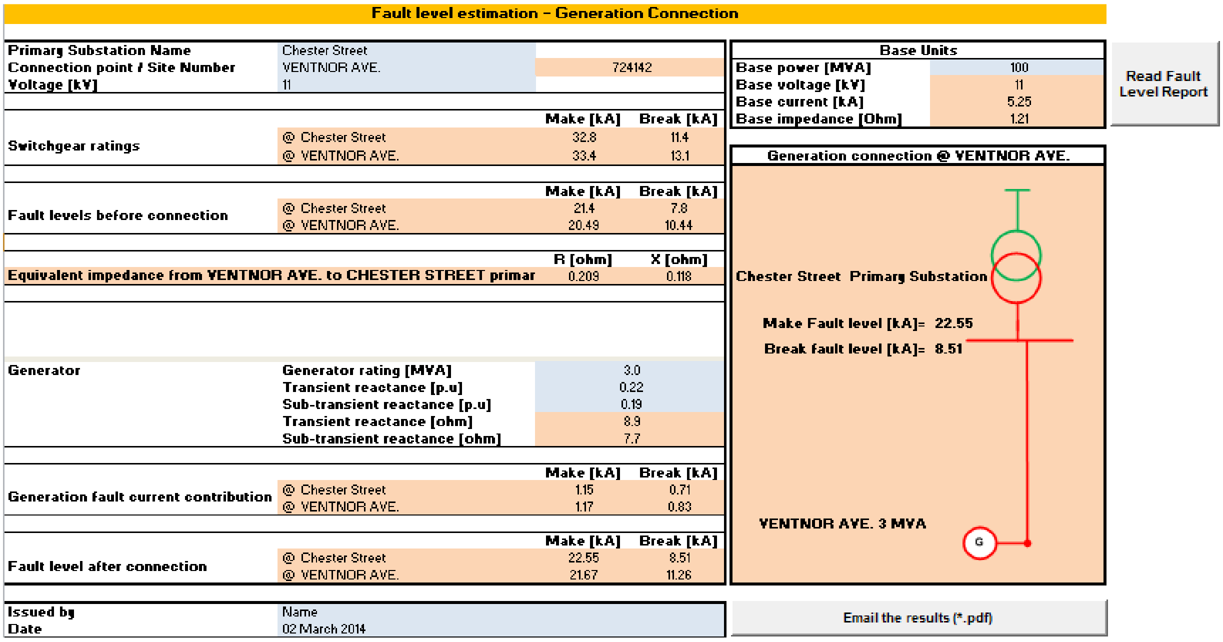

Figure 7-4: Fault Level Guidance Tool user interface

FCL modelling Tool

In order to provide WPD engineers a process for obtaining the FCLT impedance data, the "FCL Impedance Lookup Table" Excel-based tool has been developed. This tool contains the data obtained from FCL manufacturers and it can estimate Resistance (R) and Reactance (X) values of FCLs trialled in FlexDGrid in different post-fault conditions. The tool can be used, in conjunction with power systems analysis software, for the Fault Level calculations where FLMT is deployed as explained in FCL modelling methodology in Section 0. Figure 7-5 shows the dashboard of the "FCL Impedance Lookup Table".

The functional specifications of the tool are as follows:

- User can specify the FCL technology using a dropdown menu;
- Upon selection of the FCL, a single line diagram showing the FCL connection arrangement at the primary substation appears on the dashboard;
- The user can enter the pre-fault and post-fault network conditions as required based on FCL technology;
- The estimated R and X values are shown in tabular format and on the FCL impedance graphs.

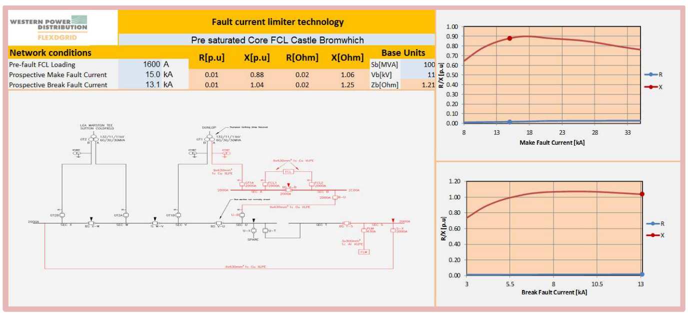

Figure 7-5: "FCL Impedance Lookup Table" excel tool user Interface screenshot

Heat map presentations

The detailed 11kV network model and the tools developed in FlexDGrid allowed us to conduct Fault Level assessments in various network conditions e.g. different primary substation busbar configurations, insertion of FCLs etc. Further enhancements in Fault Level assessment provided in FlexDGrid enabled the calculation of the Fault Levels of entire 11kV network whereas it was limited to only Fault Levels at primary substations before FlexDGrid started. One of the techniques used in FlexDGrid to show the calculated Fault Levels on the 11kV networks was a heat map style presentation, giving a visual indication of Fault Levels across a large-scale area.

The heat maps technique has been used to demonstrate the effect of FCL technologies on the Fault Levels across the HV networks of Castle Bromwich, Chester Street and Bournville Primary Substations. Three network arrangements have been considered for this demonstration:

- **Existing arrangement (split operation)** – This is a normal operation where the primary transformers are operating in split to maintain the Fault Levels within switchgear
- **Parallel operation** – This is a configuration which includes operation of two or more 132/11kV primary transformers through a closed bus-section or interconnector. The Fault Levels usually exceed the switchgear short circuit ratings in this configuration.
- **Parallel operation with FCL installed** – This is parallel operation with the FCL technology trialled in FlexDGrid is inserted in the primary substation.

Figure 7-6 shows the rms Break Fault Levels at the three FCL trial sites and for the aforementioned operation arrangement. The heat maps demonstrate that Fault Levels in large parts of the Birmingham HV network could exceed switchgear policy limits if the Primary Substations were to be operated in a parallel configuration (to improve customers' security of supply). The FCLs trialled in FlexDGrid can mitigate the Fault Level rating exceedance and maintain the Fault Levels close to those levels in split operation.

