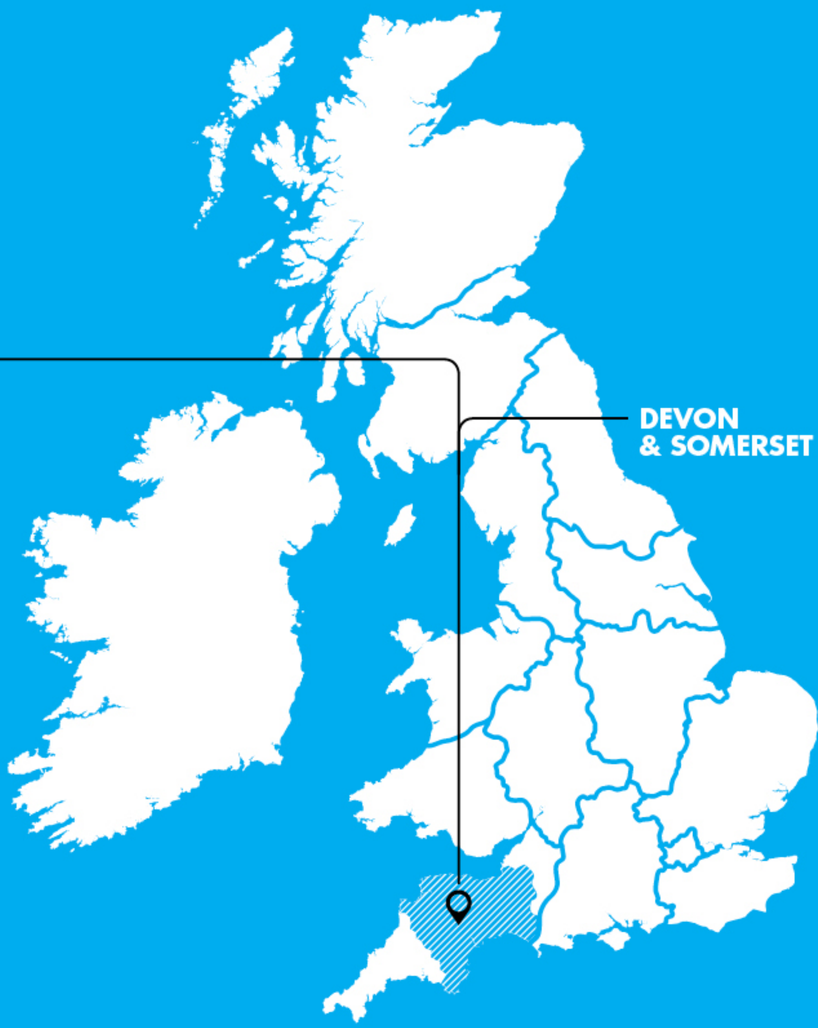
WESTERN POWER DISTRIBUTION

NETWORK EQUILIBRIUM

BALANCING GENERATION AND DEMAND



FPL Development and Improvement Report

LCN Fund
Low Carbon Networks

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Glossary

Term	Definition
AC	Alternating Current
BAU	Business As Usual
BSP	Bulk Supply Point
CER	Continuously Emergency Rated
CIGRE	International Council on Large Electric Systems
CIRED	International Conference on Electricity Distribution
CM	Control Module
CMR	Continuous Maximum Rated
CTL	Cascaded Two-Level
DC	Direct Current
DG	Distributed Generation
DNO	Distribution Network Operator
DPCR	Distribution Price Control Review
DSO	Distribution System Operator
ER	Engineering Recommendation
EVA	Enhanced Voltage Assessment
FAT	Factory Acceptance Testing
FPL	Flexible Power Link
FSP	Full Submission Pro-forma
GB	Great Britain
HV	High Voltage
HVDC	High Voltage Direct Current
ICCP	Inter-Control Centre Communications Protocol
IET	Institution of Engineering and Technology
IGBT	Insulated-Gate Bipolar Transistor
IPSA	Interactive Power System Analysis
LCN	Low Carbon Network
LV	Low Voltage
MMC	Modular Multi-Level Converter

MV	Medium Voltage
MVA	Mega Volt Ampere
MVDC	Medium Voltage Direct Current
MW	Mega Watt
NIC	Network Innovation Competition
NMS	Network Management System
NOP	Normally Open Point
OHL	Overhead Line
ONAF	Oil Natural Air Forced
PCC	Point of Common Coupling
PCS	Power Conversion System
PSSE	Power System Simulation for Engineering
PV	Photovoltaic
PWM	Pulse Width Modulation
RIIO	Revenue = Incentives + Innovation + Outputs
RTU	Remote Terminal Unit
SAT	Site Acceptance Testing
SCADA	Supervisory Control and Data Acquisition
SDRC	Successful Delivery Reward Criteria
ST	Standard Technique
STATCOM	Static Compensator
SVO	System Voltage Optimisation
TRL	Technology Readiness Level
UPS	Uninterruptible Power Supply
US	United States
VFD	Variable Frequency Drive
VSC	Voltage Source Converter
WPD	Western Power Distribution

1.0 Executive Summary

Network Equilibrium has successfully developed, trialled and tested a 33kV AC-DC back-to-back Voltage Source Converter (VSC) that is able to connect two separate 33kV networks on the South West distribution network that could otherwise not have been connected together. The Flexible Power Link (FPL) is the first of its kind to be installed on the GB distribution network. The device has been operational on the network since April 2018 during which time it has been providing real and reactive power support to the 33kV network between Taunton and Barnstaple Bulk Supply Points (BSPs) to facilitate the release of generation capacity, provide active power balancing between the networks and independent voltage regulation on either of the two networks. Analysis has shown that the FPL has released up to 20MW of additional network capacity that could be used to connect additional Distributed Generation (DG) in the trial area. It has also enabled power to be balanced more effectively across the 33kV distribution network and demonstrated the ability to provide additional substation firm capacity. The formal trial of the FPL has now concluded and the device is operating as part of Business As Usual (BAU) on WPD's network.

This report has complied and reviewed the learning generated from the FPL Method and has highlighted a number of learning items that could be used to develop and improve the FPL – or more generally – Medium Voltage Direct Current (MVDC) technology that is deployed on the distribution network in future projects. The review and subsequent analysis found that there was:

- Project specific learning that could be used to improve the execution of future projects of this nature;
- Improvements in the site selection process that could be used to optimise the delivery of further FPL installations and their respective network benefits;
- Areas where the FPL design safety factors could be optimised to generate cost savings or operational benefits;
- Modifications that could be made to the FPL's control system to improve the device's efficiency or to make it easier to operate/maintain; and
- Testing methodology improvements and considerations to streamline the process for future devices connecting to the network.

The report has also identified a number of alternative applications for the FPL technology that could provide additional benefits to distribution network stakeholders including:

- 11kV FPL
- DNO-DNO FPL
- Island Enabling FPL
- Network Mesh FPL

A critical review of these applications was performed to determine a high-level view on the benefits they could provide, and the associated cost to complete their development into a product capable of being connected to the network.

2.0 Introduction

2.1 Background of project

Network Equilibrium is a Low Carbon Networks (LCN) Fund Tier 2 project. The LCN Fund was a funding mechanism introduced by Ofgem as part of the Distribution Price Control Review (DPCR) 5 price control period. The Tier 2 mechanism was an annual opportunity for Distribution Network Operators (DNOs) to compete for funding for the development and demonstration of new technologies, operating arrangements and commercial mechanisms. The Network Innovation Competition (NIC) has subsequently replaced the LCN Fund in the current price control period (RIIO-ED1).

Network Equilibrium was successfully awarded £13m of funding in November 2014. The project started in March 2015 and is now in the closedown phase. The main aim of the project was to improve the balance of voltages and power flows across the distribution network using three Methods. The development of the Methods allowed new ways of configuring and managing the network to be trialled thus releasing capacity for the more efficient connection of DG. The three Methods are as follows:

1. Enhanced Voltage Assessment (EVA)
2. System Voltage Optimisation (SVO)
3. Flexible Power Link (FPL)

The subject of this report is the FPL Method. The FPL is a 33kV back-to-back AC-DC converter that allows two 33kV distribution networks to be connected in parallel through the device. This parallel configuration would not have been able to be safely achieved without the FPL due to circulating currents, protection grading and fault level issues. The FPL can actively manage the real and reactive power flow at its terminals to release network capacity and provide voltage support in both normal and abnormal network running conditions.

2.2 Purpose of this report

The FPL has been operating on WPD's network since April 2018 during that time it has been providing real and reactive power support to the 33kV network between Taunton and Barnstaple Bulk Supply Points (BSPs). The formal trial of the FPL has now concluded and the device is operating as part of Business As Usual (BAU).

The purpose of this report is fourfold:

1. To capture and summarise the learning generated during the design, development, testing, trial and BAU operation of the FPL on the distribution network;
2. To identify and discuss the potential FPL device and system modifications that could be made based on the performance data and learning generated from the Method;
3. To investigate the performance of the FPL since its connection to the network and make a comparison of the performance against the initial aims and objectives of the project Method; and
4. To identify and discuss alternative applications of FPL technology that could bring further benefits to the distribution network.

3.0 FPL learning review

3.1 Overview

The first part of this section aims to summarise the learning that has been generated relating to the FPL throughout the development, installation, trial and post-trial phases of the Method delivery. The learning can be categorised into three main areas:

1. **Project** – Learning that has been generated from the project management activities associated with the delivery of the FPL Method. This type of learning is general in nature and applicable to most engineering projects;
2. **FPL device** – Learning that has been gained during the design, build, testing, commissioning, trial and post-trial phases of the 33kV back-to-back AC-DC converter; and
3. **FPL Control Module** – Learning that has been gained during the design, build, testing, commissioning, trial and post-trial phases of the Control Module (CM).

The second part of this section investigates the original business case that was prepared for the FPL and compares the performance and benefits that have been observed through the trial and post-trial phases of the Method delivery with the original assumptions and outputs.

3.2 FPL learning summary

3.2.1 Project learning

The delivery of the FPL Method has generated a number of project related learning items. This sub-section documents and describes these items in more detail.

Engagement with internal stakeholders

The early and persistent engagement with internal stakeholders was a key element of the successful delivery of the FPL Method.

The delivery of an innovation project often requires the design and installation of novel systems, equipment and processes that are new to the business and may require staff members to adapt their existing work practices or learn to carry out new or additional tasks. In addition, the internal stakeholders will take ownership of the innovation technology as it transitions into service on the distribution network. It is therefore important that any change is managed correctly to ensure the technology is installed, trialled and integrated into BAU as efficiently as possible.

One of the first stages of the FPL Method plan was to develop an engagement strategy to outline the project team's approach. The first step in the strategy was for the project team to identify the stakeholders that had an impact on the requirements for the design, installation and operation of the FPL. The engagement activities were then built into the project management tools (i.e. project schedule and action log) to ensure a thorough and consistent approach. The next step was to make the stakeholders aware of the overall aims and objectives of the project as well as the specific aims and objectives of the Method. Through these initial interactions, the roles and responsibilities of each party were formalised and reporting lines were set up to ensure clear communication between the parties. A series of meetings was scheduled between the project team and the relevant stakeholders at each

Method stage gate. The regular meetings were beneficial for a number of reasons, most notably:

- **Two way transfer of knowledge and ideas** – The stakeholder teams were able to learn about the design, installation, and operational characteristics of the device (and any changes thereof) whilst the project team were able to learn from the experience and knowledge that the stakeholders have about the system. This dialogue reduced issues associated with system integration and allowed for a refined FPL design to be developed.
- **Progress monitoring** – The meetings allowed progress to be monitored regularly throughout the project that enabled early identification of issues or risks as well as resource planning.
- **Issue resolution** – The regular engagement with stakeholders allowed technical, resource and scheduling issues to be resolved in an efficient and timely manner.

Thorough design review

A major factor in the successful delivery of the FPL Method was the implementation of a procedure for thorough review of the FPL detailed design documentation. This strategy has proved to be highly beneficial in previous innovation projects and was, therefore, adopted for the design strategy of the FPL Method. The implementation of a detailed design review procedure is a critical responsibility of the purchaser of innovation technologies where TRLs are generally lower than those of well-established products. In addition, the purchaser has limited practical experience of the technology on the distribution network and much of the equipment, systems and interfaces will not be standardised.

The detailed design review of the FPL system allowed for the following:

- Verification that the design is compliant with the specification in the contract between the manufacturer and the purchaser. The contract included a number of existing company, local and international standards to standardise equipment as much as possible and thus reduce the risk associated with the installation of an innovative technology. The design review process provided an opportunity to ensure that the design was compliant with these standards prior to the installation at site.
- The early alignment of design methodologies and expectations between the manufacturer and the purchaser. In innovation projects it is often the case that manufacturers' designs do not align with the requirements of network operators for various reasons. The reasons can include that: a manufacturer has limited experience of installing a product on the distribution network; or the product being provided is aligned with the standards of a different industry or country. The design review process is used to ensure alignment is achieved at an early stage to avoid significant remedial activities during the device installation phase. The actions in the design review, therefore, acted to: reduce the probability of long delays to the project schedule; improve project cost efficiency; and ensure that the device connected to the network was safe.
- Familiarisation of the purchaser with the technical design of the FPL and its associated systems. This familiarisation and understanding process highlighted areas of the

design that required additional engineering to safely interface the technology with the distribution network.

Cross-method communication and coordination

Cross-method communication and coordination is a key element of the project learning and follows on from the cross-party communication discussed above. Three Methods were undertaken as part of the Equilibrium project. In particular, the implementation of the SVO and FPL Methods were undertaken in parallel due to the requirements of the project schedule. Both Methods were reliant on common internal stakeholder teams for the delivery of certain work packages.

As such, it became apparent that greater levels of communication were required between the SVO and FPL Method work package managers to avoid the scheduling of resources for one Method affecting the schedule for the other. An example where this learning could have reduced scheduling issues was the integration testing overlap between the SVO and FPL CM systems. The systems were both planned to be tested on two test servers that were non-operational. This allowed the testing to take place in a safe environment with no chance of the systems affecting the real network. However, the testing could only be done for one Method at a time. Since both systems were scheduled to be tested in a similar timeframe, there were some minor unforeseen delays to the FPL CM testing as this had to wait for the SVO testing to be finalised.

After this initial learning experience a greater emphasis was put on cross-method communication and coordination. There were a number of benefits acquired through adopting this learning including improving the scheduling of tasks that utilised common resources. Since SVO testing and integration with Supervisory Control And Data Acquisition (SCADA) had the priority in the schedule there was a lot of learning that was shared with the FPL CM work package team that avoided large amounts of unnecessary duplication of effort that would have otherwise occurred. An example was the configuration of the Inter-Control Centre Communications Protocol (ICCP) communication link that facilitated the signal communication between the SCADA system and the SVO/FPL CM systems. Through improved coordination, the SVO configuration was successfully utilised for the FPL CM with minimal modifications.

Policies and specifications before implementation

Another important piece of learning from the delivery of the project was the production of the FPL policies and specifications, and timing of their delivery. Policies and specifications are a critical part of the development of new technologies for the distribution network. They provide a standard set of rules that enable the safe connection and management of the technologies on the system. The policies produced for the FPL are as follows:

- Engineering Equipment Specification – documents the technical and functional requirement to enable the procurement of future FPLs;
- Operation and Control Policy – documents how to control the device and actions to take if there is an error with the systems.
- Inspection and Maintenance Policy – describes the inspection and maintenance requirements for the device.

In terms of timing, it is key that the engineering specifications and policy documents are produced and submitted for approval a minimum of two months prior to the connection and energisation of the device. This strategy has been adopted in previous innovation projects and has allowed the project stakeholders time to successfully familiarise themselves with the requirements for controlling and maintaining the new device prior to connection. Allowing sufficient time for this familiarisation ensures that the main operational staff that are responsible for the device can take the correct control actions in an efficient manner after the device is connected to the network. The planned and timely approach with this type of documentation not only ensures that the safety of the network is maintained, but also increases the ‘buy in’ for innovation technologies from stakeholders in the main business.

3.2.2 FPL device

Site selection

Selecting the appropriate site to install the FPL was a critical part of the successful implementation and trialling of the FPL Method. SDRC-3 detailed the site selection process that was followed to determine the most suitable location for the FPL. Exebridge was chosen as the most suitable site due to the power transfer capability, availability of space, connection arrangement and effect on customers. Allowing sufficient time to analyse the different sites helped to inform the early stages of the design and helped contribute to the overall success of the trial.

Despite Exebridge substation having a large footprint, the existing equipment arrangement was not an efficient use of this space and modifications had to be carried out so that the FPL could be installed. Allowance was made in the Method budget costs for these modifications, however, if these could be avoided for future installations there could be significant financial savings.

The layout of the FPL device components was optimised as far as possible during the design stage. The final device footprint was still around 30m by 14m and took around 17% of the footprint area of the entire site. For the same power rating it is expected that the footprint would remain the same and, therefore, this should be allowed for in future designs.

Another aspect that should be considered in future FPL site selection is the LV supplies that are required for the device. Locating the FPL at an existing substation meant that LV supplies were readily available. This is a key factor as the FPL required two separate supplies: a 120kVA rated supplied for the pre-charger unit for the DC link; and an 80kVA supply for the auxiliary supplies (including controls, cooling and heating). Preferably the LV supplies should come from two separate sources to provide redundancy. For the Exebridge installation, the existing pole-mounted supplies to the 11kV switchroom were replaced as they were not large enough to cater for the new demands of the FPL. These modifications were combined with the overall re-design of the site to create space for the FPL installation itself.

