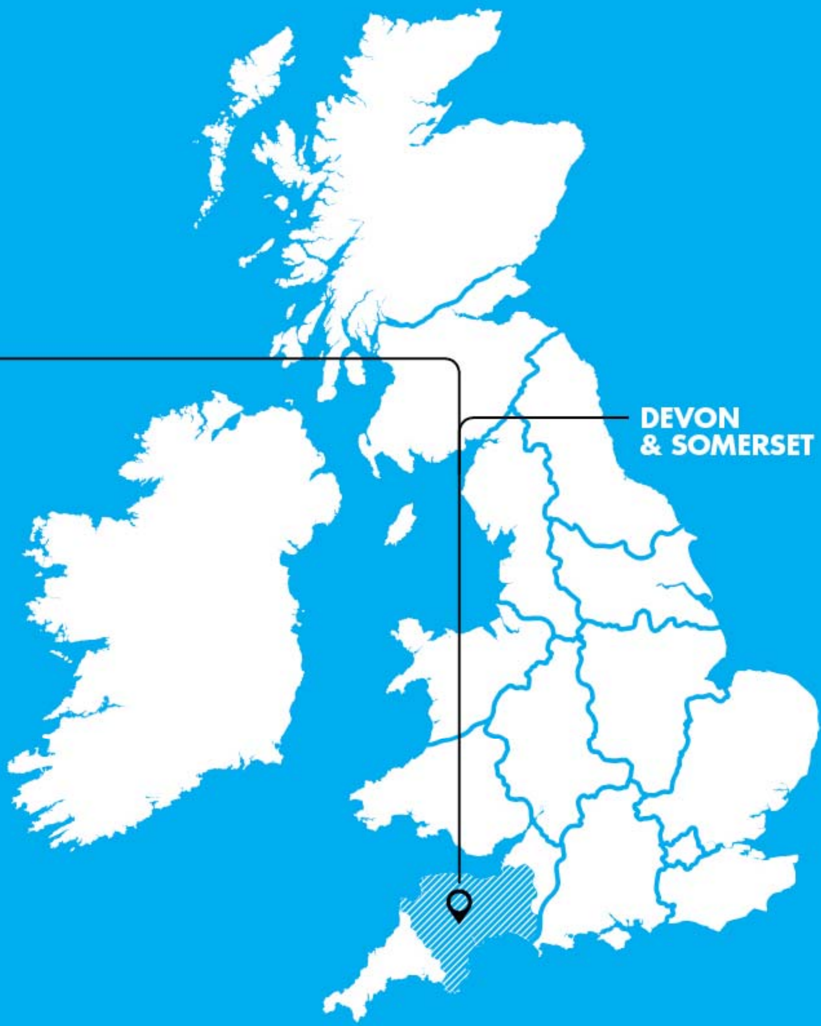
WESTERN POWER DISTRIBUTION

NETWORK EQUILIBRIUM

BALANCING GENERATION AND DEMAND



SDRC-6

Trialling and Demonstrating the FPL Method

LCN Fund
Low Carbon Networks

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Contents

Executive Summary

Network Equilibrium is a Tier-2 Low Carbon Networks Fund project which aims to demonstrate how novel voltage and power flow management can release network capacity. This release in capacity will allow the connection of new customers including distributed generation and Low Carbon Technologies (LCT), to the distribution network during both normal and abnormal conditions.

The Flexible Power Link (FPL) Method of Network Equilibrium aimed to provide a connection between two Bulk Supply Points (BSP) using a back-to-back AC-DC converter. This would enable the local control of voltage, through the use of reactive power on both networks while providing a means to transfer real power between the networks unlocking additional network capacity.

This report forms one of the eight deliverables as part of Network Equilibrium. SDRC-6 entitled, “Trialling and Demonstrating the FPL Method”, providing a detailed description of how the FPL method has been implemented within the project’s trial area and demonstrates the FPL’s performance and capacity released during the trials.

This report provides an overview of the two main components that together make up the FPL technology; the FPL Device and the FPL Control Module. A detailed overview of the design and site modifications that were required at the selected substation is also provided. Finally, the testing, installation and commissioning of the FPL technology are detailed.

Significant learning has been gained up to this point from the installation, commissioning and operation of both the device and Control Module. The device required significant modification to existing and the creation of new operational practices and standard equipment designs that have been robustly captured in policies and procedural documents; this will enable WPD and other Distribution Network Operators (DNO) to roll out the technology as appropriate. The integration of the Control Module with the network management system utilised skills and knowledge gained from the System Voltage Optimisation (SVO) Method, also part of Network Equilibrium, in the operation of ICCP links. Lessons were also learnt on how the system was to be tuned to maximise the operation and wider system benefit of the FPL device.

The FPL Technology was closely monitored to ensure the safe operation of the network and that the technology met the required availability and reliability. Utilising Power Systems Analysis (PSA) tools, developed as part of the project, the quantification of the capacity released on the network from the FPL Method was achieved. This indicated that an average of 20MW of additional generation capacity has been released.

Throughout the design, installation and trialling of the 33kV FPL a significant amount of learning was captured and consideration given to the implementation of a similar device on the 11kV. This has been captured and provides considerable information to enable further device implementation.

The performance of the system and the capacity released will continue to be analysed during the remainder of the trials and will be reported in SDRC-7, Trialling and demonstrating the integration of the Enhanced Voltage Assessment (EVA), SVO and FPL Methods.