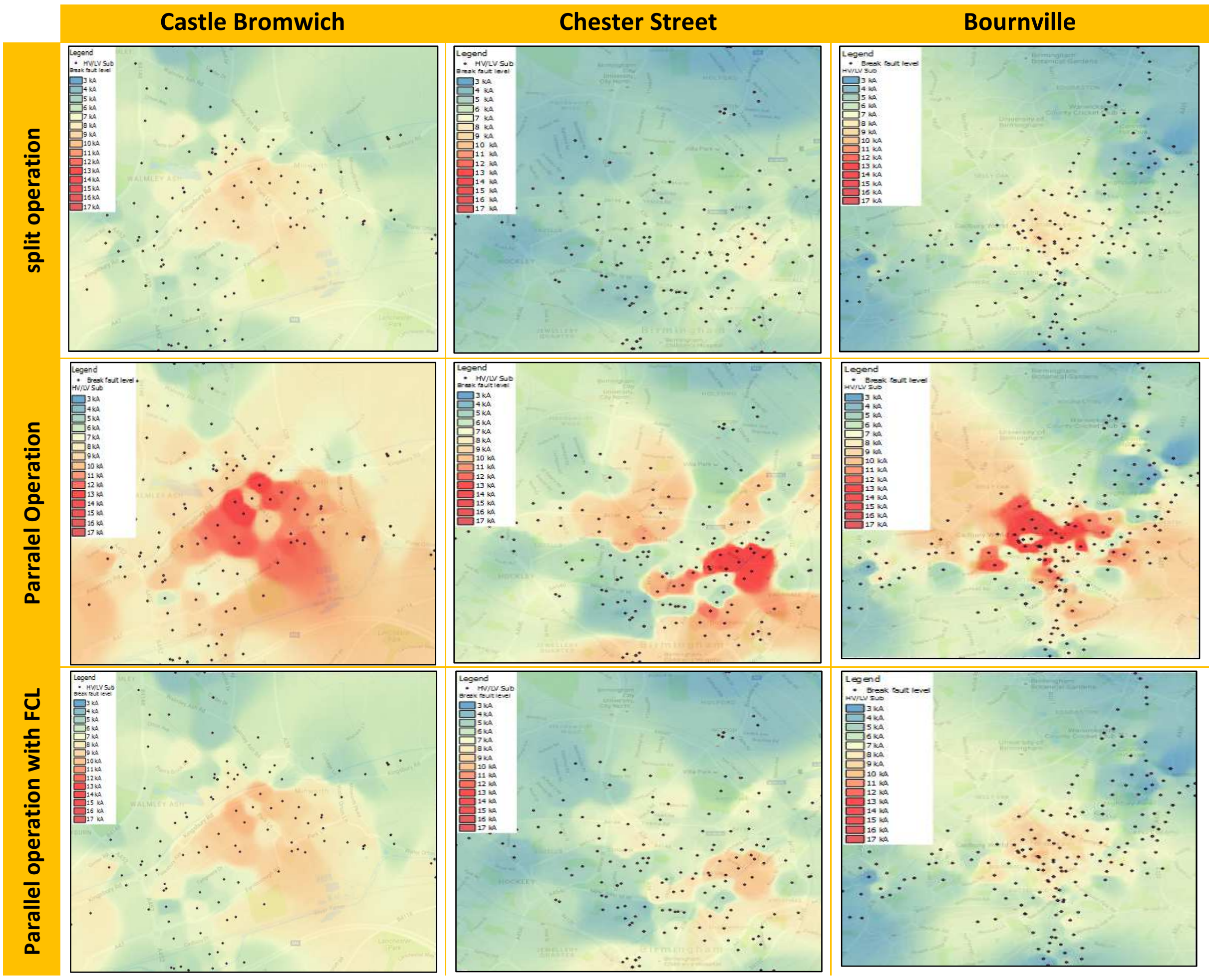

Figure 7-6: RMS Break Fault Levels at the three FCL trial sites in different operating arrangement

7.2 Outcomes for Method Beta

As described in section 0, the project successfully installed an FLM in ten substations within the Birmingham area. Through the operation of the FLM device the following outcomes were achieved.

Customer Flexibility

Following the installation of the FLMs and the acquisition of Make and Break Fault Level values it was possible to enable the network to be operated based on these values, both to increase network security and to facilitate additional, otherwise unfeasible, customer connections. Enhancing existing alternative connections, previously developed by WPD, in the form of policies and procedures, was undertaken as part of FlexDGrid. This involved using our soft-intertrip connection variant, which comprises the use of a constraint panel, shown in Figure 7-7 that was installed to trial the solution as part of the project, and an enhancement to the existing alternative connections customer's connection agreement.

This enables the use of the real-time Fault Level data to determine, based on an appropriate safety factor (as detailed in SDRC-11), and whether a generator can remain connected to the network or must be removed due to a potential Fault Level rating infringement. Analysis, again detailed in SDRC-11, evidenced that a generator is likely to experience around three signals to disconnect from the network each year for an average of four minutes.

Figure 7-7: Fault Level Generation Constraint Panel

Fault Level Data

Collected Fault Level data that was fed back into models developed in Method Alpha informed updates to planning Fault Levels. Using artificial and natural disturbance data along with load and voltage information, it was possible to calculate the MVA/MVA Fault Level infeed at a given substation. By breaking down the load types using metering data, it was possible to determine the Fault Level infeed based on the generic load type. Figure 7-8 shows a graph of MVA/MVA Infeed vs the percentage of domestic load at the substation.

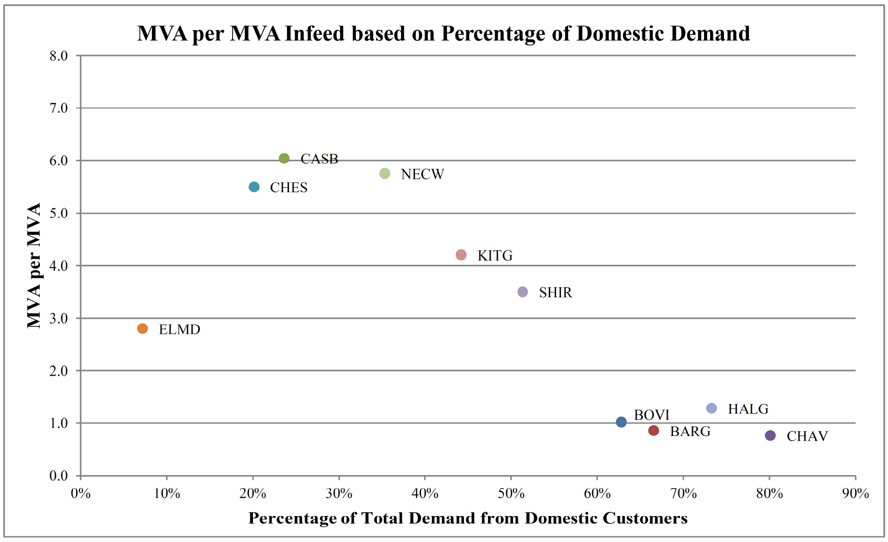

Figure 7-8: MVA per MVA Load Infeed based on % of Domestic Demand at each Substation

TRL Change

At the start of the project the FLM was assessed to be at a TRL of 7. This was due to an installed prototype of the device from the WPD LCNF Tier-1 project “Implementation of an Active Fault Level Management Scheme”. Further development was carried out by manufacturers to meet the requirements of FlexDGrid with refinements added to the device through lessons learnt during testing, installation, commissioning and operation.

The device has been successfully operated at all ten substations for around 18 months with the first device commissioned in October 2014. Through the quantification of results both from the test laboratory and from connection to the live system, the FLM device is now at TRL 8. TRL 9 could be achieved through the development of a consolidated monitoring and communication solution not presently available.

FLM Policies

For FlexDGrid, new policy documents were developed to assist engineers with the connection and operation of FLMs for current and future use. All these policies are live documents available for use within the whole of WPD, and have been previously circulated to other DNOs at various dissemination events via the ENACT portal.

Application and Connection of FLMs – Standard Technique SD4R

This policy details the WPD approved connection options for the FLM along with details of recommended equipment and protection requirements. The document also details other factors to be considered when designing the connection of an FLM.

FLM Specification – Engineering Equipment Specification 201

This policy describes the performance requirements and specifications that all FLM devices to be connected to WPD's 11kV network must adhere to. This details the applicable British and ENA standards to be met along with all WPD specific amendments.

Operation and Control of FLMs – Standard Technique OC1V

This policy describes the standard operational and control requirements for the S&C FLM to ensure that all operators are able to safely control and operate the equipment.

Inspection and Maintenance of FLMs – Standard Technique SP2CAB

This policy provides details to operational staff on how to inspect and maintain each component of the S&C FLM. This policy covers only general maintenance tasks to be completed by WPD staff to ensure reliable operation. Complex inspection and maintenance tasks would be completed by the device manufacture.

7.3 Outcomes for Method Gamma

Overview

The following sections summarise the outputs of Method Gamma. Method Gamma successfully installed and connected three FCLs onto the Birmingham 11kV distribution network:

1. A PSCFCL (Pre-Saturated Core Fault Current Limiter) at Castle Bromwich 132/11kV Primary Substation
2. A RSFCL (Resistive Superconducting Fault Current Limiter) at Chester Street 132/11kV Primary Substation
3. A RSFCL at Bournville 132/11kV Primary Substation

It was originally planned to implement five FCL installations, however, two of the devices could not be installed due to issues with one of the FCL technologies that was being trialled. This is described in more detail in Section 9.4.

A detailed description of the testing, installation and connection works for Method Gamma can be found in SDRC 8 – Installation and Open-loop Tests of Fault Level Mitigation Equipment.

Castle Bromwich PSCFCL

Installation, Connection and Energisation

The Castle Bromwich PSCFCL successfully passed all factory and external laboratory tests on 6th September 2014. After testing, the device was shipped to the UK from Melbourne, Australia and was delivered to site on 10th December 2014. Figure 7-9 below shows the process of skidding the PSCFCL into its final position at site. The device was successfully energised on the 8th April 2015.