Design/Safety Factors

The design and integration of a new technology as part of an innovation project involves many different risks that require analysis and mitigation. The design and integration of the FPL was the first of its kind in the UK and, as such, presented a number risks from a technical and safety perspective. The analysis of these risks resulted in the requirement to increase safety and design margins to mitigate the likelihood or impact.

Now that information has been obtained regarding the testing and trialling of the FPL, consideration can be given to optimisation of the design and possible reduction of the margins applied. Reduction of these factors could help to reduce the cost, size and complexity of the FPL. Initial analysis shows that there are some areas where marginal benefits could be achieved as listed here:

- **Pre-charger** – the transformer and system used to pre-charge the DC link was already optimised during the design stage, however, by reducing the time taken during the "Start-Up" procedure the rating of the system could be lowered.
- **Transformer** – the 33/3.25kV transformer for the FPL was similar to other transformers previously built by Koncar (the transformer supplier), however, the design was unique for this particular installation from a rating and voltage perspective. During testing it was noted that the transformer performed well within the prescribed limits set out in the specification. Further optimisation of the design could help reduce the size and cost of the transformer for future installations.
- **Cooling** – The cooling system proposed for the FPL did not deviate much from the standard system normally supplied by ABB. Gathering data on the real-time operation of the FPL over one full year of operation could enable the optimisation of the cooling design to meet the typical demand profiles and ambient temperatures experienced.

Switchgear Integration

The FPL is designed to integrate with the existing network through 2 nos. 33kV circuit breakers connected across the device. These circuit breakers are required for three primary functions:

- To provide protection to the FPL from both network and internal faults;
- To provide a means to connect and disconnect the FPL as part of the control sequence; and
- To accommodate measurement devices used to monitor current, voltage and frequency.

Figure 3-1 shows the switchgear requirements to allow the integration of the FPL at the Exebridge site. ABB did not provide these circuit breakers as part of their design, therefore, WPD had to install them and the associated equipment for the interface with the control system as part of the site design. The design of the interface is complex in that:

- The FPL has to control the operation of the circuit breakers as part of the start-up/switch-off sequence;
- Information regarding the positions of circuit breakers, three position switches and statuses of alarms needs to be sent to the FPL; and
- Mechanical interlocking between the 33kV switchgear and FPL is required as part of the earthing procedure.

This was a significant departure from standard WPD practice as normally only Network Management System (NMS) or operational engineers on site can control HV switchgear.

However, the changes were successfully implemented and captured in updated policy and procedure documentation.

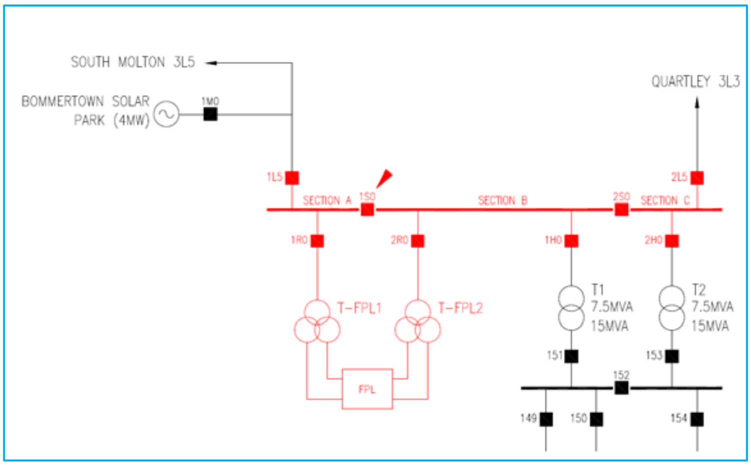

Figure 3-1 – Interfaces required for current FPL device

Integration with switchgear will still be required for future FPL installations where the DNO is providing the equipment. However, if the FPL manufacturer was to include the HV switchgear as an integral part of the FPL then this could significantly simplify the design and installation work. Figure 3-2 shows how a future FPL device with integrated switchgear would be configured.

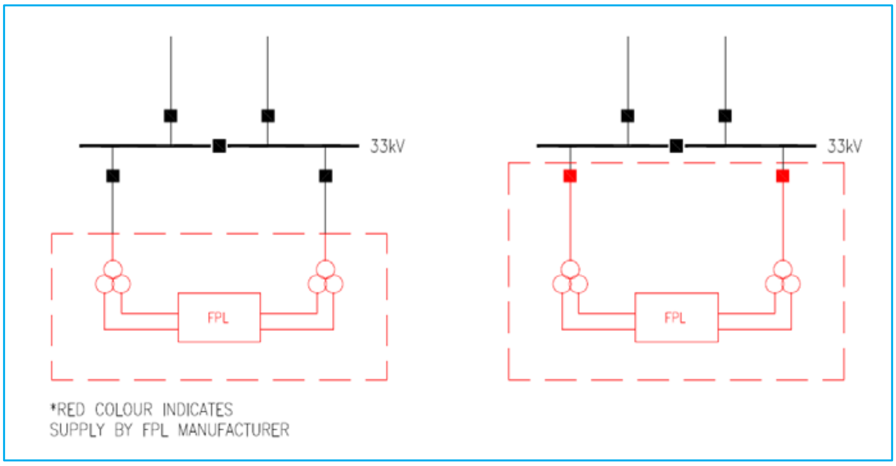

Figure 3-2 – Switchgear supplied by WPD (left) compared to switchgear supplied by FPL manufacturer (right)

Transformer Design

The FPL requires transformers on either side of the converter to step-down the grid voltage to 3.25kV to provide the interface with the power electronics. The standard design involves two separate transformers for each side of the power electronic converter. During the design stage it was identified that several financial savings could be made if these two transformers were combined into one tank:

- Material savings in the manufacture of the transformer (tank material);
- Having a single unit saves time and costs associated with testing, delivery and installation;
- Civil costs are lower as only one bund and noise enclosure are required; and

- Consolidating interface requirements reduces the number of connections with the control systems.

Combining two transformers into one tank did not increase the impact of a failure as the failure of a single transformer, when supplied as two separate units, would still result in the FPL being out of service. The only additional risk with this configuration is that a catastrophic failure may cost more to repair should this occur. Considering the savings described above and the limited impact of having two transformers in one tank, it is recommended that future installations adopt the same approach as used for Network Equilibrium.

There were also a number of other learning points from the design review process for the transformer. The main supplier for the FPL device (ABB) sub-contracted the design, build and testing of the transformer to a separate supplier, Koncar. Although Koncar had significant experience in the design and build of similar transformers, they were not familiar with WPD specifications. As such, there were several iterations of the design of the transformer during the early stages so that it aligned with WPD's requirements. In particular, WPD required modifications to the location and access for ancillary equipment such as oil sampling and mechanical relays to control safety risks that occur during maintenance. Also, electrical wiring had to be modified such that it aligned with WPD and UK standards. For future installations it would be prudent to ensure that a face-to-face meeting is held between the main supplier and any sub-contractors that are providing major equipment (such as transformers). Having this engagement early in the contract would help to mitigate time that could be lost during the design stage due to comments to/from WPD and the supplier.

Testing

The FPL for Network Equilibrium could not be tested as one complete unit in controlled laboratory conditions due to the physical size of the assembled device and the capability of the test equipment in the manufacturer's laboratory. Despite several discussions with the manufacturer there was no cost efficient method of testing the complete device in a third-party laboratory. Hence, a series of individual Factory Acceptance Tests (FAT) were determined in order to mitigate the risk of the FPL being delivered to site and not meeting the requirements of the contract. The final test would be performed on site to verify the performance of the individual components together as a single device.

The FPL successfully passed all the individual FATs in the manufacturer's laboratory following some modifications to the software (explained below). The components were then shipped to Exebridge where the final test was carried out and the device met all the criteria in the contract.

For future projects it is recommended that the manufacturer submits a clear test procedure for the device. The information submitted in the initial contractual documentation did not state clearly that the FPL components would be tested individually rather than as a complete device. This would reduce the impact of potential failures during testing and limit the time on-site for commissioning.

Witnessing the manufacturer tests also proved to be extremely valuable as a number of errors were noted during the software FAT. As WPD were in attendance at this FAT, all of the information was available to make a clear, informed decision. In this particular instance, the decision was made to cancel the software FAT and perform the tests again after a series of fixes were applied.

The testing programmes for the FPL and transformer were also areas where refinements could be made for future devices. For all the FATs performed, the timescales were extremely tight for setting up, conducting and witnessing the tests. This meant that WPD witness engineers were under pressure to ensure that the tests were conducted safely and in alignment with the test procedures. It would be prudent to highlight in future contracts that manufacturers should allow additional testing time for devices being designed and built for innovation projects (especially where deviations are being made to standard designs). In addition, it would be beneficial for the manufacturer to submit a testing programme that has milestones for them to complete a pre-FAT before witness testing occurs. This would help to prevent a similar situation to what happened during the initial software FAT.

3.2.3 FPL control module

The delivery of the FPL Method has generated a number of project related learning items. This sub-section documents and describes these items in more detail.

Network models

The FPL CM utilises an IPSA power system model of the network to validate the occurrence of voltage and thermal violations and to calculate real and reactive power set-points for the FPL to remove these violations. The model includes the 33kV network between the two BSPs that the FPL device physically connects together.

Important learning was generated throughout the project on the optimum way to approach the production, quality assurance, verification and update of power system models for innovation technologies. The initial FPL CM model was produced as part of the project, however, a significant amount of effort was required in subsequent revisions to make it more user friendly, easier to update, find faults and complete verification.

The main learning point from the project implementation is that a clear and concise design standard or guide is required to be produced at an early stage of the development of the network model. This document would specify and standardise the design of the model would capture items such as the following:

- The process for new load and generator connections;
- The process for new circuit breakers, lines and transformers;
- Avoid lumping cable and OHL impedances. This allows future modifications (i.e. a new generator connection) to be located with minimal effort;
- The direction of lines i.e. specify that the line is drawn from BSP to FPL (or vice versa);
- Component naming and numbering convention to aid fault finding and debugging of the model; and
- Configuration of network model aliases. The aliases are alphanumeric codes that link the current, voltage, power and breaker status measurements in SCADA to the components in the model.

An additional benefit of the standard or guide is that it can include a methodology for updating the model. This information can then be used to train main business staff in the update procedure or act as a reference source to enable a consistent approach. Having an up to date and accurate model is critical to ensuring the FPL behaves safely and predictably in service.

The changes that were made to the model informed the design principles described above. During the course of the project delivery, these principles were captured in an updated procedure document that was used as a reference for the staff tasked with updating the model in BAU. This document will form the basis of a specific design standard in future innovation projects utilising power system models.

Testing

There are a number of learning points that can be attributed to the FPL CM testing activities. Firstly, the contract between the manufacturer and purchaser must clearly and concisely demarcate the responsibilities of each party in relation to the various parts of the testing activities. It must also specify the parties responsible for producing the testing specification documents and any temporary works required to facilitate the testing activities.

The testing of a software based control system is complex and requires significant integration testing with existing DNO systems, namely the incumbent NMS system. The key to successful integration testing is therefore splitting the system into its constituent parts and implementing thorough offline point-to-point and end-to-end tests. This may require simulation of hardware components in the system. The benefits of this approach are: the early identification of issues relating to data interpretation; communication protocol; and logic. This greatly de-risks the commissioning activities performed at site.

The first stage of the integration testing for the FPL CM included manual simulation of data point changes from the NMS interface to the FPL CM. The second stage involved use of a non-operational test RTU and a software simulation of the FPL to recreate the communications channel from the FPL to the central NMS. After this link was tested and operational a final simulated end-to-end test was carried out. The integration testing process is shown in Figure 3-3. The software simulation of the FPL was not included in the contract with the manufacturer and therefore was an additional piece of work provided by Nortech. It is important, therefore, to ensure that the contract captures all of the anticipated integration testing requirements to reduce contract variations.

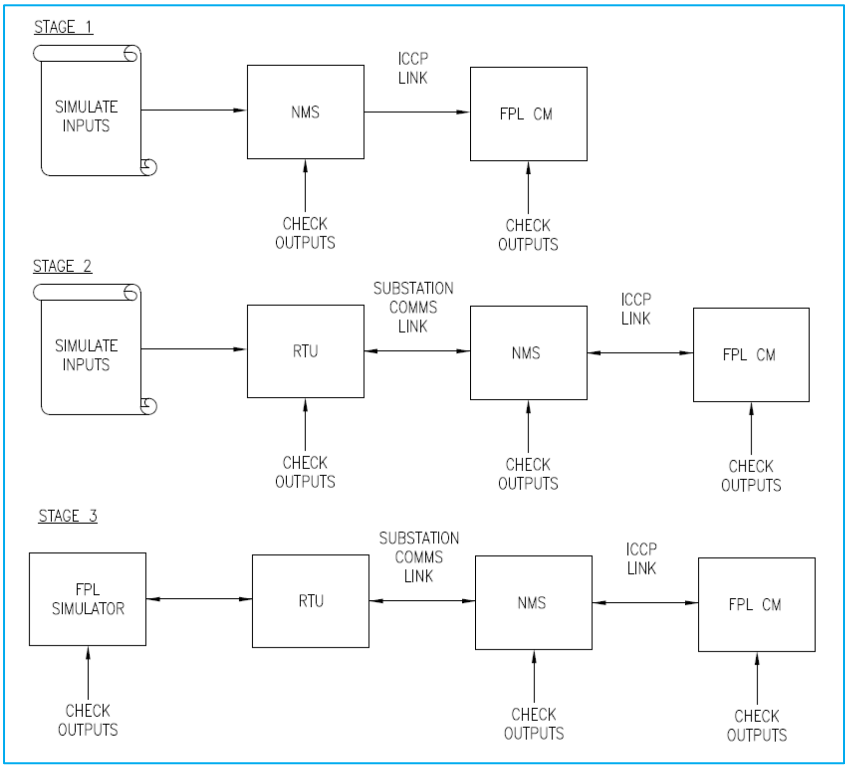

Figure 3-3 – Staging of the integration testing for the FPL CM

The contract should also specify that the operational manual for the control system is to be made available in at least a draft form a minimum of two months prior to the FAT. This was not explicitly specified in the FPL CM contract and led to the manual being unavailable during the development of the FAT test specification. This can lead to the omission of items from the test specification.

A document was produced during the detailed design phase of the FPL CM that was particularly valuable for the overall testing approach of the FPL CM and helped define both the factory and integration testing specifications. This document captured all of the operational requirements of the FPL CM (e.g. disconnect FPL if solution is not found) along with the corresponding logic response from both the FPL CM and the SCADA systems. This repository was also valuable as a central source of information that could be referenced by the project and stakeholder teams as an aide memoir during the build phase of the project. It is highly recommended that this document is produced for future control systems of this nature.

Another important learning item that was implemented to good effect for the testing phases of the FPL CM was the use of standardised drawings for system communication. These drawings were produced after the detailed design review phases of the Method and defined the signal exchange between the various systems. This had benefits such as setting a standard sign convention for measurement signals that was critical for the correct operation of the FPL CM. In addition, the drawings specified the format of the data required by each system (i.e. 16 bit integer) and the processing required to achieve this at each stage.

Optimisation

The use of a centralised control system to control a remote device such as the FPL is a highly innovative and novel solution. In this regard, it was decided to follow a relatively conservative design approach for the initial development of the CM. The FPL CM was therefore initially equipped with a simplistic set-point optimisation algorithm. The algorithm was triggered upon identification of a violation on the 33kV network between the two BSPs interconnected via the FPL, and then calculated a set-point to remove the violation(s); however, the algorithm did not periodically check whether the set-point could be optimised (or removed) after it was issued. The CM only re-calculated the set-point after being triggered by another network violation. This was identified as being sub-optimal in terms of FPL utilisation as the device could be running at an elevated set-point unnecessarily for extended periods of time.

It was correct to follow a conservative design approach initially as it allowed the number of variables affecting the development of the FPL CM to be reduced. The periodic recalculation of the set-point to optimise the utilisation of the FPL has subsequently been integrated into the FPL CM during the FPL trials. Additional optimisation algorithms could be applied to the FPL CM to make it more efficient and reliable. These are discussed further in Section 4.4.2. It is recommended that a more ambitious design approach is considered for the development of future control systems. The testing and operational learning gained from the existing FPL CM installation provides a strong foundation to ensure more detailed and complex operational requirements are included in future contracts with system manufacturers.

Network Analogues

The successful operation of the FPL CM is dependent on the accuracy and reliability of a number of digital and analogue measurements taken from various strategic locations across the network. There are two classifications of measurements defined by the FPL CM:

1. Critical measurements that were required to run the load flow analysis on the power systems model; and
2. Non-critical measurements that were used to validate the state estimated results of the load flow analysis.

It is imperative that the list of critical and non-critical analogue measurements is compiled as part of the detailed design phase of the project. This list will then be used to check that the analogue measurements are available from SCADA, have the correct sign convention as per the standards and are sufficiently reliable from historic SCADA data. It should not be assumed that analogue measurements are necessarily available for all data points on the network. Ensuring that these data points are checked early in the design phase will allow the necessary modifications to the physical measurement devices well before the testing.