Figure 7-9: Castle Bromwich FCL being prepared for skidding into the spare transformer bay

Fault Level Comparison

The requirements for Fault Level reduction of the Castle Bromwich FCL were specified in the initial stages of the project. The information in compares these contractual requirements with the actual fault limiting performance as recorded in the type testing of the device in the laboratory. The values presented are the values the devices limited the Fault Level to. It can be seen that the Castle Bromwich FCL has exceeded the contractual requirements for Fault Level reduction at both peak make and RMS break conditions. This has led to an overall break Fault Level reduction of 20.3% with the FCL connected compared to the network without the FCL installed.

Table 7-1: Fault Level comparison between contract limitation requirements and actual limitation for Castle Bromwich

Scenario	Contract Requirement	Actual Limitation	Margin Over Contract
Peak Make (nom. DC Bias):	10.16kA	10.13kA	+0.1%
RMS Break (nom. DC Bias):	4.06kA	3.71kA	+8.6%
RMS Break (min. DC Bias):	4.06kA	3.75kA	+7.6%

Chester Street RSFCL

Installation, Connection and Energisation

Chester Street RSFCL successfully passed the type tests at the KEMA laboratory in Arnhem, Netherlands on the 5th October 2015. The RSFCL was energised and connected to the 11kV network on the 25th November 2016. An image of the RSFCL in its final position, fully installed and connected at site is shown in Figure 7-10.

Figure 7-10: Chester Street RSFCL positioned and installed at site

Fault Level Comparison

The requirements for Fault Level reduction of the Chester Street FCL were specified in the initial stages of the project. The information in Table 7-2 compares these contractual requirements with the actual fault limiting performance as recorded in the type testing of the device in the laboratory. It can be seen that the Chester Street FCL has exceeded the contractual requirements for Fault Level reduction at both peak make and RMS break conditions. This has led to an overall break Fault Level reduction of 29.8% with the FCL connected compared to the network without the FCL installed.

Table 7-2: Fault Level comparison between contract limitation requirements and actual limitation for Chester Street

Scenario	Contract Requirement	Actual Limitation	Margin Over Contract
Peak Make:	9.90kA	9.14kA	+7.7%
RMS Break:	3.68kA	2.87kA	+22.0%

Bournville RSFCL

Installation, Connection and Energisation

Bournville RSFCL successfully passed the type tests at the KEMA laboratory in Arnhem, Netherlands on 7th December 2015. The device was then successfully transported and installed at site. The RSFCL was energised and connected to the 11kV network on 17th February 2016. An image of the RSFCL in its final position, fully installed and connected at site is shown in Figure 7-11.

Figure 7-11: Bournville RSFCL shown in its final position at site

Fault Level Comparison

The requirements for Fault Level reduction of the Bournville FCL were specified in the initial stages of the project. The information in
compares these contractual requirements with the actual fault limiting performance as recorded in the type testing of the device in the laboratory. It can be seen that the Bournville FCL has exceeded the contractual requirements for Fault Level reduction at both peak make and RMS break conditions. This has led to an overall break Fault Level reduction of 36.6% with the FCL connected compared to the network without the FCL installed.

Table 7-3: Fault Level comparison between contract limitation requirements and actual limitation for Bournville

Scenario	Contract Requirement	Actual Limitation	Margin Over Contract
Peak Make:	7.70kA	6.64kA	+13.8%
RMS Break:	3.05kA	2.05kA	+32.8%

7.4 FCL Network Security

Overview

This section describes the improvements in network security at the sites where an FCL has been installed. A detailed description of the benefits that each FCL technology has provided to the 11kV distribution network is described in SDRC 8 – Installation and Closed-Loop Tests of FLMs and FCLs.

Castle Bromwich PSCFCL

The ability of the PSCFCL to ride-through fault conditions makes it suitable for installation in series with a transformer. The Fault Level reduction provided by the PSCFCL allows for two 11kV transformer windings to be operated in parallel at Castle Bromwich. The security of the 11kV network is increased by the device remaining in service throughout a transformer LV winding fault, with no customers lost. There is no increase in security against 132kV faults due to the configuration of the 132kV network supplying Castle Bromwich not allowing parallels between GT1 and GT2. However, at substations with transformers supplied from diverse 132kV supplies, the device would enable the two transformers to be paralleled with no 11kV customers lost if either 132V circuit experienced a fault.

Chester Street/Bournville RSFCLs

At Chester Street there is a Normal Open Point (NOP) on the 132kV network between GT1 and GT2/GT3 which ruled out the paralleling of GT1 and GT2/GT3 via the FCL. Therefore, the Chester Street RSFCL is connected across the bus section.

At Bournville the 132/11kV transformers are fed from the same GSP. It was chosen to install the RSFCL in the existing interconnector between busbar sections.

The RSFCLs parallel two grid transformers at both Chester Street and Bournville sites. This parallel configuration improves the security of the network. The transformers have to be run in split configuration without the FCL connected due to the existing Fault Level exceeding the equipment ratings. If there is a network fault on the 132kV network one of these transformers will trip, disconnecting the supply to the customers on the respective bus section until the network is reconfigured. Similarly, one of the transformers will trip in the same scenario with the FCL connected in the circuit; however, in this instance the FCL will back feed the bus section that would have been disconnected from the supply in the split configuration. Therefore, no customers are disconnected for a 132kV network fault in this configuration and hence network security is significantly improved.

7.5 FCL Technology Readiness Level

Method Gamma aimed to build upon work that had been carried on previous innovation projects (IFI, ETI and LCNF) to improve the performance of FCLs and align the technologies with the design characteristics normally expected by UK DNOs. As part of the project it was a conscious decision to select technologies at differing TRLs to ensure a wide range of technology types and solutions were trialled.

One of the main focus areas during Method Gamma was the thorough design review process that was implemented with manufacturers. Stage gates throughout this review allowed WPD the opportunity to comment on the designs and make changes before the FCLs began the manufacturing process. The most important requirement for WPD was that the FCLs had to be fail-safe, thus eliminating the possibility of Fault Levels ever exceeding equipment ratings. This was due to the fact that the FCL was paralleling two parts of the networks together and therefore if the FCL were to fail to operate, then Fault Levels could be significantly over the limits of the equipment. In addition the FCL designs closely followed existing equipment principles where possible. For instance, the design review would often refer the manufacturer to follow the requirements of ENA Technical Specifications and adopt standard WPD operational practices.

GridON FCL

The GridON FCL was the most developed technology with a 10MVA unit installed on UK Power Networks 11kV network as part of an ETI project in 2013. Wilson Transformers are partners with GridON and assisted with the device design and were responsible for the manufacture. The FCL supplied for Castle Bromwich was significantly larger than the unit supplied to UK Power Networks as it was rated for currents up to 2000A (in emergency situations). The basic design principles of the FCLs were identical, the only major change being the DC power supply arrangement (the larger FCL had a stepped power supply providing more efficient control of DC power supplies). Having had previous experience of supplying a FCL for a UK DNO and inherent knowledge of building transformers meant that there was only minor points that were addressed during the design review.

The GridON FCL technology was around TRL 7 at the beginning of FlexDGrid as the UK Power Networks unit was the first to be connected to a real operating environment. However, after the installation of the second FCL for FlexDGrid the TRL is thought to be in the region of 8.

Nexans RSFCL

Nexans RSFCL had already been deployed in two trial projects in the UK with ENW and Scottish Power prior to FlexDGrid. The RSFCLs supplied for ENW and Scottish Power were rated at 100A and 400A respectively. It is believed that as both these RSFCLs were trial devices they were not in operation at the start of FlexDGrid. As such the TRL for these RSFCLs was around 7 at the beginning of FlexDGrid.

A number of changes had to be made to the RSFCL during the design review process including:

- The modification of component layouts to ensure maintenance could be performed safely and efficiently;
- The modification of testing specifications to ensure that the functional and operational requirements expected of the device were achieved; and
- Changes to panel wiring to ensure compliance with standard UK DNO practices.