During the development of the FPL CM, a document was created that listed all of the measurement signals that required either modification to align the measurement to the required standard, or where a new measurement device was required to be installed at the network location. However, there was a minority of analogue measurements that were not available in time for the FPL CM integration testing. These signals were, therefore, given temporary placeholders in the network model and simulated manually through a test version of the SCADA system, i.e. a non-operational version. Whilst this is a valid step to take to enable the testing to continue, it did mean that the FPL CM was tested with partly simulated analogue data. An ideal situation would be that a full real-time dataset is used as an input to the module during testing. In addition, there was a significant amount of temporary works required to port the manually simulated data into the module, which adds extra complexity and additional variables for errors. It is therefore recommended that every effort is expended to rectify analogue data measurements prior to the integration testing of future control systems.

3.2.4 Summary

The review of the learning generated from the FPL Method has highlighted a number of project learning items that will be applicable to future innovation projects, particularly projects that aim to develop active control on the distribution network. In addition, the review has identified FPL device specific learning that indicates that there could be cost and space savings associated with reduced design/safety factors and modifications to the way the FPL is integrated into the network. This section has also provided significant learning on the development of the FPL CM and provided recommendations for the development of similar systems in the future.

3.3 Business case comparison

This section presents a comparison between the benefits of the FPL Method as stated in the original Network Equilibrium bid and the benefits calculated from the subsequent trials of the FPL Method on the network.

The original bid was presented in the Network Equilibrium LCN Fund Full Submission Pro-forma (FSP) submitted to Ofgem in August 2014. The benefits calculated from the FPL trial are documented in SDRC-6 “Trialling and Demonstrating the FPL Method” and SDRC-7 “Trialling and Demonstrating the Integration of the EVA, SVO and FPL Methods”.

The original bid calculated the FPL could release up to 36.2MVA of network capacity. This was calculated through the preliminary modelling work to aim to account for both the benefits brought by real power transfer and reactive power to actively control the system voltage. Through analysis of the FPL trial data and subsequent modelling of the FPL performance, there is an average capacity release of 20MW per FPL installation. This is lower than the initial calculation, however, this has not had the effect of changing the original business case for FPL. The FPL business case was based on the comparison of the FPL capacity benefit with the average cost of the traditional reinforcement for the equivalent capacity release. This hasn’t been affected by the revised FPL capacity because the same equipment would still need to be installed in both base case scenarios.

3.4 Policies and procedures

A range of policies and procedure documents were produced as part of the development of the FPL to enable the device to be safely controlled, operated, inspected and maintained by main business staff. These documents also capture important learning for dissemination to the wider DNO community, enabling others to replicate the FPL on their networks with reduced risk and cost. This is a fundamental requirement and deliverable of projects delivered with innovation funding. The documents produced are as follows:

- **ST:OC1AC - Operation and Control of ABB 33kV Flexible Power Link installed at Exebridge Primary Substation for use on the Network Equilibrium project**
  This document describes how the ABB FPL should be operated and controlled on WPD's 33kV network as part of the Network Equilibrium project.
- **ST:SP2CAD - Inspection and Maintenance of ABB 33kV Flexible Power Link installed at Exebridge Primary Substation for use on the Network Equilibrium project**
  This document describes WPD's inspection and maintenance requirements for the ABB FPL as part Network Equilibrium project.
- **FPL Control Module Update Guide**
  This document describes the process to be followed to ensure that the electrical models within the FPL CM are kept up to date, accurate and manageable.

4.0 FPL development and improvement

4.1 Overview

The FPL was the first of its kind to be installed on the 33kV network in the UK. The design, integration, installation, testing and trials have generated substantial learning that has been captured in Section 3.0. This learning is beneficial to most innovation projects and in particular those that involve AC-DC converters. In most cases the learning gathered could be used to reduce:

- The capital cost of building and installing a similar device through the reduction in materials, footprint and testing time; and
- The operating cost of the device by optimising the performance and maximising the efficiency.

The following sections describe how the learning captured to date has informed changes that have already been implemented during the trials and modifications that could be made to future installations.

4.2 Modifications during the trials

The FPL has been in service for over a year and during that time data has been gathered on the performance of the device and CM. A number of minor changes have been implemented over this time to help improve the operation of the device.

4.2.1 LV supply reliability

The FPL has two incoming LV supplies; a supply to the pre-charger and a supply for other ancillary equipment. During the design phase it was determined that two new supplies should be installed as part of the enabling works. These supplies would be derived from the 11kV feeders that supplied the surrounding area around Exebridge. These new supplies were also to be used to supply the auxiliary supplies to the local 33/11kV substation Figure 4-1.

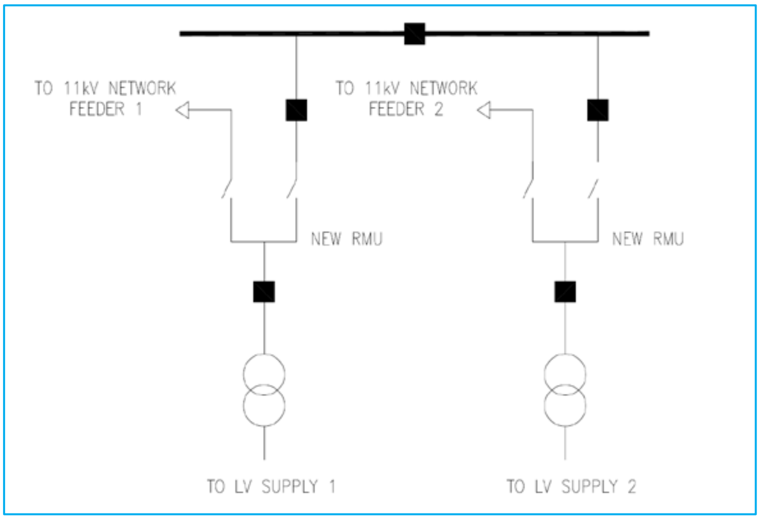

Figure 4-1 – FPL LV supply

During the trial phase of the FPL the primary 11kV circuit which supplied the ancillary equipment experienced a number of transient faults. As the FPL is equipped with a UPS, the supply interruptions did not cause the FPL to immediately shutdown. However, if the supply was not able to be restored following the fault (i.e. the 11kV circuit locked out after auto-reclose attempts) the FPL would eventually have to be shutdown. A decision was made to swap the LV ancillary supplies on to the adjacent “back-up” distribution substation (that was supplied from a different 11kV feeder) due to the number of interruptions. This was a relatively simple solution until the high interruptions associated with the original feeder could be resolved.

4.2.2 FPL CM server configuration

The FPL CM is a bespoke application produced by Nortech and operates within their iHost central data management platform. Two dual redundant operational servers were specified to run the iHost environment and the FPL CM software: the primary server runs the main instance of the FPL CM program and a standby server operates in hot standby with a secondary instance of the program that takes over operation if the primary server fails. Both servers have a connection to the WPD’s operational NMS. A third server was included as a test server that was used to test updates/patches to the FPL CM in a safe offline environment.

During the implementation of the project it was decided to add a fourth server that operated as a second test server. This was achieved at minimal additional cost to the project and allowed a full replication of the operational system. This was beneficial for testing modifications to the FPL CM software as a full replication of the operational environment is more likely to identify bugs in the system. An additional benefit is that server failover can be fully tested in a safe environment and the failover process can be demonstrated for operator training purposes. Server failover is the process of transferring the FPL CM to the standby server if the primary server becomes unavailable. The final server configuration is shown in Figure 4-2.

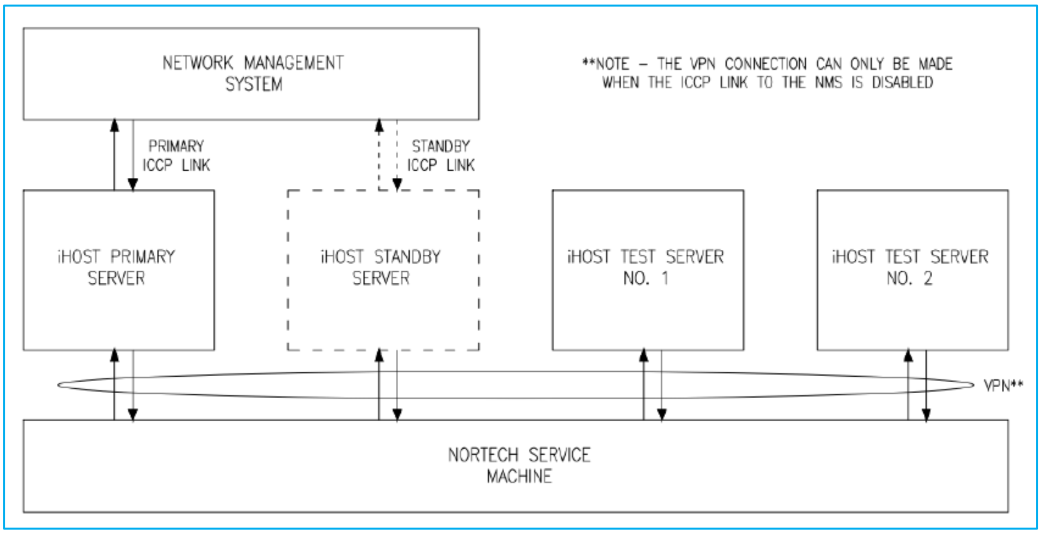

Figure 4-2 – FPL CM final four server configuration

4.2.3 FPL CM optimisation

One significant change that has been implemented is further optimisation within the FPL CM. Developing an optimisation element within the CM had already been identified during the design phase, however, it was decided to postpone this development until after the FPL had been in initial operation using a more simplified control logic. This conservative approach was justified given the novelty of the device on the distribution network. In addition, the FPL CM is implemented in software, and therefore unlike hardware systems, it can be updated and tested relatively quickly allowing updates to be installed on the operational system in short timescales.

The FPL CM design that was implemented for the initial energisation of the FPL involved calculating and applying an FPL set-point when a network violation was detected. If the violation remained unchanged, the FPL would continue to operate at this set-point.

The optimisation that has now been implemented involves the CM continually evaluating the set-point. If a violation is now no longer present or has reduced in severity, the CM will adjust the set-point to ensure that the FPL is not transferring more real or reactive power than necessary. Figure 4-3 shows the operation of the FPL before the CM optimisation was implemented and Figure 4-4 shows the operation of the FPL after CM optimisation.

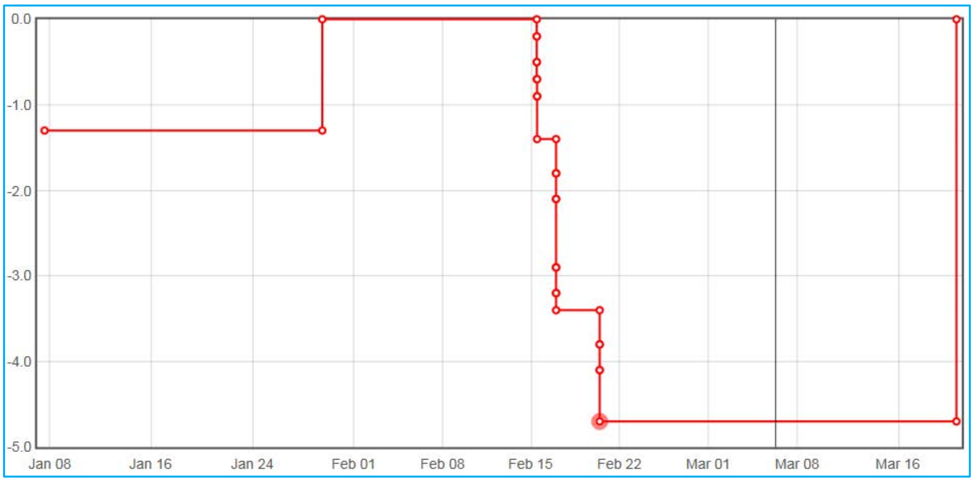

Figure 4-3 – FPL operation before set-point optimisation (Q on FPL1)

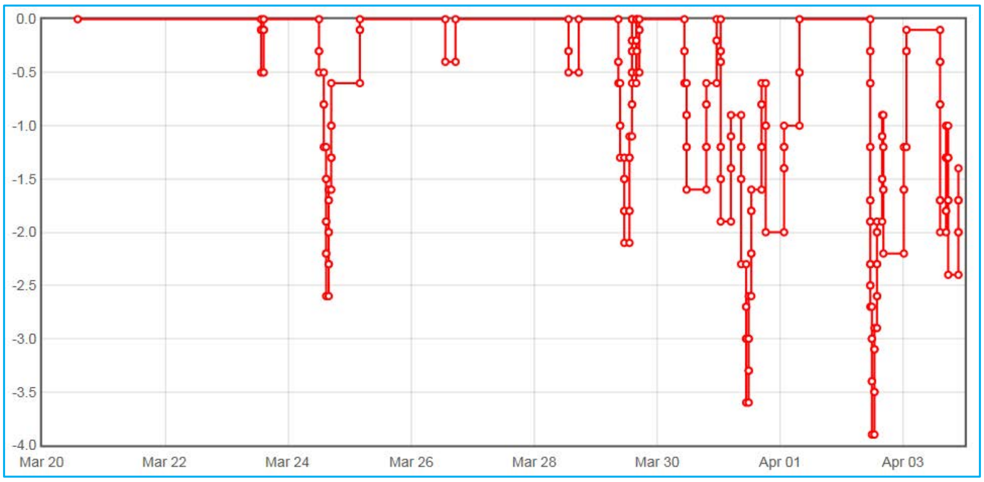

Figure 4-4 – FPL operation after set-point optimisation (Q on FPL1)

It can be seen that the FPL set-point changes far more frequently with the CM optimisation and that the output of the FPL is on average much lower with optimisation enabled. By calculating the respective areas under the graphs the relative increase in efficiency can be determined. By implementing this calculation, the FPL was found to be on average 64% more efficient utilising the optimised set-point logic when compared to the non-optimised system. This translates to lower electrical losses for the device and consequently makes the device more cost effective to operate on the network.

4.3 FPL device

4.3.1 Rating

Existing solution

A number of power system studies were carried out as part of the initial work to understand the behaviour of the FPL on the network. The results of these initial studies showed that the required rating of the FPL was ±20MW and ±5MVAr on each side of the device as demonstrated in the operating window shown in Figure 4-5.

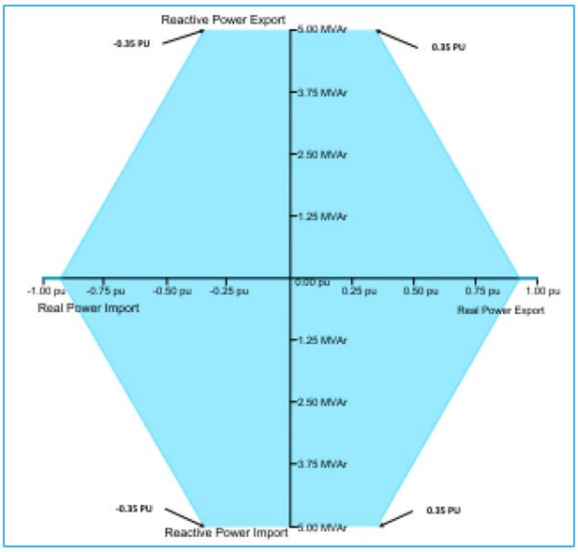

Figure 4-5 – FPL contractual operating window

Operation outside of this operating window could result in both thermal and voltage violations on the 33kV network where the FPL is installed. These requirements were included within the specifications for the FPL for Exebridge.

The manufacturer selected for the design and supply of the FPL was ABB. Their preferred solution for the FPL was their PCS 6000 converter that can be used as a power flow controller, frequency converter and statcom device. The PCS 6000 is an existing product supplied by ABB and was supplied with the operating window as shown in Figure 4-6 for the FPL application.

It is important to note that the FPL operating window is limited by the rating of the transformer that is connected in series with the FPL. In Figure 4-6 the graph is plotted on the basis that the transformer is able to be operated at its emergency rating of 20.2 MVA which does not limit the FPL rating. The corresponding graph with the lower ONAN rating is shown in Figure 4-7 and it can be seen that the operating window is reduced accordingly.

The figures both highlight that the power capability of the FPL is also dependent on the voltage levels of the two 33kV networks that are being connected. The operating window shown in Figure 4-6 also overlays the contractual requirement (shown as the shaded blue colour) and this indicates that the reactive power capability of the converter is significantly higher than the specified ±5MVAr for the majority of operating points.