These changes were crucial to ensure that the device met the standard requirements of a UK DNO. Although these changes helped improve quality of the RSFCL, the problems experienced with the closed cooling system has meant that the TRL has not increased significantly and is around 7/8.

GE PEFCL

The GE PEFCL had many issues that were identified during the design process as described in Section 9.4. Despite beginning a detailed design process the device was never tested in a laboratory therefore the TRL is 5.

FCL Policies

Developing new procedures and specifications is a critical part of connecting new technologies to the distribution network. WPD have two types of document for each of the main components installed on the network:

- Engineering Equipment Specification (EE Specification) – This type of document details the information that would be sent to potential suppliers of equipment. The document includes information on the functional, design, construction and testing requirements of equipment.
- Standard Technique (ST) – This type of document details the procedures associated with equipment. The documents generally cover aspects including the integration of equipment into the network and how to safely operate, control, inspect and maintain equipment.

For FlexDGrid a suite of new policies were developed to assist engineers with the connection and on-going operation of FCLs. The policies, as with all others generated as part of FlexDGrid, have been shared with other DNOs via the ENACT Portal. The following section provides an overview of each of policies developed.

Application and Connection of FCLs – Standard Technique SD4S

During the initial stages of FlexDGrid a significant period of time was allocated to defining a standard process of when and how FCLs should be connected to the system. This process was applied for the FCLs for FlexDGrid and captured in a separate WPD policy document "Standard Technique : SD4S – Application and Connection of 11kV Fault Current Limiters (FCLs) for FlexDGrid". This policy is a live document on WPD's intranet and has been circulated to other DNOs at various dissemination events.

FCL Specification – Engineering Equipment Specification 202

The process of producing the technical contract documentation for FlexDGrid and the subsequent review of the FCL manufacturer proposals meant that the project team gained a lot of experience with all different technologies. The key elements of the rating, design, construction and testing of different FCL technologies were captured in a new WPD policy document "Engineering Equipment Specification: EE202 – Fault Current Limiter (FCL) Devices for use on the 11kV Network (FlexDGrid)". The document amalgamated the relevant clauses from other WPD engineering policies along with specific requirements for FCL technologies. This document can now be used by DNOs when tendering for further FCLs on the 11kV network. The document was disseminated to other DNOs during a workshop held on 14th May 2014.

Operation and Control of FCLs – Standard Technique OC1Y/1 & OC1W/1

Prior to connecting any new device to the network it is imperative that policy documents are produced to ensure that all operators are able to safely control and operate the equipment. A Standard Technique was developed for the operation and control of each FCL technology. Before the technology was connected to the system the document was circulated to the relevant departments in WPD for comment before final approval. Each Standard Technique explained how the technology operated and what processes must be followed for safe energisation and de-energisation. In addition, each of the main device functions are described along with reference documentation so that operators can easily identify any alarms or faults should they occur.

Inspection and Maintenance of FCLs – Standard Technique SP2CAA & SP2CAC

Two separate Standard Techniques were produced for the inspection and maintenance of the FCLs. Similar to the operation and control Standard Techniques, these two documents were produced and approved before the FCLs were connected to the network. The documents were produced in collaboration with the FCL manufacturers to determine the routine inspection and maintenance procedures for each technology. Safety is at the forefront of these documents as they describe the processes that should be followed when carrying out both visual inspections and intrusive maintenance.

The maintenance intervals associated with these Standard Techniques are included in WPD's maintenance logging system, CROWN. After the FCLs were connected to the system, the details were logged and the system automatically generates work items based on the maintenance intervals. The operators undertaking the maintenance can then refer to the relevant Standard Technique.

7.6 Outcomes of Societal Investigation

The socio-economic research work conducted as part of the FlexDGrid project has investigated the attitudes towards district heating schemes of a representative sample of residential energy consumers in Birmingham, the likelihood that they would join a local district heating scheme if this opportunity was offered to them and the potential financial benefits possible through the uptake of such a scheme. The research also looked at the potential benefits in terms of the monetary gains and increased comfort which could accrue to vulnerable consumers, such as those who could be classed as fuel poor and those who exercise fuel rationing for lack of affordability.

The analysis of the likelihood of residential consumers to participate in local district heating schemes and the potential benefits accruing to them was based on a telephone survey of residential energy users in Birmingham, conducted between May and June 2014. The survey generated a sample of 800 individuals generally representative of the Birmingham population.

Our results highlight a generalised lack of knowledge about district heating and its potential economic and environmental benefits. Despite this, there is a high level of interest in finding out more and considering the possibility of connecting to a district heating scheme, provided the payback time for the initial investment is relatively short (or subsidised). While the participation in district heating schemes would be most beneficial to vulnerable consumers, financial and technical issues may prevent such adoption. The characteristics of the dwellings in which vulnerable customers commonly reside might create significant issues to the installation of district heating schemes.

Our results indicate that vulnerable consumers could benefit from joining a district heating scheme not only in financial terms but also through improved levels of comfort, and possibly wellbeing. However, vulnerable consumers might require additional support in making the decision to join a scheme in order to overcome concerns about a technology which is not well known and in some cases has a reputation of unreliability. Financial help, in the form of subsidies or discounts, might also be needed to reduce the upfront cost of the technology, which can be perceived as unaffordable by low income and credit constrained groups.

8 Performance Compared to the Original Project Aims, Objectives and Success Criteria

8.1 Overview

The three Methods of FlexDGrid aimed to achieve the following upon completion of the project:

(i) Defer/avoid capital investment for customers and DNOs;
(ii) Avoid long connection lead times for low carbon generation;
(iii) Increase network efficiency and reduce Customer Interruptions (CIs) and Customer Minutes Lost (CMLs); and
(iv) Secure long term sustainable and affordable electricity prices with assisted living benefits from Combined Heat and Power (CHP).

8.2 Method Alpha

Method Alpha successfully contributed to the two FlexDGrid's original aims and objectives as described in Table 8-1 below:

Table 8-1: The contribution of Method Alpha to the original project aims

Project Aim	Contribution	STATUS
Defer/avoid capital investment for customers and DNOs	A detailed model of the HV network developed in FlexDGrid can provide a better voltage profile along the HV networks and subsequently more accurate calculated Fault Levels compared to those in BaU approach. As demonstrated in SDRC-4, an enhanced and granular network modelling may result in up to 5% reduction in calculated fault current contribution from generators. This can defer the investment that otherwise may be required for connection of new customers. In addition, Method Alpha has enhanced the network modelling knowledge by demonstrating sensitivity of calculated Fault Levels to the network model parameters. This enhancement can inform Primary System Design engineers to ensure the most influential network model parameters are checked and verified prior to Fault Level analysis. This can reduce the possibility of over estimation of Fault Levels and requesting unnecessary network upgrade for connections of customers.	✓
Avoid long connection lead times for low carbon generation	The automation process for modelling the HV networks which was developed in FlexDGrid has significantly reduced the network modelling time and consequently the lead time of connection studies. Data is now available in a quicker and more accurate way by extracting the latest network topology from the most up to date asset data base in the business.	✓

	Fault Level Guidance Tool was also developed for planning engineers who may not have access to the power system analysis software. This tool provides existing network data and network equivalent impedances which usually require a time-consuming process to be obtained. Fault Level Guidance Tool provides quicker access to necessary network data and a reliable Fault Level calculation tool. The FCLs that were trialled in Method Gamma are now live assets and they need to be considered in BaU Fault Level calculations. The modelling of FCLs can be time consuming as they are complex and nonlinear devices. Method Alpha provided a simple and fit-for-purpose approach for modelling of FCLs and incorporating their models in BaU Fault Level analysis process. The proposed approach eliminated any adverse impact on lead time of Fault Level calculations when the FCLs are taken into account.	