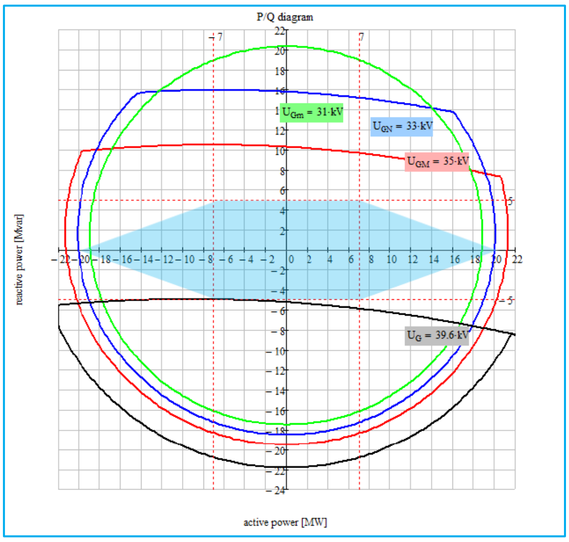

Figure 4-6 – ABB PCS 6000 operating window with emergency rating (20.2 MVA)

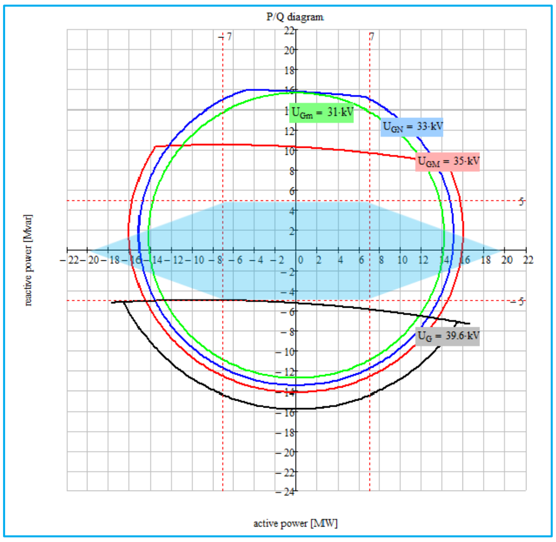

Figure 4-7 – ABB PCS 6000 operating window with ONAN rating (14.1 MVA)

Analysis/Proposed solution

The rating of the converter is generally fixed by the real power (P) requirements of the converter. Since the real power requirement is usually in excess of the reactive power requirement, the converter will generally supply more reactive power than is necessary due to the circular 4-quadrant operating window. The FPL manufacturer should confirm that both the real and reactive power requirements are satisfied for maximum and minimum permissible network voltages during the tendering phase of the project.

As mentioned earlier, the FPL rating is also dependent on the rating of the transformers that are connected in series with the device. The transformer rating must be chosen carefully to ensure that the converter output is not unnecessarily being curtailed by transformer thermal limits. The selection of an appropriate transformer rating would be aided by studying the likely power transfer profiles of the proposed FPL i.e. daily/seasonal variations. Incorporating this information into the tender specifications would assist the manufacturer in determining the most appropriate rating (i.e. continuous emergency rating, continuous maximum rating etc.).

Another important aspect to consider is the 33kV line rating that the FPL will be connecting to. The maximum real power rating of the FPL will be limited by the maximum thermal rating of the 33kV line and care should be taken not to over specify the device in this regard.

The FPL installed as part of Network Equilibrium had an appropriately selected rating for the application. This is indicated in the graphs shown in Figure 4-6 and Figure 4-7. The selection of a Continuous Emergency Rated (CER) transformer was based on studies that indicated the

FPL would only need to operate above the ONAN rating for a very small percentage of time. The FPL can provide significantly more reactive power than required in the specification, however, this is not an area where efficiency savings can be made as this capability is built into the converter technology.

In summary, no significant changes can be made to the existing FPL rating to improve the efficiency or cost of the device. The way in which the FPL is controlled on the network has a much larger impact on the FPL efficiency and operating cost. This is explored in detail in Section 4.2.3.

Cost benefit analysis

The FPL rating was selected appropriately and therefore are no significant changes that have been proposed to the device in this regard.

4.3.2 Size

Existing

The size of the FPL device was limited to the footprint and configuration of the equipment required to integrate the ABB FPL on the distribution network. The final equipment and site layouts of the ABB FPL are shown in Figure 4-8 and Figure 4-9 respectively. The FPL consists of the following main pieces of equipment:

1. Converter container – this is a 12.2m bespoke container that houses the converter power electronics, the FPL protection and control room, and the cooling system control room that also houses the pumps for the converter water cooling circuit.
2. FPL transformer – The converter requires two transformers (one on each side of the FPL) to step down the 33kV grid voltage to 3.25kV, which is suitable for connection to the converter power electronics. It was decided to house the FPL transformers in a single tank for this installation.
3. Grid filters – A grid filter is connected at 33kV on each side of the FPL. It is made up from passive components and its role is to reduce the harmonic distortion that is created by the converter.
4. External heat exchanger – An external heat exchanger is used to dissipate heat from the water cooling circuit that is circulated to cool the power electronics inside the converter container. The heat exchanger was a standardised piece of equipment.

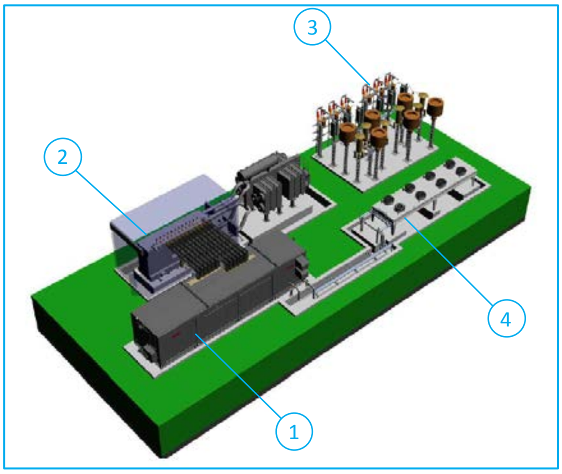

Figure 4-8 – ABB FPL final equipment layout

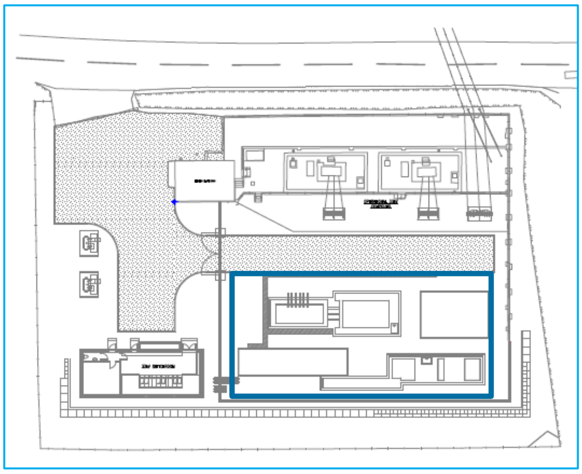

Figure 4-9 – FPL final site layout

Analysis/Proposed solution

The converter container is based on a 12.2m bespoke container housing developed by ABB over several years. Hence, there is little scope for footprint reduction as the equipment is already optimised. It is possible that the site footprint could be reduced by installing the converter and its associated ancillary equipment inside the main substation building provided that there is sufficient space available. This alternative layout could save up to 27% of the 33kV operational compound footprint. A drawing showing this alternative layout is given in Figure 4-10. The drawback of this alternative solution is that existing FPL equipment has been designed as a containerised solution and separating the equipment in this manner would greatly increase the site integration and on-site commissioning works. One of the primary benefits of the containerised solution is the ability to implement full pre-commissioning tests in the factory and a 'plug-and-play' commissioning process.

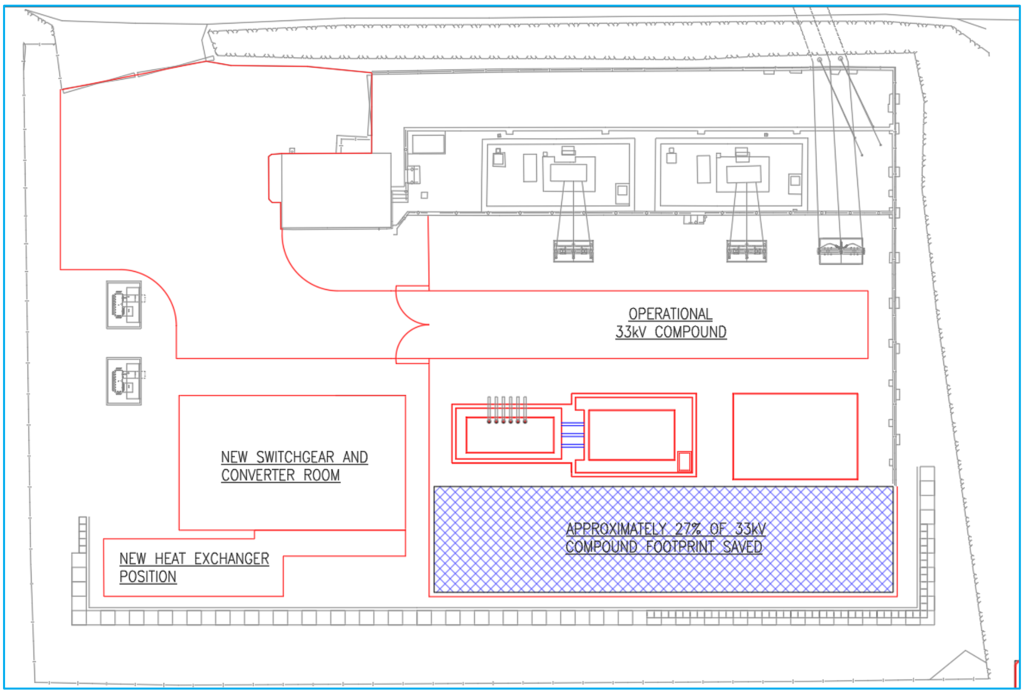

Figure 4-10 – FPL alternative site layout with combined 33kV switchgear and converter building

There have already been significant footprint savings generated by housing both of the FPL transformers within a single tank. The main factor determining the size of the FPL transformer is its maximum power rating, which is matched to the FPL converter power rating. There could be scope for reducing the size and weight of the transformer by ensuring that there is minimal over specification of the associated FPL power rating.

The FPL transformer was designed to be a Continuous Emergency Rated (CER) transformer with a rating of 14.1/20.2 MVA. This rating philosophy allows the operation of the transformer at its maximum rating (20.2 MVA) for a short period of time without any additional transformer ageing. This solution has advantages of reduced transformer size and cost when compared to Continuous Maximum Rated (CMR) transformers that are sized to cater for continuous operation at the maximum rating. The CER transformer rating was chosen because studies showed that the FPL at Exebridge does not operate at its maximum rated output on a continuous basis. It is recommended that this approach is followed for future applications to determine the transformer rating by carrying out a detailed modelling study of the FPL behaviour when connected at the prospective network location. It is also worth noting that the type of generation that the FPL is expected to transfer across grid groups is likely to have an impact on the transformer rating that is selected. CER transformers will be better suited if the generation profile is predominantly intermittent e.g. solar.

Another variable that determines the overall transformer size is the bridge arrangement of the converter. The FPL utilises a 12-pulse bridge configuration that requires two windings on the LV side of the transformer, one of which is configured in a star configuration, while the other is in a delta configuration. This establishes a 30° phase difference between the two sets of three phases and has a much better harmonic performance compared to the alternative 6-pulse converter configuration. A schematic diagram of a 12-pulse bridge configuration is shown in Figure 4-11. The 6-pulse configuration only requires a single secondary winding and therefore could be used to reduce the size of the transformer, however, this would require a larger filter to ensure compliance with ER G5/4 planning levels. A schematic diagram of a 6-pulse bridge configuration is shown in Figure 4-12.

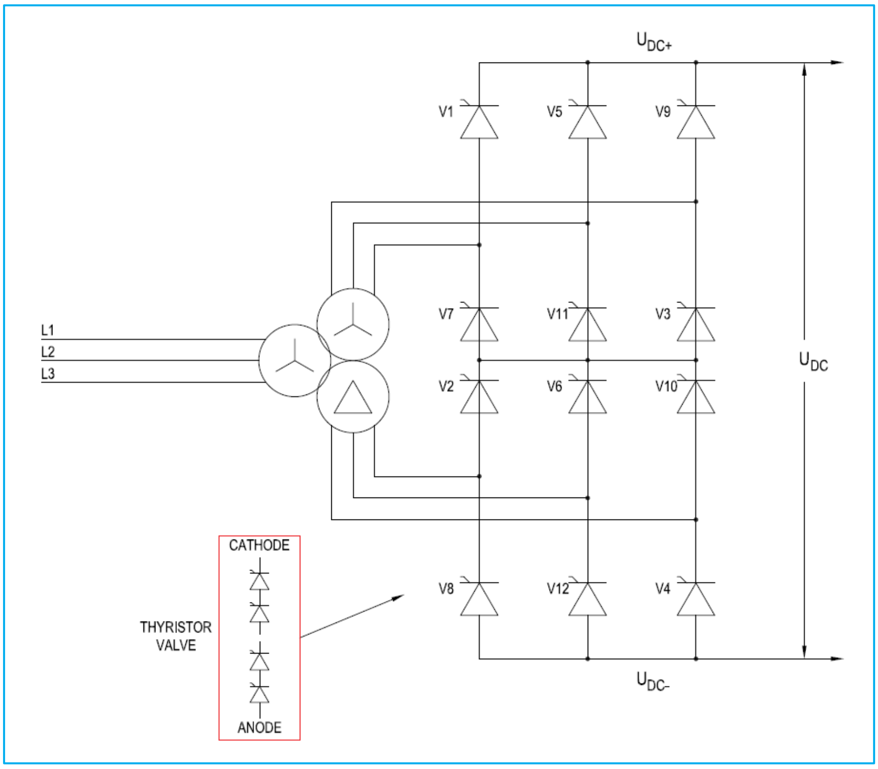

Figure 4-11 – Schematic diagram of 12-pulse bridge configuration

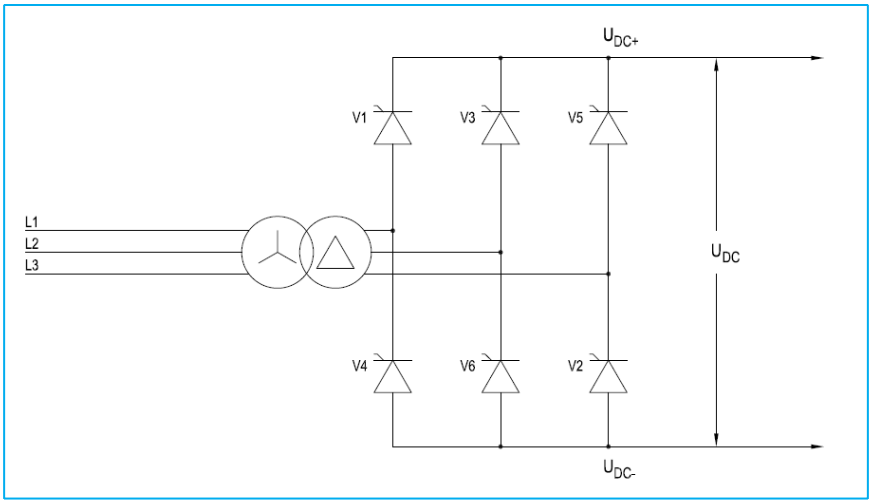

Figure 4-12 – Schematic diagram of 6-pulse bridge configuration

There is limited scope for size reduction of the 33kV grid filters as sizing of the components have been selected by careful calculation to ensure that the device is compliant with ER G5/4 planning levels. The results of the harmonic measurement test carried out as part of the FPL SAT is shown in Figure 4-13. The graph shows that a suitable margin has been incorporated in the calculations to ensure compliance with ER G5/4. It would not be recommended to reduce these safety margins to gain what would be very minor improvements in grid filter size.

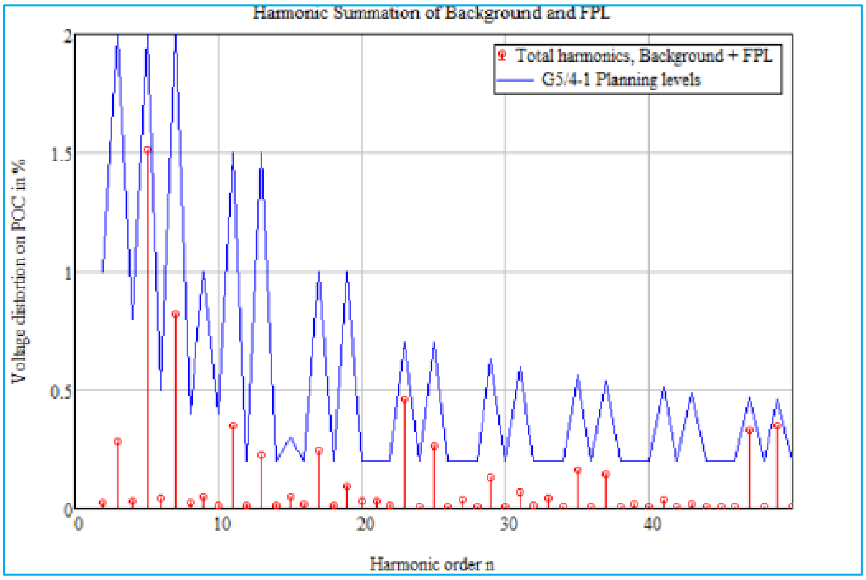

Figure 4-13 – Test results of harmonic distortion caused by the FPL in service

There is also limited scope to reduce the size of the external heat exchanger. The size of the heat exchanger is dependent on the diameter of the fans that force air to cool the circulating water. The fan diameter cannot be reduced in the existing design as this would cause the noise sound power level to exceed the contractual requirement.