8.3 Method Beta

The installation and operation of FLMs has provided greater understanding and granularity of existing Fault Levels in Birmingham. The information and data being collected has been integrated into WPD main business providing both real-time and historic Fault Level information. This information is now being utilised by system planners for informing capital investment plans and for the planning of generator connection options. The inclusion of Fault Level soft-intertrip within WPD's alternative connections policy means that a standard system is in place for the connection of customers based on the real-time data of the FLM. This type of constrained connection would enable customers to connect without the need for major capital investment works. In turn this will lead to a dramatic reduction in the lead times for connection of low carbon generation in Fault Level constrained networks. The ability to allow greater penetration of Low Carbon Generation and CHP units within fault limit constrained networks will assist in securing long term sustainable and affordable electricity.

The FLM data is available in real-time to control engineers. This allows the network condition to be monitored and switching decisions made based on controlling Fault Levels. This enables switching to reduce potential CIs and CMLs through paralleling of the network or the safe transfer of loads under fault conditions.

Table 8-2: The contribution of Method Beta to the original project aims

Project Aim	Contribution	STATUS
Secure long term sustainable and affordable electricity prices	The availability of the real-time FLM data and the use of Fault Level soft-intertrip alternative connections enables much greater utilisation of existing assets, which enables capital investment to be significantly reduced and therefore secure the long term affordability of electricity.	✓

8.4 Method Gamma

Method Gamma contributed to the success of all four of the project aims detailed above. The following Table 8-3 describes the successful contribution of Method Gamma to each of the project aims in turn.

Table 8-3: The contribution of Method Gamma to the original project aims

Project Aim	Contribution	STATUS
Defer/avoid capital investment for customers and DNOs	Each of the FCL devices installed as part of this project has exceeded the contractual requirement for Fault Level reduction at the respective sites where they have been installed. This has had the effect of allowing either more load or distributed generation to connect before existing switchgear Fault Level ratings are exceeded. This is highlighted in Table 8-4 below.	✓
Avoid long connection lead times for low carbon generation	The FCLs have increased Fault Level headroom at the sites where they have been installed. This increase in headroom means that there is now increased capacity at the primary substation to connect low carbon generation without the need for traditional network reinforcement which is associated with lengthy lead times and high costs.	✓
Increase network efficiency, CIs and CMLs	The FCLs have contributed to increased network efficiency and security. This is described in more detail in Section 7.4 of this report.	✓
Secure long term sustainable and affordable electricity prices	Each of the contributions described above acts to satisfy this project aim. The FCLs have allowed the deferment/avoidance of costly network reinforcement whilst also introducing Fault Level headroom for the connection new CHP generation. This will have a significant benefit of allowing affordable heating to homes as well as long term sustainable electricity.	✓

Table 8-4 below indicates the additional generation, in MVA, that can be connected to the associated substation based on a typical generator infeed of 4.5MVA/MVA. The table shows that 52MVA of additional generation can be installed on the Birmingham 11kV distribution network following the installation of the three FCLs as part of this project.

Table 8-4: Additional generation that can be connected to each site where an FCL is connected

Substation	Generation Increase (MVA)
Castle Bromwich	13MVA
Chester Street	19MVA
Bournville	20MVA
TOTAL	**52MVA**

9 Required Modifications to the Planned Approach during the Course of the Project

9.1 Overview

As is good practice in all innovation projects specific methodologies and processes identified at the outset of the project were modified and developed to ensure that the project both delivered the prescribed and committed learning but also delivered to the original budget and the timelines set out in the bid document. In the following sections specific detail is provided regarding the modifications to the planned approach to the project.

9.2 Method Alpha

Modelling additional 11kV network and automating the modelling process

The initial plan was to develop computer models of the 11kV networks of ten primary substations selected to implement Method Alpha and Method Gamma. The models were intended to provide a test bed for demonstrating the enhance Fault Level assessment and evaluating performance of Method Gamma and Method Beta. The following modifications were undertaken in modelling the network.

(i) **Developing an automation process:** It was planned that models would be developed mainly manually as this approach was carried out in the proposal preparation stage. However, in delivery stage and as project progressed, an automation tool was developed which significantly improved the quality of the models and ensured repeatability, which reduced the possibility of human error in the modelling process.

(ii) **Modelling additional substations:** As project progressed, some of the primary substations which were initially selected for implementation of Method Beta were replaced with new primary substations. Consequently, it was required to develop the model of the new substations. In addition, it was decided to develop the 11kV network model of Summer Lane substation as it was an opportunity to test the automation process on the most electrically complex substation in Birmingham with 78 circuits. In total, the models of 11kV networks of 15 primary substations were developed as part of Method Alpha.

9.3 Method Beta

At the start of the project it was set out in the bid document to develop alternative connection methodologies for new connecting customers where the restriction and / or constraint on the network connection was Fault Level related. At this point no DNO, including WPD, had created any alternative connection processes or documentation, however, throughout the delivery of FlexDGrid WPD as well as other DNOs have created detailed alternative connection methodologies, policies and procedures based on thermal and voltage limitations. This meant that for FlexDGrid not only did we develop alternative connections methodologies but we also created a suite of policies and procedures, in line with what had been created for voltage and thermal connections.

9.4 Method Gamma

As discussed in previous sections the original aim of FlexDGrid was to install five FLMTs on to the 11kV network, however, throughout the delivery of the project, the GE Power Electronic FCL was not suitably developed and delivered to support the project's timescales, this meant that the number was reduced to three. This process was handled as part of a formal change request to Ofgem, whereby it was demonstrated that significant learning and benefits could be driven from the installation of only three FLMTs. At the outset of the project it was identified that to provide the greatest amount of learning on the project a number of FLMTs should be installed and at differing TRLs, which drove the selection of the lowest TRL FLMT, GE's Power Electronic FCL. As part of this change request it was also highlighted that the cost of the installation of the three successfully integrated FLMTs was greater than originally planned. Within the approved and accepted change request the true cost of each FLMT installation was highlighted and presented to ensure that this learning can be shared amongst interested parties and stakeholders. These details are also captured in Section 10. It should be noted that this change in cost did not increase the cost of delivery for the full project, where the total project budget reduction was £2.32M.

10 Significant Variance in Expected Costs and Benefits

Table 10-1: FlexDGrid Finance by Line Item

	Original Total Budget	Re-baselined Budget	Actual	Var £	Var %
Labour	1809.49	1480.68	1114.13	-366.55	-25%[1]
WPD Project management	320.00	320.00	246.90	-73.10	-23%
Detailed Investigation of Substation for Technology Inclusion	71.26	71.26	29.44	-41.82	-59%
Detailed Investigation of Technologies	71.14	71.14	29.43	-41.71	-59%
Detailed design of substation modifications for Technology Inclusion	72.43	72.43	0.00	-72.43	-100%
Determine Enhanced Assessment Processes	71.88	71.88	0.00	-71.88	-100%
Create Advanced Network Model	72.32	72.32	0.00	-72.32	-100%
Installation of Fault Level Measurement Technology	5.75	5.75	0.00	-5.75	-100%
Installation of Fault Level Monitoring Technology	296.65	296.65	323.35	26.70	9%
Installation of Fault Level Mitigation Technology*	445.10	313.38	313.38	0.00	0%
Installation of VCU Technology*	148.11	0.00	0.00	0.00	0%
Capture, Analyse Data and performance	234.85	185.87	171.63	-14.24	-8%
Equipment	9779.63	8162.65	8156.20	-6.45	0%
Procurement of Fault Level Measurement Technology	117.01	117.01	128.96	11.95	10%
Installation of Fault Level Measurement Technology	9.58	9.58	8.52	-1.06	-11%[2]
Procurement of Fault Level Monitoring Technology	1554.99	1554.99	1494.85	-60.14	-4%
Installation of Fault Level Monitoring Technology	494.52	494.52	539.03	44.51	9%
Implementation of Real Time Modelling	3.76	3.76	3.13	-0.63	-17%[2]
Procurement of Fault Level Mitigation Technology*	5830.14	5214.14	5214.14	0.00	0%
Installation of Fault Level Mitigation Technology*	741.84	765.57	765.57	0.00	0%
Procurement of VCU technologies*	777.86	0.00	0.00	0.00	0%
Installation of VCU Technology*	246.85	0.00	0.00	0.00	0%
Equipment to enable modelling and technology installation	3.08	3.08	2.00	-1.08	-35%[2]
Contractors	1927.36	1927.36	1836.67	-90.69	-5%
PB Project Support	340.94	340.94	317.00	-23.94	-7%
Detailed Investigation of Substation for Technology Inclusion	96.14	96.14	103.60	7.46	8%
Detailed Investigation of Technologies	102.89	102.89	107.98	5.09	5%
Detailed Design of Substation Modifications for Technology Inclusion	48.85	48.85	51.04	2.19	4%
Determine Enhanced Assessment Processes	64.85	64.85	65.88	1.03	2%
Create Advanced Network Model	51.38	51.38	52.00	0.62	1%
Implementation of Real Time Modelling	350.94	350.94	315.61	-35.33	-10%
Capture Monitored & Measured Data	49.61	49.61	48.18	-1.43	-3%
Analyse Monitored and Measured Data	157.49	157.49	146.64	-10.85	-7%
Verify and Modify Advanced Network Models	253.89	253.89	251.32	-2.57	-1%
Gather Performance of Mitigation Technologies	50.07	50.07	48.69	-1.38	-3%
Knowledge Capture and Learning Dissemination	281.62	281.62	251.46	-30.16	-11%[3]
Procurement & Installation Support	78.69	78.69	77.27	-1.42	-2%

IT	57.73	**57.73**	**43.15**	**-14.58**	**-25%**
IT Costs	57.73	57.73	43.15	-14.58	-25%[4]
IPR Costs	3.29	3.29	1.94	-1.35	**-41%**
IPR Costs	3.29	3.29	1.94	-1.35	-41%[5]
Travel & Expenses	465.62	**465.62**	**402.06**	**-63.56**	**-14%**
Travel & Expenses	465.62	465.62	402.06	-63.56	-14%[6]
Contingency	1407.05	**1030.24**	**111.37**	**-918.87**	**-89%**
Contingency*	1407.05	1030.24	111.37	-918.87	-89%
Other	27.21	**27.21**	**17.45**	**-9.76**	**-36%**
Other	27.21	27.21	17.45	-9.76	-36%
TOTAL	15477.38	**13154.78**	**11682.97**	-1471.81	**-11%**

*Line cost changed as per change request

Many of the variances to the expected costs have been described in previous six monthly progress reports submitted. Below is a description of each under or over spend of greater than 10%.

Note 1 – All Labour costs are underspent due to the previously documented change in split of activities between WPD internal and WSP's external resource.

Note 2 – for the three identified equipment underspends of greater than 10% their underspend total is £2.77k. The supporting equipment to enable the implementation of monitoring technologies was lower cost than originally anticipated.

Note 3 – Additional internal resource was provided for the knowledge capture and dissemination activities in the form of a Data Analyst, which reduced the reliance on contractors to provide this resource.

Note 4 – Existing WPD IT has been used to date minimising the projected expenditure.

Note 5 – No protectable foreground IPR was generated throughout the project and therefore the costs associated were reduced.

Note 6 – Remote working facilities were used and online storage repositories which reduced the requirement to travel.

11 Lessons Learnt on the Method

11.1 Method Alpha

Table 11-1: Lessons learnt Method Alpha

Item	Learning
Detailed network model	Detailed network model of the HV network can provide a more accurate pre-fault voltage conditions, resulting in more accurate Fault Level calculations.
Tap setting impact on FL	The tap position at Primary Substations has a large effect on the calculated fault currents. Care should be taken to model the network with the tap at the position which results in a network voltage profile representing the system condition in real life.
Generator's power factor impact on FL	The generator power factors have a large impact on their fault current contributions. For a similar power export, a generators fault current contribution when operating in leading power factor is smaller compared to operation in lagging power factor. Thus, if possible the actual power factor of the generators should be considered when modelled. The power factor control strategy may be also considered for a real-time FL management scheme.
General Load fault infeed	General load fault infeed largely affects the making fault current where it has little impact on Breaking fault current. It is recommended that large synchronous and asynchronous motors (or large concentrations of such motors) are modelled if possible.
Circuit equivalent calculation technique	The equivalent impedance (X and R) between a source and a load point in a network can be calculated through calculation of active and reactive network losses.
PSCFCL pre-fault impedance impact	Insertion of PSCFCL in series with one leg of three winding primary transformers can affect the firm capacity. The FCL impedance in normal operation is large enough to cause an unbalanced power flow in secondary windings.
FCL Modelling	The complex transient FCL models developed in house by manufacturers are not fit for purpose for BaU Fault Level assessment studies. In order to develop a fit for purpose model a look up table for impedance of the FCL at Breaking and Making times may be used.
PSCFCL modelling/ performance	Larger fault currents when the DC bias is low (130A) in the PSCFCL may result in a lower Impedance at peak time (10ms) compared to the break time (70ms). This usually happens when the pre-fault FCL loading is low, and a low DC bias is required to saturate the FCL core. In this condition, the fault current at transient time can be high and that pushes the FCL magnetisation status through the non-saturated state through to a further saturation point, after transient time the fault current decreases and therefore the core would be "less" saturated, increasing its impact on fault current reduction.

RSFCL modelling	The resistance of the RSFCL at a time during a fault may depend on the magnitude of fault currents in previous intervals during the fault. This is due to the amount of heat generated in the HTS during the fault in different intervals. For example, the devices' instantaneous impedance at the breaking time may depend on both Make fault current and Break fault current.

11.2 Method Beta

Benefits Affected

Analysis of the data from the FLMs showed that measured Fault Levels in most cases were higher than estimated. This was found to be caused by larger 11kV MVA/MVA Fault Level infeed values than previously used for the 11kV network. This has meant that the benefits are reduced as the predicted Fault Level capacity release did not materialise in operation.

Learning Points

Table 11-2: Lessons learnt Method Beta

Item	Detail
FLM Device Accuracy Issues	Initial testing of the FLM device identified several issues with the accuracy of the recording equipment and current transducers. Installation of devices on the network and the provision of actual data, enabled the manufacturer to develop the measurement software further so when retested the device performed to specification.
Integration of FLM within existing substations	Many substations were unable to accommodate the FLM or available space was restricted. This will potentially limit the installation of the current FLM device in the wider electricity network. The FLM therefore may need further development to be more widely accessible.

11.3 Method Gamma

Financial Benefits

The original business case for Method Gamma was based on the cost of traditional network reinforcement compared against the costs for installing FCL equipment. It was estimated that the cost of traditional reinforcement would be around £9.7m per substation, whereas the method would deliver this at around £2m per substation. The overall savings for WPD West Midlands was estimated to be around £38.4m if the method was deployed across the region.

Despite the complex installation and high procurement costs for the technology, the actual method cost per substation is just under £2m (average cost across the three FCL installations – detailed provided in the project's change request). Therefore, the original business case for the project is still valid and could achieve substantial savings if deployed across UK DNOs.

Learning Points

Table 11-3 summarises the main learning points that have been captured within this report that could be used for future innovation projects.

Table 11-3: Lessons learnt Method Gamma

Item	Learning
PSCFCL Magnetic Field	The high magnetic field emitted from the presented a number of challenges during the design and installation. For any future PSCFCL installation the following points shall be considered: i) The magnetic field should be controlled as much as possible to ensure that only a small controlled exclusion zone is required. ii) Sensitive auxiliary equipment should be located away from the main source of the magnetic field. iii) Detailed designs for magnetic field mitigation should be submitted at an early stage so that it can be included in the initial design phase.

12 Lessons Learnt for Future Innovation Projects

This section describes learning that was generated as part of the FlexDGrid project and is considered useful for future innovation projects to ensure that outputs and benefits are realised. A key learning point throughout the project is the availability of data and the location of such data. Projects focussing on Common Information Models (CIM) would have a significant benefit to many elements of this and future projects. Some generic learning for technology projects is included within Table 12-1.