In summary, the FPL device already represents a highly optimised solution in terms of overall size and footprint. The biggest saving on the FPL overall footprint would be achieved by installing the converter power electronics and associated ancillary equipment in the main substation building and therefore remove the requirement for the external converter container. This would only be feasible if there was sufficient space available in the existing building or additional space incorporated as part of works to upgrade the substation to cater for the FPL i.e. new switchgear installation.

Cost benefit analysis

The existing footprint of the FPL installation at Exebridge is approximately 320m^2. If the equipment in the FPL container was installed within an existing substation building this would reduce the FPL footprint by the area of the FPL container, which is 30m^2. This represents a reduction of 9.4%.

As previously discussed, the disadvantage of moving away from a containerised approach is increased commissioning time at site. A conservative estimate would be that it would take an additional two weeks of commissioning time to install the converter components and connections within the main substation building. This represents approximately £150,000 of additional cost. It is recommended that the containerised approach is maintained as the standard for the FPL design and the decision to move the converter electronics into the substation building should only be considered if there are considerable space constraints at the site.

4.4 FPL control module

4.4.1 Server failover

Existing

Server failover is the process of transferring primary server function to a standby server after a failure or scheduled maintenance of the primary server. The FPL CM operates on dual redundant operational servers. The failover between these servers was designed to be a manual process with an operator having the duty of accessing the standby server and executing a set of commands to transfer operation to the standby server and initialising the ICCP link so that the FPL CM can communicate to WPD's NMS. These instructions formed part of the FPL CM manufacturer's (Nortech) technical product literature.

When the primary server becomes unavailable, the 'heartbeat' signal between the FPL CM and the NMS is no longer active and a timer is initiated. If the failover process is not completed before this timer reaches its timeout value, a command is issued to remove the FPL from service to avoid the FPL being left uncontrolled on the network.

The manual failover process was implemented to keep the server architecture as simple as possible. However, the manual nature of the process has two main disadvantages. Firstly, it is susceptible to human error even though this is unlikely due to design steps taken to minimise the interaction required from the operator. More importantly the manual process is slow to implement and if it isn't complete within the ICCP timeout period, the FPL will be disconnected from the network at site. This was more of an issue for periodic maintenance of the servers and one workaround was to disconnect the FPL prior to the planned maintenance activities to avoid any unnecessary pressure being applied to server operatives.

Proposed

An automatic server failover is a proposed solution to address the weaknesses of the existing system. The automation of the server failover requires an additional operational server that would bring the total number to three. The role of the third server is to act as a 'witness' to monitor the condition of the primary server and automatically execute the failover to the standby server and implement all the necessary initialisations so that there would be no loss of service on the FPL should the primary server have a failure. This would increase the availability of the FPL as it would not need to be disconnected from the network for routine server maintenance. A diagram of this failover architecture is given in Figure 4-14.

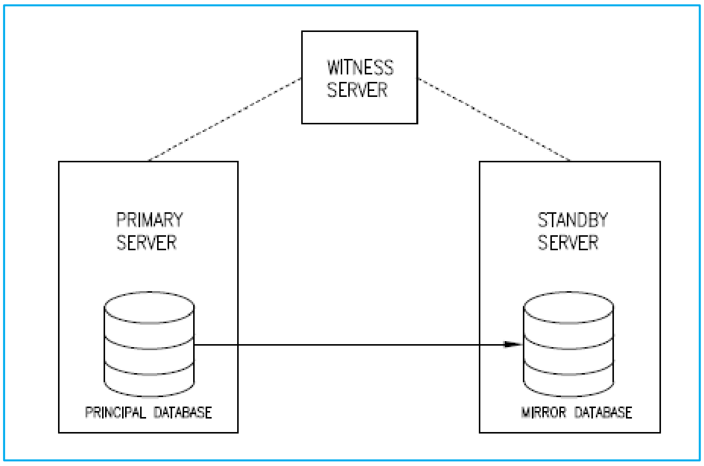

Figure 4-14 – FPL CM server failover proposed architecture

Cost benefit analysis

The costs associated with the new failover solution are mainly incurred in the additional witness server hardware and bespoke software required to implement the automatic failover mechanism into the system architecture. Additional testing would also be required to ensure the system was operating correctly.

The benefits of automatic failover is a much faster failover time that would enable the FPL to continue to operate for server failures or routine server maintenance. The frequency of server maintenance will have an impact on the decision of whether to implement an automatic failover. For example, if there are multiple scheduled events per year, an automatic process would significantly reduce unnecessary FPL outages. However, the cost of implementing the automatic failover is a relatively small percentage of the overall cost of the FPL CM and therefore it would be recommended to include this functionality as standard in future CM installations. It is important to note that there have been no server failures or server maintenance activities that have triggered a server failover since the installation of the FPL.

4.4.2 Set-point optimisation

Existing

The FPL CM logic implements a set-point calculation for the FPL when it identifies either a thermal or voltage violation on the network. This set-point is then issued to FPL in the field that then moves to the new operating point and removes the network violation. The conditions on the network are changing constantly therefore the FPL CM has been designed to implement periodic optimisation algorithms called "P/Q Minimisation Logic". These algorithms check to see whether the existing real and reactive power set-points can be reduced without causing further violations, ensuring the FPL device is running efficiently by reducing FPL electrical losses.

Proposed

A further improvement in set-point optimisation could be found by incorporating machine learning algorithms into the set-point calculation logic. Machine learning algorithms typically utilise mathematical models to make decisions and perform tasks without being specifically programmed to do so; they do this by recognising patterns in datasets based on some initial 'training' data. The application of this technology to the FPL could improve the performance of the FPL CM:

Speed of set-point calculation – The machine learning algorithms would have the ability to increase the speed that the CM takes to find a set-point solution. It would do this by recognising patterns in the network data that it receives from the NMS and more quickly converging to a valid solution over purely iterative logic.

Non-violation driven optimisation – The set-point calculation process is currently violation based i.e. it is instigated by a network violation that is identified on the network. Machine learning algorithms could be used to implement constant optimisation and remove the need for user defined voltage limits. For example, the machine learning algorithms could be trained to search for solutions that satisfy a priority requirement such as balancing power flows through the BSP transformers or maximising generation capacity release for the network.

Data quality – The machine learning algorithms could be used to improve the data filtration and data handling capabilities of the FPL CM. It would do this by recognising patterns in unreliable data points or historic load profiles. For example, if a data point is consistently unreliable the algorithm could learn to discard this data point and use an alternative. If a data point is missing from the dataset it could utilise the available information and historic load profiles to infer a value. This capability would improve the stability of the CM as it would increase the likelihood of successful set-point calculations that in turn would reduce unnecessary disconnection of the FPL from the network.

Cost benefit analysis

The cost associated with implementing machine learning algorithms in the CM's set-point calculation and optimisation logic will likely be considerable and a large proportion of the cost of the existing FPL CM system. This is because the logic will require re-specification, re-design and significant factory/integration testing before it can be safely operated on the system. The cost of the solution will ultimately be dependent on the level of re-specification of the CM and the complexity of the machine learning functionality that is proposed. In addition, the application of machine learning techniques to control systems on the distribution network is novel with a low TRL. A high level estimate is that it would cost approximately £200k to implement this additional technical functionality. The knowledge to carry out the modifications to the FPL CM may not be available in the traditional DNO supply chain and therefore this task carries a high level of innovation risk and may therefore be suitable for further innovation funding.

4.4.3 Power systems model

Existing

The existing power systems model used within the FPL control module was developed in the IPSA power system software package. The information for the model was originally extracted from the master power system model that the WPD network planning team use to validate changes to the network on a day-to-day basis. The master model for the South West licence area is built and kept up-to-date in the PSSE power system software package and therefore a process had to be implemented to transpose the information across to the IPSA environment.

The model used in the FPL control module needs to be an accurate representation of the actual network so that the module calculates accurate set-points for the FPL in the field. The model is kept up to date by the WPD NMS team when they are informed about a change to the network or a new load/generator is connected to the network. This is a manual process that has to be carried out by an engineer trained to carry out this task using the approved procedure and guidance documentation.

Proposed

An improvement could be made to the way in which changes to the network are captured in the model by using an automated system that transposes the changes applied in WPD's master model to the model in the FPL control module. The master model by definition is an accurate representation of the network and therefore using a software tool to extract the network information and import it into the IPSA model would ensure the models do not diverge over time. In addition, the process would be largely automated thus reducing the need for specific resource to be dedicated for updating network models.

Cost-benefit analysis

The software tool to perform the transposition of network changes from the master model into the FPL control module model will need to be developed by a specialist engineer and this will cost approximately £50k. However, the tool will be able to reduce the human resource required to manually update the model with the network changes. It is anticipated that the saving in man hours provided will mean that the capital expenditure for the tool is paid back in approximately 2-3 years.

5.0 Alternative FPL applications

5.1 Overview

This section identifies and seeks to understand the alternative applications for the FPL technology on the distribution network and whether these applications have additional benefits to the FPL developed as part of Network Equilibrium.

The first sub-section summarises the results of a literature review to identify other planned or operational MVDC / FPL style installations in the UK and internationally. A range of literature sources has been compiled and reviewed. A list of examples that are most applicable to the UK network and demonstrate the most benefit have been provided.

The second sub-section details the main alternative applications of the FPL technology. For each application a technical and financial review has taken place to quantify the possible benefits and to describe the barriers that exist to their implementation.

5.2 Literature review

5.2.1 Scope

The scope of the literature review is limited to examples of MVDC installations on utility distribution networks i.e. 132kV and below. The scope includes both back-to-back converters and converters separated over a DC link.

5.2.2 Methodology

A range of technical papers and publically available reports have been reviewed to identify applications of MVDC technology that are currently being deployed in the market. The review identifies and describes the latest practical installations of MVDC technology both in the UK and internationally.

5.2.3 Summary

The first step of the literature review was to understand the existing applications of MVDC technology. It was found that the main markets that utilise MVDC technology are outside the utility power distribution industry. They are described as follows:

- Renewable generation – MVDC inverters and converters are used extensively to facilitate the connection of renewable generators to the AC network. Inverter technology is predominantly used to connect solar farms to the network by changing the source DC power to grid frequency AC power. Power converters provide the necessary decoupling of the generator and grid frequencies to allow the connection of wind turbine generators as well as providing additional benefits such as P and Q control if required.
- Machine drives and traction – MVDC technology is also used extensively in Variable Frequency Drives (VFD) power supplies for AC electrical motors. This technology can either utilise inverter or converter technology and is able to adapt the motor speed to the actual motor demand, thus optimising energy consumption. These drives are now commonly used for light rail and tram applications where the vehicles require to

operate at variable speeds and thus a drive that is decoupled with the AC grid frequency is required.

- Network interconnection – MVDC technology is currently well established in the interconnection of power networks with different frequencies. Many industrial private networks and railway networks operate at different frequencies to the main grid and therefore utilise back-to-back frequency converters to provide this supply. The FPL is in fact based on ABB's PCS6000 converter technology that is used predominantly for railway network interconnections in Europe, a large proportion of which operate at a frequency of 16.7 Hz. A fairly recent development is the installation of MVDC technology at ports and harbours to enable power to be supplied to ships moored at these locations from onshore frequency converters. This avoids the ship's auxiliary systems being supplied from on-board diesel generation thus reducing emissions and local sound pollution.

The review has determined that there are currently very few practical applications of MVDC technology on utility owned distribution networks. There appears to be a growing trend towards the adoption of Modular Multi Level (MMC) VSC technology for HVDC installations, however, there is no clear topology standard for MVDC. The examples that have been found largely utilise scaled back HVDC technology.

There is particular interest in utilising MVDC technology for the "power collection network" of large scale solar PV and offshore wind farms that could bring significant benefits such as reduced system losses and consolidate the requirements for AC substation equipment that could reduce costs and substation footprints/weight [1]. The schematic diagrams in Figure 5-1 show a traditional PV power plant structure on the left hand side and a MVDC power collection architecture on the right hand side. The difficulty in adopting this new structure is a lack of experience with MVDC and immaturity of DC/DC converter technology.

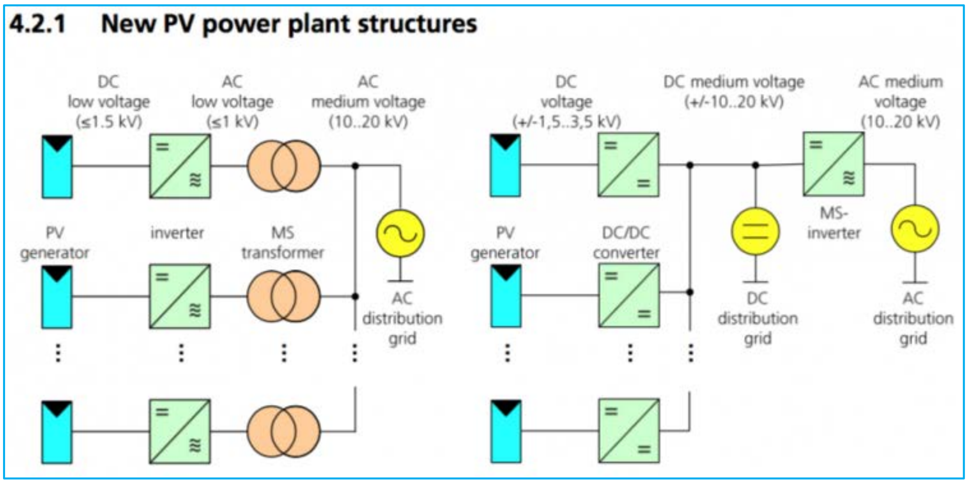

Figure 5-1 – New PV power plant structures [2]

The following sections describe some of the examples identified in the literature review in more detail.

5.2.4 Angle DC

Angle DC is a Network Innovation Competition (NIC) Project developed by Scottish Power Energy Networks (SPEN). It was awarded funding from the UK energy regulator, Ofgem, in 2015 and is due to be completed in April 2020. The aim of the project is to convert an existing AC double circuit 33kV line into a symmetrical monopole MVDC link i.e. each circuit carries one of the poles +/- 27kV DC in this case [3]. The double circuit connects Lanfair PG substation on Anglesey Island with Bangor substation on the North Wales mainland. A high level schematic showing the location of the link and the components of the system in Figure 5-2 and Figure 5-3 respectively.

The island of Anglesey is experiencing both load and distributed generation growth in the form of renewable generation such as wind, solar and tidal. The 33kV circuit in question is forecast to experience thermal limitations and voltage will be increasingly difficult to manage. It is anticipated that changing the existing AC circuits to DC operation will increase the cable nominal rating by 23% allowing for increased power flows. The MVDC link will allow greater control of the power flow through the circuit and also improve voltage management at either end of the link.

The MVDC technology is being supplied by GE and for this application they are utilising 12 units of their MV7000 converters at each converter station [4]. This product is normally used as a Variable Frequency Drive (VFD) system for MV motors and it is unknown at this stage how they will be adapted for the MVDC link application. This information will likely become known when SDRC-4 and SDRC-5 project reports are published by SPEN.

The Technical Specification for MVDC Converter Stations (SDRC-2) has been published and a summary of the requirements are as follows [5]:

- Fully rated power is required in both directions through the MVDC link;
- The nominal DC voltage is ±27kV;
- Real power control implemented either by set power levels (i.e. 90%, 80% etc.) or through Vernier control; and
- Independent reactive power control at each MVDC terminal.

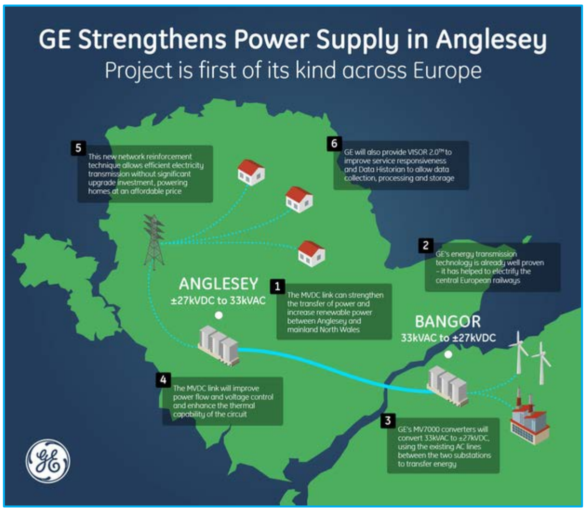

Figure 5-2 – Location of Angle DC MVDC link [4]

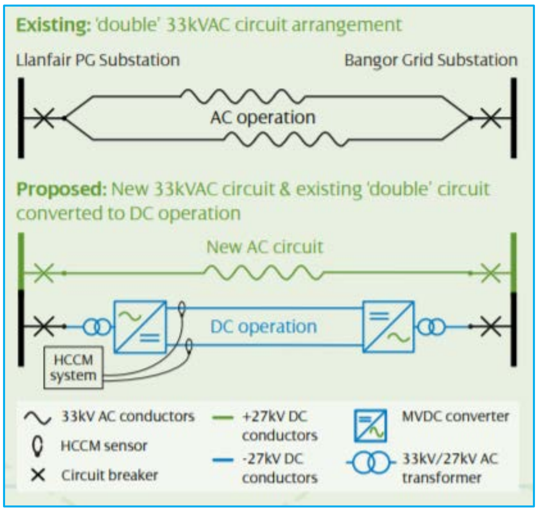

Figure 5-3 – Angle DC high level system diagram

5.2.5 ABB HVDC Light

HVDC Light is a VSC converter technology developed by ABB. It is particularly suitable for small to medium scale applications and has been implemented in over 20 international projects. The majority of these projects utilise transmission level voltages, however, there are a limited number of applications that are approaching distribution level voltages and these are described below:

Eagle Pass

This was a 36 MVA back-to-back VSC installation at Eagle Pass Substation in the State of Texas, US, which is a part of American Electric Power (AEP) electricity network. The location of the installation is provided in Figure 5-4. The converter was designed to interconnect the transmission grid of Texas with the Mexican power system. The Eagle Pass Substation is supplied by two 138kV transmission circuits but is situated a large distance from the nearest generation, which gives weak voltage support to the area; this is especially the case for a loss of one of the transmission circuits. The Piedras Negras substation is located just across the border in Mexico and is connected to Eagle Pass via a single circuit 138 kV transmission line. This circuit is normally open and utilised only for emergency conditions to support the load at Eagle Pass.