Table 12-1: Learning points from design and installation of Technologies

Item	Learning
Increased footprint and weight	All the dimensions and weights of technologies that were provided in the original ITT documentation increased during the design phase. WPD provided an additional 20% margin on top of these original figures when designing the integration of the technologies. This meant that the increases during the design phase could be accommodated with only minor changes to the original integration designs. Allowing an appropriate margin for changes in design is recommended for projects where new technology is being installed in existing substation sites.
Cooling	During the project a number of issues were discovered with cooling systems. If a cooling system is to be used for any future innovation devices, it is imperative that the cooling system is designed such that: i) Sufficient margin is provided in the cooling power required to keep the device at its set point temperature. ii) Ensure that the cooling system is fully tested and also run for an extended period of time to confirm that the cooling system can dissipate the required energy and is reliable prior to installation on site. iii) If possible avoid having cooling systems with a significant number of moving parts and connections. This reduces the on-going maintain requirements and energy consumption of the device.
Schedule of responsibility	During the installation of technologies there are a number of instances where the manufacturer and contractor disagreed on the responsibilities for carrying out certain tasks. This was partly

	due to the manufacturers being less experienced in the installation of equipment in high voltage substations. It is recommended that both manufacturer and contractor attend regular site visits before and during the construction phase to agree the safe working methods and responsibilities.

12.1 Method Alpha

In order to facilitate the integration of a solution into Business as Usual after completion of an innovation project, it is recommended that, post-trial users within the business are identified and engaged as project progresses.

The methodologies and algorithms trialled in an innovation project may be integrated into tools which can be used to enhance the BaU process after project completion.

12.2 Method Beta

Table 12-2: Lessons learnt from Method Beta

Item	Learning
Close working relationship with Suppliers	Development of a close working relationship with suppliers during the project ensured that when issues arose, solutions could be discussed and assessed openly, leading in most cases to a quick resolution.
Replicating learning across installations	For projects involving installation of a device or equipment at multiple sites, staging works in such a way to allow a period of time between installation of the first site and the next ensures that lessons learnt through installation and commissioning can be suitably captured and reflected at all other sites

12.3 Method Gamma

Table 12-3 summarises general 'lessons learnt' that could be used for the betterment of future innovation projects.

Table 12-3: Lessons learnt from Method Gamma

Item	Learning
Developing Contracts	The contracts that were produced for the FCL devices captured the requirements of WPD in great detail and were a useful instrument to ensure manufacturers met expectations. However, there are some aspects of the contracts that could be made more robust to strengthen the position of customer and make the responsibility of the manufacturer clearer.

	The main areas that would be strengthened are: • Strict compliance with UK DNO specification and policies • Payment milestones weighted towards successful testing and installation • Tailor the contract more towards the requirements for individual technologies In addition, the contract documentation should confirm the key members of the manufacturer's team required to deliver the project. It is a recommendation that the contract should specify the procedures that should be followed if one of the key members changes during the course of the project. This would mitigate the customers exposure to risks associated with the delivery of the project.
Detailed design review	Throughout the project significant effort was focussed on the design review of manufacturer designs. The investment of time and resource at this stage of the project allowed many technical, operational and safety aspects to be resolved efficiently prior to testing and installation at site. It is also recommended that future innovation projects set aside regular face-to-face stage gate review meetings with equipment manufacturers to address open design review issues efficiently.
Testing Specifications	It is the recommendation of this report that testing specifications for new innovation equipment are treated with a high priority. Innovation equipment is often at a low TRL and is not directly represented by international standardisation. As such, additional effort is required to identify the appropriate tests to be performed; finalise the test method and test set-up; and select the appropriate test acceptance criteria. A further learning point would be to allow sufficient time in the project programme for draft submissions of the testing specification well in advance of factory testing. This can be combined with the detailed design stage gate review meetings. This is to ensure that the final version is ready well in advance of the testing and that all parties are satisfied with its contents.

13 Project Replication

13.1 Method Alpha

To replicate the production of the enhanced network models a semi-automated model builder was developed. This builder, when input with network data details, such as cable lengths, types, substation loads and network switching points, can build a full database suitable for the production of a PSS/E network model. This model builder would enable the replication of the enhanced network models to be produced in a much shorter time that taken as part of the project.

As well as the facility for a quick and accurate model production tools have also been developed and trialled as part of the project that have enabled a new set of network engineers to have access to Fault Level data not previously available. This is in the format of a HV guidance tool.

Finally FLMT modelling tools have been created that would both serve to enable the replication of the effects of the FLMTs on the network to be modelled but to also advance the methodology for the selection of a suitable FLMT to be installed on another network.

13.2 Method Beta

Equipment

The FLM installed was developed by S&C Electric and consisted of the following components:

- S&C Electric IntelliRupter Pulse Re-closer
- Outram Research PM7000 plus current transducers
- Nortech Envoy FLM controller
- HVR Resistor block

To replicate the work carried out as part of Method Beta, two WPD polices were created. Application and Connection of FLMs – Standard Technique SD4R provides details of approved FLM equipment and how the FLM can be connected to the network. The second policy FLM Specification – Engineering Equipment Specification 201, provides a detailed engineering specification for all FLM devices to be connected to the WPD network.

Business as usual costs

Standardised designs for the FLM have been developed and are available for replication across the business reducing design costs considerably. Going forward, following safe and reliable operation of all FLMs, the necessity of requiring dedicated FLM circuit breakers could be relaxed. This will allow the FLM to be connected directly to the existing network without the expense of new circuit breakers. Additional costs will be incurred to fully integrate the FLM data and control operations into the existing network management system for each substation.

Based on the learning generated from the project, described above, it is expected that for the installation of an FLM there would be a reduction of 20% meaning £165k per install. This would typically enable 3MW of generation on a flexible basis meaning a saving of £435k based on £200 per kW connections as per the charging methodology.

13.3 Method Gamma

Equipment

As part of the project it has been proven that both the Pre-Saturated Core FCL and Resistive Superconducting FCL can be successfully integrated in to the network and specific policies have been produced to facilitate this replication. The policies produced to enable this focus on the Engineering Specification that enables an appropriate tender and procurement activity to be carried out and the technical policies, Application and Connection, Inspection and Maintenance and Operation and Control, which enable the devices to be connected and operated on the system.

Business as usual costs

Following the development of the technologies as part of the project there was significant effort from the project team as well as design and testing costs for the device manufacturers, these costs can now be removed as the initial system design and testing is now complete. As documented in the Application and Connection policy it specified as part of the project that a number of circuit breakers were to be installed to enable appropriate protection and operational provision of the devices, however, based on the learning generated from the project the requirements for the additional circuit breakers, as per the FLM, could be removed and this would significantly reduce the installation costs of each FLMT device.

The capital and operating running costs of each of the technologies over the lifetime of the project, when extrapolated to be considered over the whole lifetime asset assessment have shown that the technologies are viable alternatives to traditional Fault Level solutions.

14 Planned Implementation

14.1 Method Alpha

The development of an enhanced Fault Level assessment methodology has been successfully completed and reported earlier in this document and as documented in several SDRC submissions. This assessment has highlighted the value of providing greater granularity of the full network model. The planned implementation is to assess the requirement for this additional detail on a case by case basis, which will also include which elements to implement for a given scenario. An example would be the granular aggregation of load across the system as opposed to following the existing G74 methodology, where all load is lumped at a specific network location. The expansion of the modelling methodology to other dense urban environments such as Nottingham and Bristol is planned and will be considered as part of our business planning process where prioritisation is planned as part of active consultation through our connections stakeholders.

14.2 Method Beta

As documented in both SDRC 9 and SCRC 11 the necessary commercial policies and customer facing documents have been updated to include provision for the roll-out of the commercial arrangement trialled within FlexDGrid. The WPD SD10/2 policy covering ‘Alternative Connections’ has been amended to include provision for ‘Fault Level Soft-Intertrip’ connections at the sites where WPD have FLM equipment available.

Whilst the technology deployed as part of FlexDGrid is scalable, robust and accurate further development would provide even greater flexibility in terms of the locations of installations and applications and it is likely that this further development would be required to enable wider deployment of FLMs on the system. Two potential future applications have been identified. Firstly, a mobile FLM that can be moved between sites providing short term monitoring to assist in identifying Fault Level issues. The second is the development of a Power Electronic FLM. This is likely to have a smaller footprint then the current technology enabling easier installation at a wider range of substations. Both options would minimise interfaces with existing equipment with potential benefits being a lower installation cost, improved accuracy and reliability. The technical policies for staff to utilise these solutions for the benefits of customers, as described above, are readily available.