The back-to-back VSC was installed across the NOP at the Eagle Pass site. Refer to Figure 5-5 for the simplified single line diagram of the installation. The device provides the required voltage support at Eagle Pass by being able to inject or absorb reactive power (+/- 36MVar). In addition, the device allows uninterrupted bidirectional active power transfer between the USA and Mexican grids, enhancing the reliability of the power supply [6]. The VSC utilises IGBT power electronics controlled by Pulse Width Modulation (PWM). The DC link voltage is +/- 15.9kV and the AC output voltage from the VSCs has a nominal value of 17.9kV, which is stepped up to 138kV to interface with grid.

Figure 5-4 – Eagle Pass VSC location

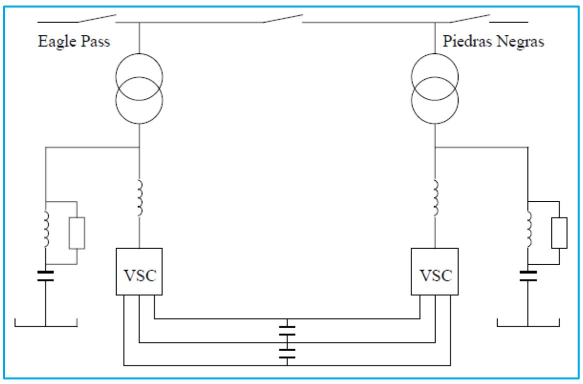

Figure 5-5 – Eagle Pass VSC simplified single line diagram

Mackinac

This project involved the installation of a 200MW back-to-back VSC installation at Mackinac Substation near St. Ignace, Michigan (US). It has been operational since 2014.

The American Transmission Company (ATC) identified a need for a new solution to introduce power flow control between Michigan's Upper Peninsula and Lower Peninsula. This was in response to increasing levels of hydro and wind generation to the West of Lake Michigan pushing power across the Upper Peninsula and causing voltage and thermal constraints on this network. The traditional approach was to split the network in the Upper Peninsula to force the generation to the load centre in the South. This is shown in Figure 5-6. Splitting the network in this manner reduces network security and the reconfiguration can cause network transients. It was found to be prohibitively expensive to build new high voltage lines to resolve this issue and therefore a HVDC VSC solution was adopted [7].

The Mackinac HVDC converter station was connected to the 138kV AC network between the Upper and Lower Peninula as shown in Figure 5-7. The converter was designed for 200 MW bi-directional power transfer and also to provide reactive power (+/- 100 MVAr) for local voltage support during steady state and dynamic conditions. A symmetrical monopole topology was chosen. The converter is a Cascaded Two-Level (CTL) converter with reduced losses and reduced harmonic generation compared to older generations of VSC converters. The simplified single line diagram is shown in Figure 5-8. A DC voltage of ±71 kV was selected to achieve the 200MW bi-directional power transfer [8].

There are additional benefits of the VSC technology such as the ability of the converter to automatically enter a Power Transfer Mode that can temporarily serve an island created on the North side of the device under certain contingencies. In this mode the converter designed to operate at fixed frequency / voltage mode with droop settings. The converter is also able to provide black start capability.

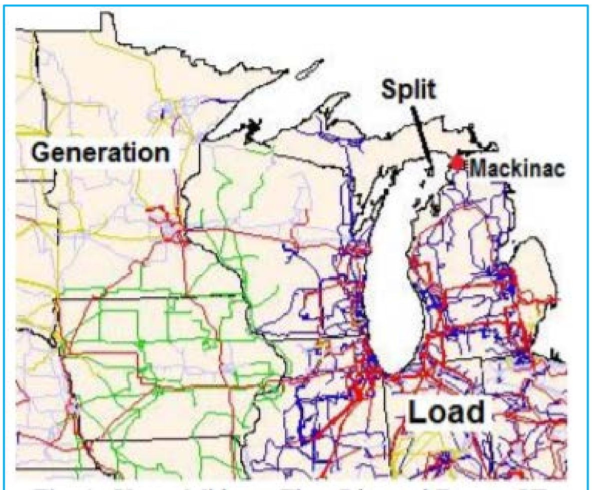

Figure 5-6 – Mackinac VSC location

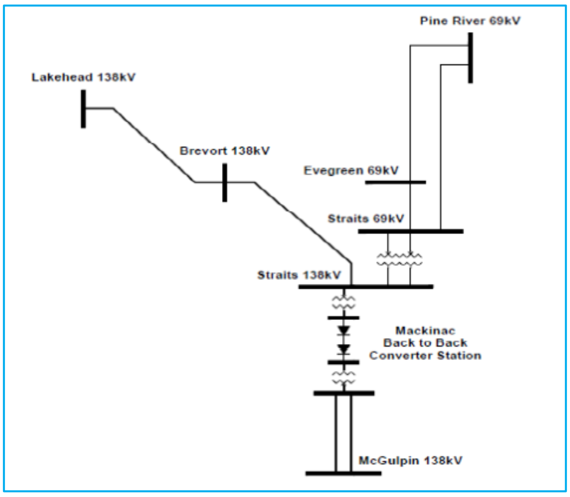

Figure 5-7 – Mackinac VSC proposed scheme

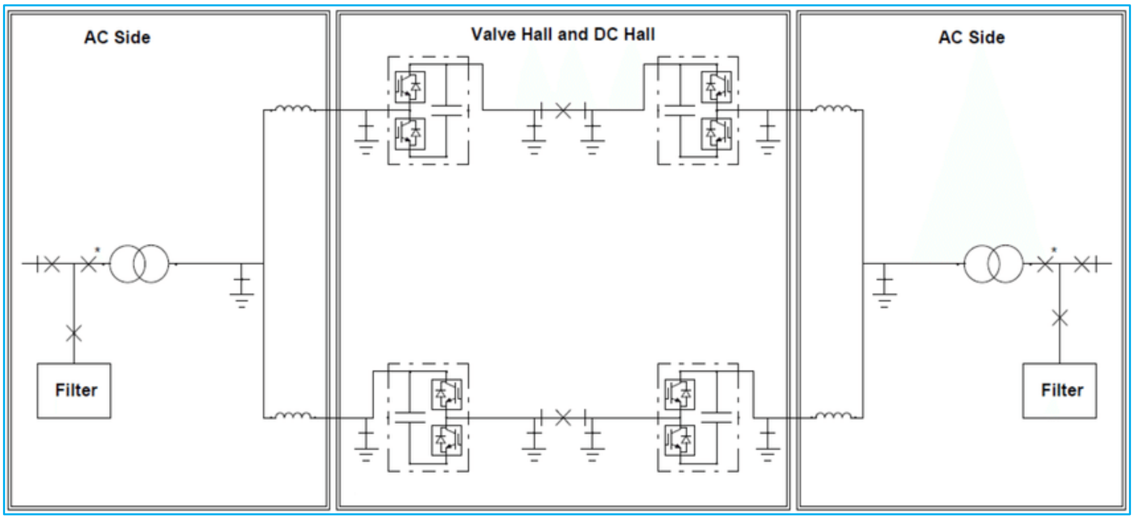

Figure 5-8 – Mackinac VSC simplified single line diagram

Åland Islands

Åland is an archipelago of 6500 islands in the Baltic Sea. It is a self-governing region of Finland but is geographically closer to Sweden. Kraftnät Åland owns, operates and maintains the electrical infrastructure that supplies power to the region. Åland has relied on its main power supply coming through a submarine 110 kV AC power connection to the Swedish grid rated at 80-100 MW. There is also a 45kV connection to mainland Finland, however, this is only rated at 10MW and cannot be synchronised to the Swedish system [9].

The utility commissioned a 100 MW +/- 80 kV HVDC transmission link between the main island of Åland and mainland Finland that is shown in Figure 5-9 and Figure 5-10. The two converter stations are connected together by two 80kV submarine cables 158km long. The link will provide security of supply to the island, allow existing fossil fuel back-up generation on the island to be closed and allow a much faster black start capability. The black-start system can restore power in under five minutes [10].

The HVDC link was designed with a multi-terminal configuration, which allows for additional in-feed from stations, such as future wind power plants.

Figure 5-9 – Aland HVDC link location

Figure 5-10 – Aland converter station

5.2.6 Siemens MVDC PLUS

Medium Voltage Direct Current Power Link Universal System (MVDC PLUS) is a new DC transmission system developed by Siemens launched in 2017. Figure 5-11 shows a layout of the MVDC technology. It is designed to serve medium voltage AC grids between 30-150kV. The MVDC PLUS technology can transfer DC power over a maximum distance of 200km and is offered in three ratings (50, 100 and 150 MW) at DC transmission voltages of 20kV and 50kV [11].

The Siemens MVDC PLUS technology is a reduced version of their HVDC PLUS technology that is used on Siemens' HVDC transmission system projects. The MVDC PLUS system uses VSC technology utilising a Modular Multi-Level (MMC) architecture. The number of sub-modules and DC voltages are selected based on the application. Siemens' have made cost efficiencies by using AC components where possible in the design to increase standardisation. The system utilises a symmetric monopole design as shown in Figure 5-12. The sub-modules used are the same as those used in the HVDC systems ensuring nominal current ratings are comparable. Since fewer sub-modules are required relative to HVDC applications the size of the converter housing can be reduced [12].

At the time of writing there does not appear to be any MVDC PLUS devices that have been commissioned on the distribution system. Siemens list the following benefits that the MVDC PLUS solution could bring to customers:

- Connect island, platforms and remote areas;
- Integrate and stabilise weak grids;
- Enhance existing infrastructure
- Fulfil new tasks as a DSO; and
- Minimise the visual impact.

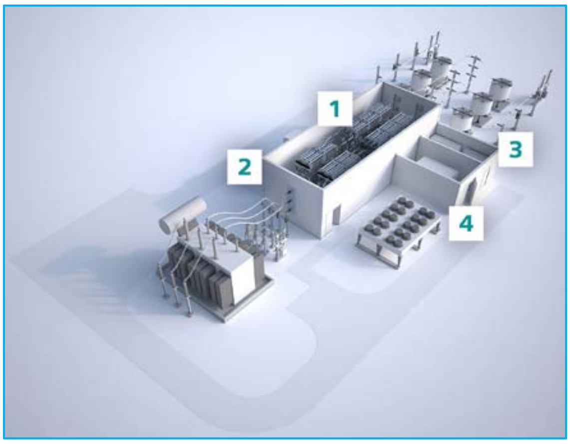

Figure 5-11 – Siemens MVDC PLUS technology

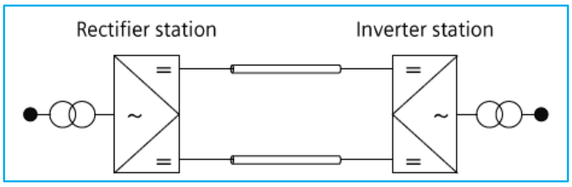

Figure 5-12 – MVDC PLUS symmetrical monopole configuration

5.2.7 RXPE

Rongxin Power Engineering (RXPE) is an international developer based in China and provider of high voltage power electronic solutions that include statcom and HVDC systems. RXPE are also able to offer MVDC solutions as part of their offering. They are able to provide 5kV-50kV VSC MVDC systems able to transmit power up to 100km.

RXPE have installed a number of MVDC systems to facilitate power supplies for offshore oil platforms. An example of one of these projects is given below:

Wenchang Project

A main oil platform in the Western South China Sea was supplying a remote platform via three single phase AC subsea cables. One of the cables suffered an insulation failure and meant that the remote platform had to run on back-up diesel generation. An 8MVA +/-15kV MVDC system was installed to restore the electricity supply. A block diagram showing the MVDC system layout is shown in Figure 5-13. The system was a symmetrical bipole arrangement that utilised the healthy AC phases as the positive and negative DC cables and the faulted phase as the neutral. The MVDC solution has been operating successfully since 2013 [13].

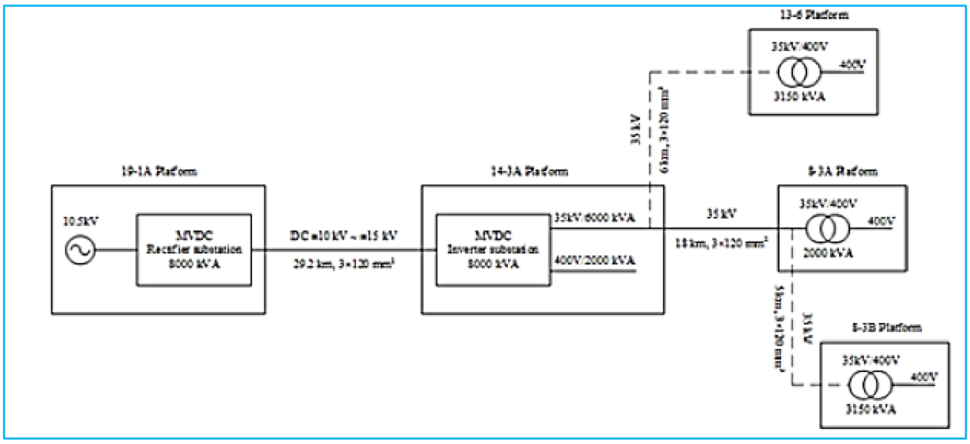

Figure 5-13 – Wenchang MVDC system layout

5.3 Alternative applications

5.3.1 11kV FPL

Description

A detailed description and analysis of an 11kV FPL has been given in SDRC-6 “Trialling and Demonstrating the FPL Method”. The SDRC report documents the benefits that could be gained from the development of the 11kV FPL, different network configurations where they could be installed and a detailed analysis of the FPL technology and control system requirements for each configuration.

This section therefore provides a high level summary of the information that has previously been presented in SDRC-6.

The device is based on similar technology to the 33kV FPL and could be installed in three possible network configurations:

1. In an 11kV interconnector between two primary substations (see Figure 5-14);
2. At the Normally Open Point (NOP) between two 11kV networks (see Figure 5-15; or
3. Across an 11kV bus-section at a primary substation (see Figure 5-16).

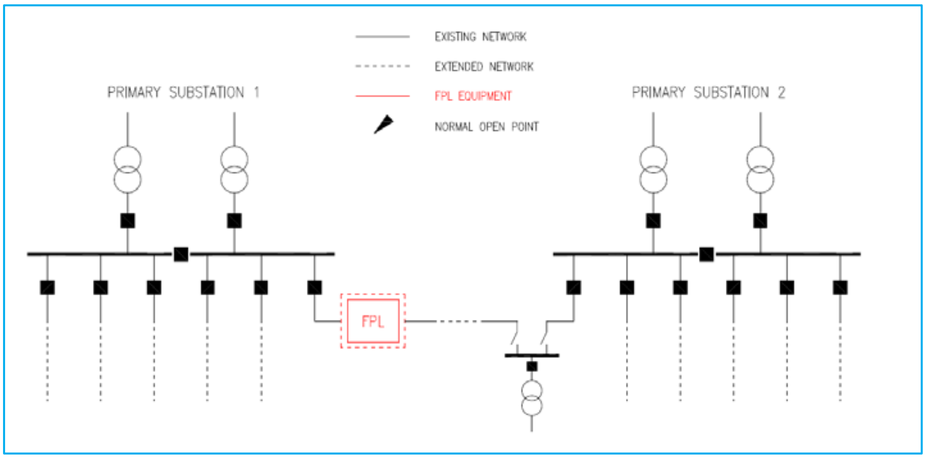

Figure 5-14 – 11kV FPL system configuration 1

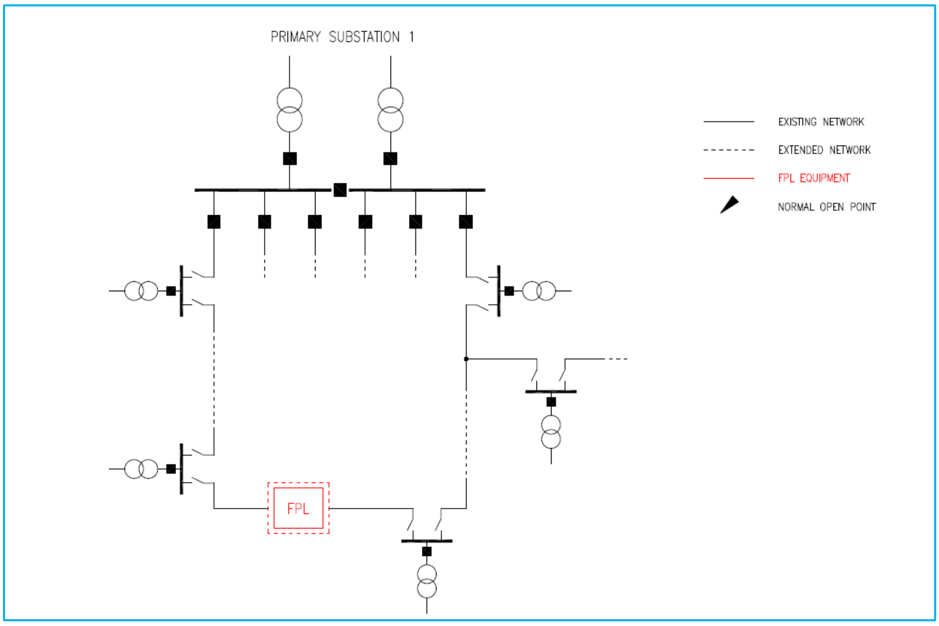

Figure 5-15 – 11kV FPL system configuration 2

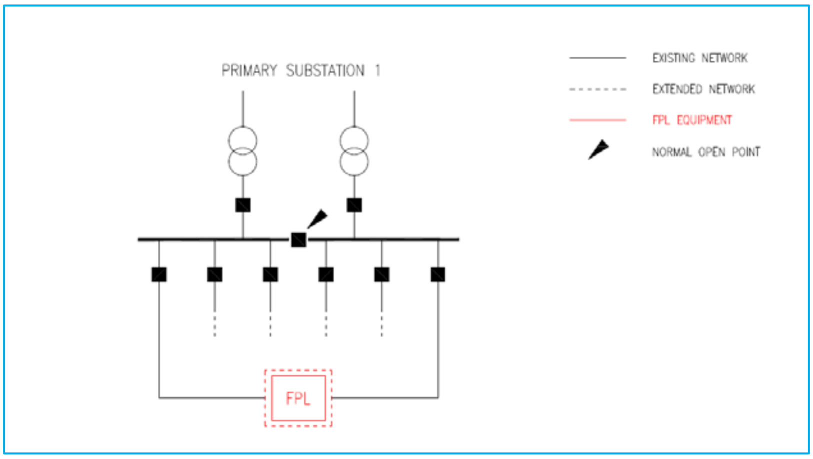

Figure 5-16 – 11kV FPL system configuration 3

In addition, the 11kV FPL could be developed to act as an interface between 11kV and 6.6kV networks. The 6.6kV network is increasingly seen as legacy, with asset replacement programmes favouring replacement with modern 11kV equipment. However, this replacement can be expensive as large sections of network have to be replaced. Therefore, one solution could be to supply legacy sections of 6.6kV network with an 11/6.6kV FPL. This may enable DNOs to defer asset replacement costs.

Benefits

One key feature of the FPL is the ability to provide voltage control through reactive power at both sides of the device. The need for voltage control is particularly important at remote ends of the network where fluctuations in load and generation can cause the voltage profile to vary significantly. Whilst the fluctuations in voltage can be controlled at the 11kV busbar using tap changers on primary transformers, remote ends of the network can suffer as fluctuations here cannot easily be managed locally. Voltage control is particularly beneficial for the system configuration shown in Figure 5-15.

Most adjacent primary substations will have 11kV networks that operate with the same vector group, however, it is possible for vector groups to be different (for instance, the primary substations could be fed from separate BSPs with different vector groups). The FPL has the ability to connect two networks together that have different vector groups and allow power flows between these networks.

Paralleling 11kV networks reduces system impedance and as a result increases to system fault levels. In many cases it is not possible to permanently parallel parts of the 11kV network due to increased fault levels exceeding equipment ratings. In addition, paralleling 11kV networks can also cause large, undesirable swings in power flow due to an imbalance in network impedance. The increase in fault levels due to paralleling 11kV networks is most pronounced when the parallel involves networks with a lower impedance (i.e. at a primary substation across an interconnector between two primary substations, Figure 5-14 or paralleling between two adjacent busbars, Figure 5-16).

The installation of an FPL has the effect of producing a high impedance between two parallel networks, therefore limiting the increase in fault levels. This may mean it is then possible to run two networks in parallel and balance power flow across transformers or substations. Being able to balance power flows can increase transformer life expectancy and reduce the likelihood of customers being disconnected by transformer protection. In addition, being able to balance power flows between substations increases operational flexibility.

Barriers

The FPL technology would require significant modification and re-design in order to produce a compact and cost effective solution for the 11kV distribution network. The FPL technology will need to be re-specified and repackaged to produce an 11kV FPL design. This would require careful study and a design process similar to the one implemented as part of the 33kV FPL trial will need to be repeated to ensure the device is fit for purpose and safe to be installed on the 11kV network.

Technical Assessment

Table 5-1 provides a summary of the technical areas that require consideration when assessing the design and performance requirements of an 11kV FPL.

Table 5-1 – Technical Assessment for 11kV FPLs

Area	Contribution
Rating	The rating of the 11kV FPL will differ based on the connection configuration that is employed. For example: **Configuration 1** – the rating would need to match the continuous current rating of the 11kV circuit breakers installed at primary substation 1 and 2. Typically this would be around 630A. **Configuration 2** – as the FPL could be located some distance from the primary substation circuit breaker, a lower rating than 630A could be applied. However, care shall be taken to ensure the rating of the FPL is future proofed should circuits be upgraded in the future. It is recommended that the rating of the FPL is to be no lower than 400A. **Configuration 3** – with the FPL connected across the 11kV bus section of a primary substation it would need to be match the rating of the busbar (typically 2000A).
Network Interface	A 33kV FPL requires a transformer to step-down the grid voltage to 3.25kV to enable the power electronics of the device interface safely with the distribution network. At 11kV it may be possible to connect the FPL directly to the 11kV network using a multilevel converter and avoid the use of an intermediary transformer. The removal of the transformer would generate significant space/cost savings and provide a much more attractive device for use on the 11kV network.
Converter Architecture	The multilevel converter architecture could mitigate the need for an interface transformer, however, this interface typically has a reduced power range. Further investigation would be required to understand if the provisional converter ratings, discussed above, can be met. The design for the 33kV FPL incorporated dual redundant control units as it is a strategic asset on the higher voltage network. However, for FPLs connected to the 11kV network the requirement for dual redundancy is less evident and could help reduce costs and size.
Harmonic Filtering	The multilevel converter provides an inherent smoothing of the waveforms via the capacitive components in the system and therefore, could mitigate the need for external harmonic grid filters similar to the ones used on the 33kV FPL. The smoothing effect increases with the number of stacked converter modules. A study would have to be implemented to determine the number of stacked modules for continuous rating that would provide the required minimum voltage rating and harmonic performance.
Thermal Management	The 11kV FPL will have a lower rated power level than the 33kV FPL potentially mitigating the need for a large complex water cooling system. However, the 11kV FPL will still have higher levels of current flow through the device when compared to the 33kV FPL. As such, a detailed study would be required to determine if a forced air cooling system would provide sufficient levels of cooling.
Switchgear	The 11kV FPL will require circuit breakers and a bypass circuit breaker similar to the 33kV FPL. This configuration provides the appropriate level of control and flexibility for the operation of the FPL. However, it may be possible to integrate the 11kV switchgear within the FPL container, rather than separately within a dedicated switchroom.

Area	Contribution
Housing	One of the key design principles for successful deployment of ground mounted equipment on the 11kV network is standardisation of the associated housing. As such, developing a standard solution for the 11kV FPL that incorporates interface switchgear is key. The size and construction of the housing will depend on the level of miniaturisation that can be achieved through design and development process for the 11kV FPL. The equipment shall be arranged in the optimum layout for performance, safety and maintenance access requirements.
Interlocking	Incorporating all the 11kV FPL components together into one enclosure will help to simplify the interlocking design required for operation and maintenance purposes. The system shall ensure that the device is isolated and earthed prior to an operator being granted access to any exposed 11kV conductors or converter parts.
DC link pre-charging	A DC link pre-charger is unlikely to be required for an 11kV FPL as magnetic inrush will not be a major consideration with a small rated interfacing transformer (drawing a much smaller magnetising current when compared to the 33kV device). Similarly, if a multilevel converter architecture is implemented an intermediary transformer is not necessary and hence there will be no requirement for a DC link pre-charger.
Control Module	The control module for the 11kV FPL will require an accurate model of the surrounding 11kV network to allow the calculation of set-points to remove thermal and voltage violations. The 11kV network tends to have less analogue and status information compared with the 33kV network, and therefore the control module will need to rely heavily on state estimation. In some instances it may be necessary to deploy additional transducers on the 11kV network to improve the accuracy of the state estimator. The scale of the model required for the control module will depend on the configuration that is used. For example, Configuration 3 would only require a simple model as it is connected across two 11kV busbars where local status and analogue information will be readily available. Configuration 2 would require a more complex model as information will be required on the interconnected 11kV network downstream of the substation.

Financial Assessment

As discussed previously, the FPL technology would require significant modification and re-design in order to produce a compact and cost effective solution for the 11kV distribution network. The design process will therefore require similar resources to those utilised for the design of the 33kV FPL. The upfront development cost of the 11kV FPL would be similar to the 33kV FPL except for the cost of the hardware components, which would be lower due to its compact size and simplified system architecture. It is anticipated that the post-development cost of an 11kV FPL would be approximately £1m inclusive of the control system.

5.3.2 DNO-DNO FPL

Description

The quality and security of supply often diminishes towards the boundary between DNO licence areas. This is typically due to a lack of network interconnection at the boundary; loads in these areas are normally supplied by long radial feeders that leads to poor voltage regulation and difficulty in the efficient restoration of supplies after a fault.

The DNO-DNO FPL would be a new application for the FPL technology and would be installed at the boundary between two DNOs to interconnect their respective networks. The FPL could interconnect these networks at the 33kV or 11kV voltage level dependent on the primary function of the device. The device would allow real and reactive power flows between the networks with the aim of providing benefits to both DNOs. Figure 5-17 shows the high level system configuration of this application.

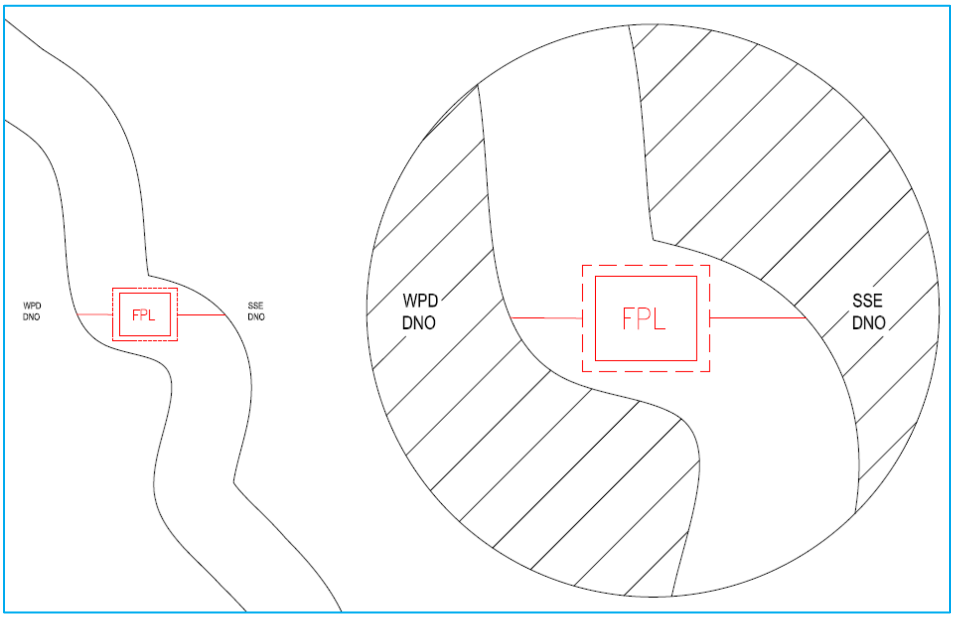

Figure 5-17 – DNO-DNO FPL system configuration

Benefits

The DNO-DNO FPL has the capability to improve the voltage regulation of the network either side of the DNO boundary by supplying or absorbing reactive power as required by the systems. It therefore has the ability to improve the power quality for customers connected close to the boundary.

The DNO-DNO FPL is a flexible device that can provide precise real and reactive power support at the point of installation. Therefore, it is foreseeable that in this application the FPL can be utilised in DSO flexibility markets i.e. it can be thought of as flexibility service that can be called upon when network conditions either side of the boundary require support. For example, in the scenario that a 33/11kV substation has a planned transformer outage the FPL could be called upon to provide load support for the duration of the outage thus reducing the risk of customers being disconnected. Figure 5-18 shows a schematic view of this scenario.

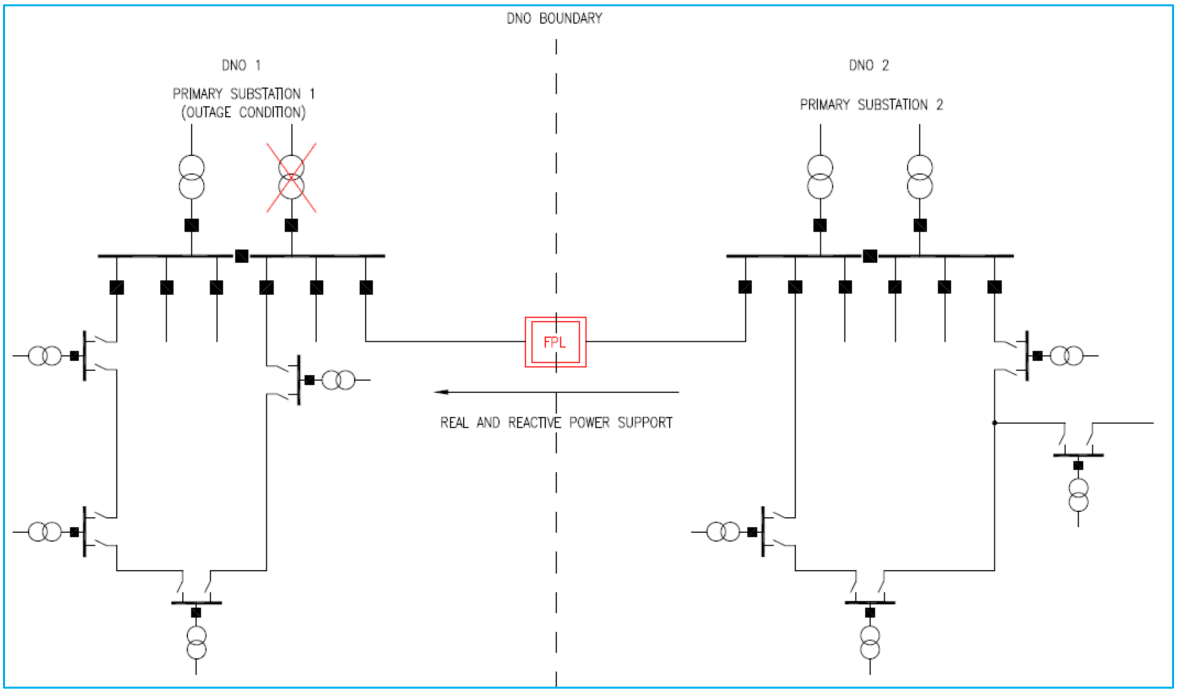

Figure 5-18 – DNO-DNO FPL providing network support to primary substation with transformer outage

At the boundary between two DNOs there are typically a number of single transformer substations that utilise 11kV backfeeds to restore demand if there is an unplanned outage. The DNO-DNO FPL could be used to increase the interconnectivity of the 11kV network at the DNO boundary and therefore increase the security of supply for customers under N-1 conditions. The FPL does this by being able to transfer real power across the boundary to support either side of the network after the occurrence of a fault. Figure 5-19 shows a schematic view of this scenario.