As with the modelling process we will be making customers aware of this technology availability through our connections stakeholder group.

14.3 Method Gamma

The two different FLMT types installed as part of the project, pre-saturated core and resistive superconducting have been shown to release greater network capacity and improve system security than traditional Fault Level solutions. The pre-saturated core device has been shown to be the most appropriate for future network inclusion, based on the systems availability and reliability. The existing policies will be updated to enable these devices to be considered as an alternative to traditional network Fault Level solutions immediately. The policies to enable the installation, operation and maintenance of the FLMTs are complete and available to facilitate this.

Further work relating to the operation and reliability of the resistive superconducting devices is required to suitably demonstrate that their availability and reliability are great enough to ensure that a customer's connection is robust and secure. This will include changing the cooling methodology of the device from a closed loop to an open loop cooling system.

15 Learning Dissemination

WPD have actively engaged with stakeholders to obtain opinions, gain learning and share outcomes throughout the course of FlexDGrid. This engagement has helped develop the understanding of Fault Level issues in the UK and address the aims originally set out at the start of the project.

Learning dissemination has taken place in various forms during the project including:

- Workshops with UK DNOs and other stakeholders
- Presentations (individually led and also at events / conferences)
- Site visits with UK DNOs
- Publication of technical papers
- LCNI Conference
- Website

Various presentations and workshops were held on a regular basis and attended by UK DNOs and other stakeholders. Feedback on the proposed methodologies and processes for FlexDGrid were received during the initial workshops and this was very useful for ensuring the successful delivery of the project aims. The primary focus for later presentations and workshops was the learning that was obtained from delivering the methods.

Trialling of the different methods resulted in new processes and procedures being developed. These in conjunction with the learning from the methods, were used to produce a number of technical papers which were published and presented at various conferences and events. The generator constraint panel used to issue generator commands are already installed as business usual across the four licence areas and, as mentioned previously, the necessary policy updates have been undertaken and documented as part of the SDRC 11 report.

Throughout the project there has been a significant element of international interest in the learnings and outcomes of the project. This has focussed on the various international dissemination events and principally at CIRED over the lifetime of the project. The project has now been globally recognised as a leading project in Fault Level and has been invited to host a Fault Level Tutorial at the 2017 CIRED event in Glasgow, Scotland.

UKPN have carried out a thorough peer review of the information provided in the Closedown Report and supporting documentations and have produced a letter documenting the project's findings, outputs and learning attached as an appendix.

16 Key Project Learning Documents

16.1 Project Progress Reports

Dec 2012 - May 2013: https://www.westernpowerinnovation.co.uk/Document-library/2013/PPR_WPD_FLEXDGRID_MAY2013_PUBLIC.aspx
June 2013 - Nov 2013: https://www.westernpowerinnovation.co.uk/Document-library/2014/Project-Progress-Report-Nov-2013-FlexDGrid.aspx
Dec 2013 – May 2014: https://www.westernpowerinnovation.co.uk/Document-library/2014/WPDT2004_FlexDGrid_May14PPR_Issue1.aspx
June 2014 – Nov 2014: https://www.westernpowerinnovation.co.uk/Document-library/2014/FlexDGrid-Nov-14-PPR-V1-0.aspx
Dec 2014 – May 2015: https://www.westernpowerinnovation.co.uk/Document-library/2015/FLEXDGRID-Progress-Report-May-2015.aspx
June 2015 – Nov 2015: www.westernpowerinnovation.co.uk/Document-library/2015/FLEXDGRID-Heat-and-Power-for-Birmingham.aspx
Dec 2015 – May 2016: https://www.westernpowerinnovation.co.uk/Document-library/2016/WPDT2004_FLEXDGRID_PPRMAY2016_V1.aspx
June 2016 - Nov 2016: https://www.westernpowerinnovation.co.uk/Document-library/2016/Jun-16-Nov-16-PPR-FlexDGrid-V2F.aspx

16.2 Presentations

Presentation - Balancing Act September 2016:
https://www.westernpowerinnovation.co.uk/Document-library/2016/Balancing-Act-FlexDGrid.aspx
Presentation – Active FLM in Birmingham:
https://www.westernpowerinnovation.co.uk/Document-library/2014/FlexDGrid-Workshop-1-Programme-2013-05-02.aspx
Presentation – Fault Level Mitigation Technologies:
https://www.westernpowerinnovation.co.uk/Document-library/2013/FlexDGrid-Powerpoint-presentation-Sep-2013.aspx
Presentation – The Implantation of Enhanced Fault Level Assessment Processes:
https://www.westernpowerinnovation.co.uk/Document-library/2013/FlexDGrid-Workshop-3-Presentation-Oct-2013.aspx
Presentation – Technical Dissemination:
https://www.westernpowerinnovation.co.uk/Document-library/2017/FlexDGrid/FDG-Tech-Diss-Event-26-04-17.aspx

16.3 SDRCs

SDRC1 Report – Development of an enhanced Fault Level assessment process:
https://www.westernpowerinnovation.co.uk/Document-library/2013/2013-12-06-SDRC-1-Report-Appendices-V007.aspx
SDRC2 Report – Confirmation of the project detailed design:
https://www.westernpowerinnovation.co.uk/Document-library/2013/2013-12-06-SDRC-2-Report-Appendices-V005.aspx
SDRC3 Report – Fault Level Mitigation Technologies Workshop:
https://www.westernpowerinnovation.co.uk/Document-library/2014/FlexDGrid-SDRC-3-Report-Appendices-V001.aspx
SDRC 4 Report – Simulating and applying enhanced Fault Level assessment processes:
https://www.westernpowerinnovation.co.uk/Document-library/2013/FlexDGrid-SDRC4-report-and-appendices.aspx
SDRC 5 Report – Value for Money Report: Commercially Sensitive and Confidential
SDRC 6 Report – Methodology of Method Gamma:
www.westernpowerinnovation.co.uk/Document-library/2017/FlexDGrid/1-2013-10-29-Report-SDRC-6-V003.aspx
SDRC 7 Report - Installation of 10 FLMS:
https://www.westernpowerinnovation.co.uk/Document-library/2017/FlexDGrid/SDRC-7-FlexDGrid-V1-0.aspx
SDRC 8 Report – Open Loop Testing FCLs:
https://www.westernpowerinnovation.co.uk/Document-library/2016/SDRC-8-Open-Loop-Testing-FCLs-V1F.aspx
SDRC 9 Report – Installation and Closed-Loop Tests of FLMs and FCLs:
https://www.westernpowerinnovation.co.uk/Document-library/2016/SDRC-9-FDG-V1F.aspx
SDRC 10 Report – Analysis of test results:
https://www.westernpowerinnovation.co.uk/Projects/Current-Projects/FlexDGrid.aspx#FAQLink71;javascript:void(0);
SDRC 10 Report – Appendix 2: https://www.westernpowerinnovation.co.uk/Document-library/2016/SDRC-10-App-2-CIRED-Papers.aspx
SDRC 10 Report – Appendix 3: https://www.westernpowerinnovation.co.uk/Document-library/2016/SDRC-10-App-3-Industry-Presentations.aspx
SDRC 10 Report – Appendix 4: https://www.westernpowerinnovation.co.uk/Document-library/2016/SDRC-10-App-4-DNO-Workshops-(1).aspx
SDRC 10 Report – Appendix 5: https://www.westernpowerinnovation.co.uk/Document-library/2016/SDRC-10-App-5-LCNI-Presentations.aspx
SDRC 10 Report – Appendix 6: https://www.westernpowerinnovation.co.uk/Document-library/2016/Data-Availability-(1).aspx
SDRC 11 Report – Development of Novel Commercial Frameworks with Generation and Demand Customers:
https://www.westernpowerinnovation.co.uk/Document-library/2017/FlexDGrid/SDRC-11-V1-0.aspx

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