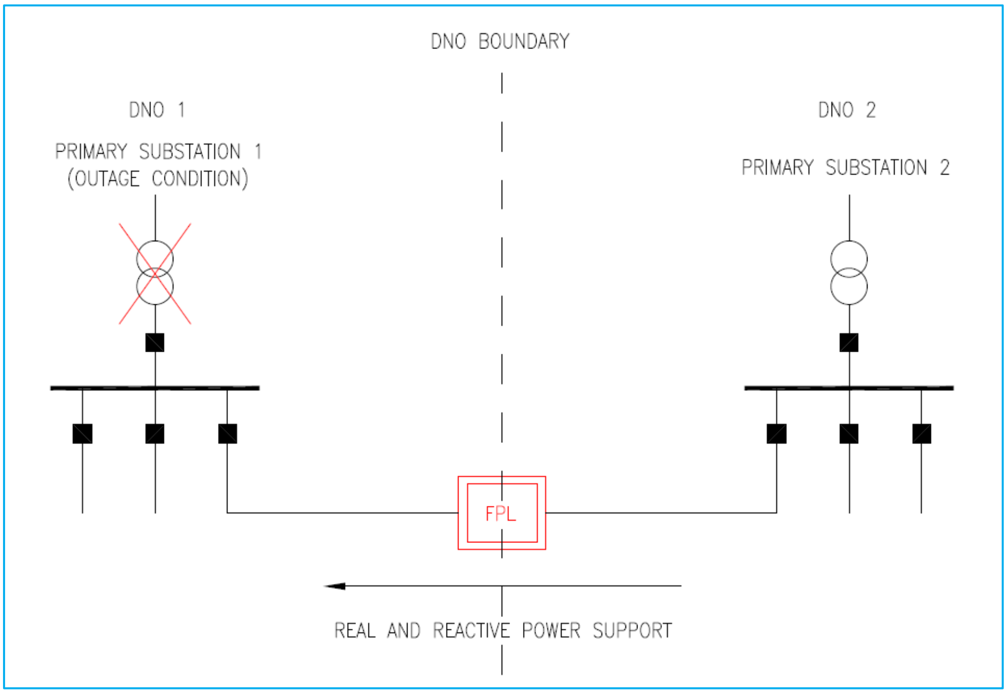

Figure 5-19 – DNO-DNO FPL providing network support to single transformer substation with transformer outage

The DNO-DNO FPL could also be used to facilitate more DG connections at the boundary between license areas. It is more likely that thermal or voltage constraints will inhibit new generator connections close to the DNO boundary due to the relative weakness of the network in these locations. The DNO-DNO FPL could allow a proportion of the generator's power output to be transferred across to the adjacent DNO's network to remove the thermal constraint that would have otherwise existed on upstream network components. The FPL is also able to adapt the reactive power at its terminals to regulate the voltage to within statutory limits thus removing voltage constraints that may be caused by the connection of new DG.

Barriers

The barriers to the implementation of the DNO-DNO FPL are dependent on the installation location, primary function of the FPL and the chosen voltage level for its operation. It may be the case that the optimum location for the FPL in terms of network performance is at odds with the existing infrastructure available for its cost-effective connection. This is particularly critical for a device connected at 33kV where it is likely that there will have to be additional 33kV infrastructure installed (such as new OHL and cable connections).

A significant barrier to the implementation of this type of FPL will be the formation of clear ownership and management model for the device since it may be providing services to both of the DNOs it is connected to. If power is being transferred from one DNO to the other there has to be clear rules that define the metering and payment mechanism for the energy that is supplied. There would also be a need to understand the regulatory impacts of deploying this type of technology on the network.

A 33kV DNO-DNO FPL device would require minimal additional design engineering as the design would be based on the FPL developed as part of Network Equilibrium. In contrast, an 11kV DNO-DNO FPL will require significant re-specification and re-design before a system would be ready to deploy in this capacity (refer to Section 5.3.1). The re-design of an 11kV FPL for this purpose would be subject to an additional complication regarding the demarcation of responsibility between DNOs. It is likely a lead DNO would take control of design, build and installation with support from the second DNO. The differing levels of interaction may be dependent on the relative benefits each DNO receives. It is clear that this type of FPL will require significant interaction between DNOs, which may increase development costs and timescales and which need to be factored into the business case for such a device.

The responsibility for the control of the FPL is another aspect that would have to be carefully agreed between each DNO. Additional costs will be incurred if the FPL has the facility to be monitored and controlled by both of the DNOs and therefore it may be more appropriate for one DNO to take sole responsibility for these activities. In addition, there will have to be an agreement on who will be responsible for the maintenance of the FPL device and its ancillary equipment.

Technical Assessment

The technical architecture of a 33kV DNO-DNO FPL would be very similar to the 33kV FPL developed as part of Network Equilibrium. The technical learning generated from the

Equilibrium project captured in this report would be able to be used to further reduce the cost and size of the device should it be adopted for this application.

An 11kV DNO-DNO FPL would require a much smaller, simpler and cost-effective design to ensure that an adequate business case exists for its deployment on the network. A detailed technical assessment of 11kV FPLs is provided in Section 5.3.1.

A power system model and associated control module may not be required for the DNO-DNO FPL if it is foreseen that the device will only be providing network support in N-1 conditions as shown in Figure 5-18. In this control mode, the device would be operated manually by a control engineer located in the network control centre to issue it with a real and reactive power set-point. If active control is required, the DNO-DNO FPL will require an accurate model of the surrounding network to allow the calculation of set-points to remove thermal and voltage violations. The model will also need to include sections of network spanning the boundary of the two DNOs. This will require input from both DNOs to produce the model and to keep it updated while it is service. In addition, the DNOs may require additional functionality from the control module to manually issue real power set-points to the device so that it can be used to provide network support for planned outages as described previously.

A key technical aspect associated with this FPL application will be selection of a suitable location for the device. A location that provides benefits in equal measure to both DNOs will be difficult to achieve. The location of the device will also determine which DNO has priority on the control, operation and maintenance of the FPL.

Financial Assessment

A 33kV DNO-DNO FPL will require minimal development and will be in line with the post-trial cost of the FPL developed as part of the Network Equilibrium project.

An 11kV DNO-DNO FPL will require significant redevelopment work as described in the previous section. A detailed financial assessment for an 11kV FPL is provided in Section 5.3.1.

5.3.3 Island Enabling FPL

Description

A key part of WPD's Innovation Strategy is to investigate whether it is feasible to intentionally island portions of the interconnected distribution system and to understand whether this can bring financial and environmental benefits for network stakeholders.

A potential barrier to intentional network islanding is the ability of the island to balance the generation and load quickly enough to maintain frequency and voltage stability under transient conditions. The FPL technology that has been developed in Network Equilibrium could be adapted for use as a novel way of maintaining stability within a network island. The FPL would be installed at the Point of Common Connection (PCC) between the island and the main interconnected network. It would then be able to create a 'virtual island' whereby the island is operating independently of the main network, however, there is still an electrical connection to the main network through the FPL's DC link. An example of virtual island system configuration is shown in Figure 5-20.

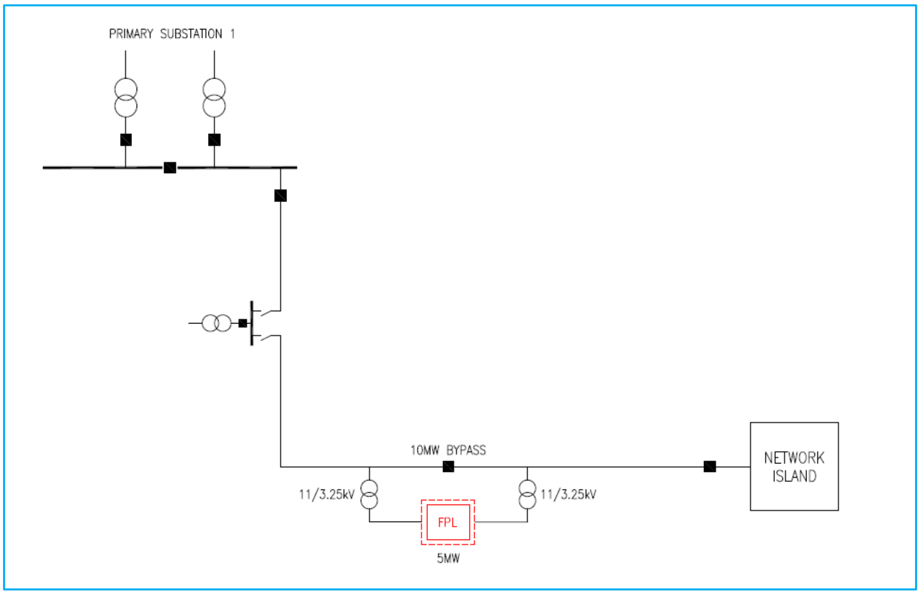

Figure 5-20 – Island enabling FPL system configuration

Benefits

There are a number of benefits attributed to the installation of an FPL at the PCC of an intentional network island. The FPL can supply real and reactive power into the network island with very fast and pre-programmed response times i.e. the ramp rate of the device can be changed in the FPL control software. Therefore, the FPL could be a key part of the islanding control system by minimising frequency and voltage transients that are caused by disturbances within the island e.g. a large load is disconnecting abruptly. It achieves this by injecting the appropriate amount of real and reactive power in the required timescales to stabilise the system back to the reference quantities. The FPL may be designed for a lower rating than the line it is connected to for this application (as shown in Figure 5-20). This would avoid over-specification of the device thus helping to reduce the size and making the device more cost effective.

This transient stability control highlighted above would otherwise have had to be performed by distributed controllers installed at the generators within the island, or by a centralised controller that has the duty of dispatching generation assets from a remote location. Therefore, the FPL could make the overall network island control philosophy much simpler and cost effective. This is particularly the case if a centralised controller is utilised as this solution would require significant levels of telecommunication between the controller and the remote assets.

It is important that the protection systems in a network island operate quickly, selectively and reliably both when connected to the main network and in islanded mode. This is a challenge to achieve technically because the fault level is usually much lower in islanded mode when compared to grid-connected mode as the island loses the fault level contribution from the main network. If an FPL was connected at the PCC it would have the capability to pass some limited fault current into the island from the main network. This could be enough fault current to ensure the correct operation of existing protection schemes or at lease reduce the modifications required the existing protection schemes to ensure they work in both grid-connected and islanded operational modes.

The Island Enabling FPL could also perform the safe re-syncing and reconnection of the network island to the main network. The FPL would initially ensure that there is no real power flowing into the island i.e. there is zero net power flow at the PCC. The FPL would then adjust the phase angle of the voltage waveforms by injecting or absorbing reactive power at its terminals. Once the waveforms are synchronised the FPL would be able to close the bypass breaker indicated in Figure 5-20. This process could be completed automatically by the FPL after instruction from an operator.

Finally, the FPL could operate as a centralised network island controller. In this application the FPL would be responsible for the majority of control functions for the network island:

- Automatic synchronisation and reconnection of the island to the main network;
- Transient stability control to ensure the frequency and voltage within the island remain within pre-defined limits;
- Balancing the load and generation within the island by dispatching controllable assets;

The benefit of this application is that the control functionality is integrated into a single package that generates both technical and cost efficiencies.

Barriers

The main barrier attributed to this application is upfront cost of designing and developing an FPL. The cost is many times higher than a simple circuit breaker that is normally located at the PCC to disconnect and reconnect the island from the main network. The FPL could, however, perform certain network island control functions thus reducing the overall cost of the island control system. A detailed study would be required to understand if the FPL is cost-effective compared to another alternative solution.

There would likely have to be modifications to the FPL control system to enable the device to perform in this new application. These may be relatively simple hardware and software changes to enable the transient stability control and grid-syncing capability. A new testing specification and FAT would be required after the changes to the device are completed. If the device was to be used as a centralised island controller, the changes would require a more fundamental re-design and re-specification of the device, especially the FPL control system. The device would have to undergo a new design review, test and trial process.

Technical Assessment

The Islanding Enabling FPL would be based on the same technology as the FPL developed as part of Network Equilibrium. It is likely that such a device would be connected as per Figure 5-20 and therefore its rating would not require to be matched to the line rating. The key functionality of the FPL in this application is the ability to supply real and reactive power very quickly in response to disturbances within the islanded network allowing the embedded generation in the island to balance changes in load on longer timescales. If the FPL was to operate as a central island controller, significant modification and re-design of the control system would be required.

If the prospective island is at the 11kV voltage level then the FPL would require a much smaller, simpler and cost-effective design to ensure that an adequate business case exists for its deployment on the network. A detailed technical assessment of 11kV FPLs is provided in Section 5.3.1.

Financial Assessment

The major additional costs associated with this type of FPL are the modifications required to the device's local control systems as well as the control module that is used to control the device remotely. The new control systems will require new technical and testing specifications to be designed. It is likely that manufacturers will have to make significant modification to existing systems, or build new control systems to cater for this FPL's requirements. The creation of virtual islands with power electronic devices is at a very low TRL and high innovation risk. Therefore, the development of a suitable business case and subsequent network trial would have to be considered to ascertain if there are financial benefits associated with such a device.

5.3.4 Network Mesh FPL

Description

The FPL developed in Network Equilibrium allowed the interconnection of two 33kV network groups. However, it is feasible that the FPL could interconnect three network groups in the configuration shown in Figure 5-21.

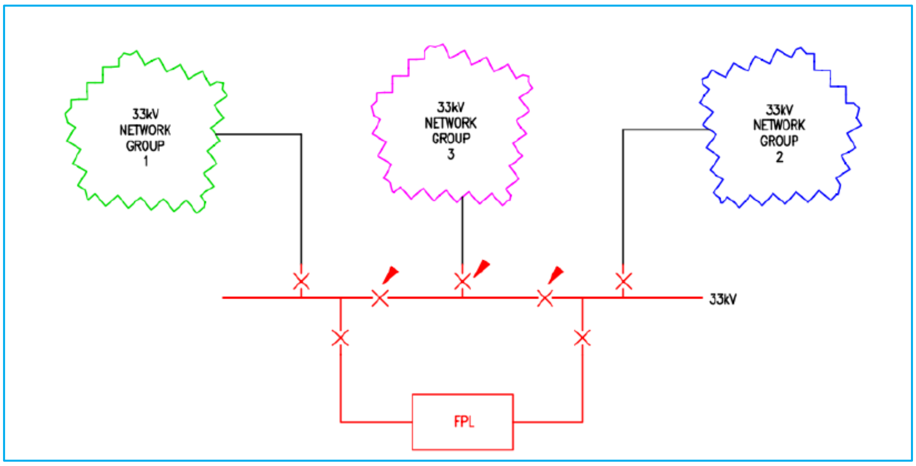

Figure 5-21 – Network mesh FPL system configuration

Benefits

Connecting the FPL in a network mesh would allow the FPL to transfer real and reactive power to/from any combination of the network groups. This gives the FPL much more operational flexibility and ability to balance load and generation. It can be imagined that the FPL control system could automatically switch the FPL to connect different network groups together at different times throughout the day to optimise the balance between load and generation more efficiently and releasing more network capacity.

Barriers

The Network Mesh FPL requires a 7-panel switchboard to provide the required level configurability for this application. This is an additional expense when compared to the 5-panel switchboard required for the FPL developed in Network Equilibrium.

The control system for the network mesh FPL would need to include a significant number of additional data points to be included in the network model since there is an additional network group that can be interconnected. The power systems model that is being used in the control system would consequently be much larger and more challenging to keep accurate as network changes occur.

The control module would require modifications to enable it to automatically reconfigure the 7-panel switchboard to connect the different network groups. This would be a significant departure to standard DNO policy where control of network circuit breakers is normally only carried out by control engineers at the distribution network control centre.

Technical Assessment

The Network Mesh FPL would be implemented on the 33kV network and therefore would be technically similar to the FPL installed in Network Equilibrium. The main technical challenges would be the additional functionality and complexity that would need to be included in the control module. The electrical model, in particular, would require considerable additional complexity to include a third network group. As described above, the control module would also require additional functionality so that it is able to switch the circuit breakers in the 7-panel board to interconnect the different network groups. A fail safe mechanism would be required in this instance since the switching would be implemented autonomously by the FPL control module. This would likely be an automated switching scheme that reconfigures the network into its default configuration if the control module goes offline or is unable to communicate with the DNO NMS.

Financial Assessment

The major additional cost associated with this type of FPL are the modifications required to the FPL control module. The new control systems will need to be tested rigorously prior to implementation on the live network as they will be able to directly control network circuit breakers. There would also be additional costs associated with the installation of two additional 33kV circuit breakers.

The Network Mesh FPL would only conceivably be applicable to the 33kV distribution network where multiple grid groups are connected in this manner. As such, the FPL developed as part of Network Equilibrium can be utilised for this new application. The costs associated with this type of application will therefore be in line with the post-trial cost of the 33kV FPL.

6.0 Conclusion

Network Equilibrium has successfully developed, trialled and tested a 33kV FPL for the first time on the GB distribution network. The device has been operational on the network since April 2018, during which time it has been providing real and reactive power support to the 33kV network between Taunton and Barnstaple BSPs. Analysis has shown that the FPL has released up to 20MW of additional network capacity that could be used to connect additional distributed generation in the trial area. The formal trial of the FPL has now concluded and the device is operating as part of BAU on WPD's network.

This report has captured the learning generated from the development, testing, trial and operation of the FPL on the 33kV distribution network. A critical review was then carried out for each of the learning items to describe how they are relevant for improving the development of future MVDC installations and/or replication of the FPL Method at other locations on the GB network. In addition, the review of the learning has identified a number of modifications that could be made to the FPL to improve its usability, performance and efficiency whilst still maintaining the safe operation of the device.

A literature review was carried out to determine the current state of the market for MVDC technology on an international scale. A range of technical papers and publically available reports were reviewed to identify applications of MVDC technology that are under development and/or currently installed and operating in the market. The review found that there has been limited change in the market since the beginning of Network Equilibrium. There are still very few practical applications of MVDC technology on utility owned distribution networks as the technology is still in its infancy. However, there is particular interest in using MVDC technology to form the basis of the power collection networks for large scale solar PV plants and off-shore wind farms.

Finally, the report has identified a number of alternative applications for the FPL technology on the GB distribution network. A thorough review of each of the alternative applications has been carried out to describe their likely benefits, barriers to their implementation, the technical considerations that may need to be addressed and financial assessment of the alternative applications relative to the 33kV FPL installed as part of this project.

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