1.0 Introduction

1.1 Overview

Network Equilibrium is a Low Carbon Networks Fund (LCNF) project which aims to demonstrate how novel voltage and power flow management can release network capacity. The project has three technical methods:

- The Enhanced Voltage Assessment (EVA) Method;
- The System Voltage Optimisation (SVO) Method; and
- The Flexible Power Link (FPL) Method.

The trial location for Network Equilibrium encompasses the 33kV and 11kV distribution networks in our South West area across the counties of Somerset and Devon.

This report focuses on the FPL Method and provides a detailed description of how it was implemented on the 33kV network within the project trial area and performance during initial trials. This forms the Ofgem deliverable for Successful Delivery Reward Criteria (SDRC) 6: "Trialling and Demonstrating the FPL Method"

1.2 Structure

The report has been structured as follows to provide an overview of the design, installation, testing and commissioning of the FPL:

- Overview of the selected FPL technology;
- Network Integration and design works;
- Installation and testing of the FPL technology;
- Evaluation of the performance and capacity released;
- Guide for the connection of future FPLs;
- Documentation produced during the trials; and
- Learning outcomes from the trial.

1.3 Background

Where possible it is advantageous to operate power networks in large groups whereby the load and generation can be equally distributed across that group. Distribution networks are typically operated in separate, smaller, network groups defined by connections to Grid Supply Points (GSPs) from National Grid (NG). The main reason for this is that paralleling or connecting network groups between different GSPs is likely to result in:

i. Abnormal power flows due to differences in network impedance between the two sources; and

ii. Higher fault levels due to the interconnection of sources from the GSPs.

Our network in the South West typically comprises multiple 132/33kV Bulk Supply Points (BSPs) fed from 400/275/132kV GSPs. The individual BSPs supply many 33/11kV primary substations through an interconnected 33kV network. A typical arrangement is shown in Figure 1-1.

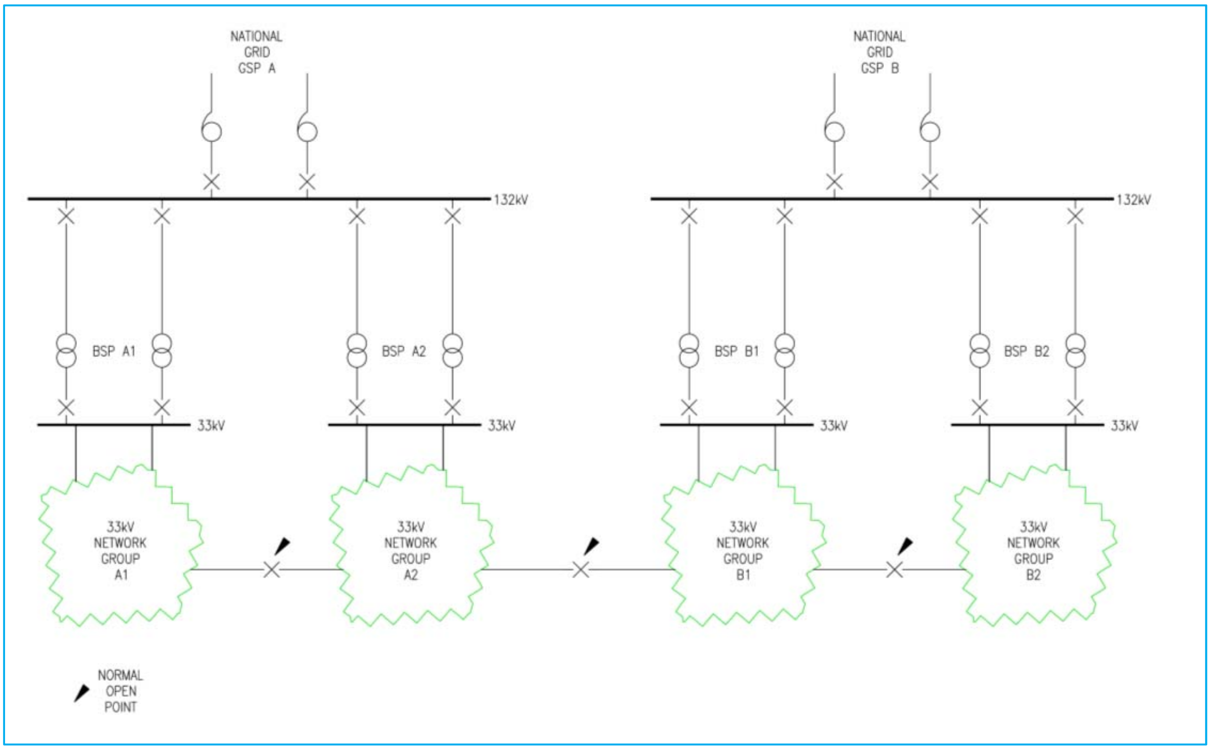

Figure 1-1: Typical Arrangement of a DNO Network

The 33kV networks are then often run as an interconnected system in rural areas as is the case in some elements of the South West distribution area. The interconnected network will generally be fed from a single BSP to ensure that power flow and voltage are not affected should a BSP transformer trip or another network fault occur.

In general, paralleling the 33kV network within the same network group (a single BSP) is achievable assuming power flow, voltage and fault levels are within thermal and voltage limits. However, connecting two separate network groups, at BSP level, in parallel through the 33kV network is not usually possible due to the issues explained.

The connection of Distributed Generation (DG) and Low Carbon Technologies (LCTs) has a direct effect on the voltage and power flows within a network group. The voltage for a whole network group is regulated by transformers via their built-in On-Load Tap Changer (OLTC) to maintain the voltage at any point in the network within statutory limits (±6% at 11kV and 33kV). The connection of DG generally causes voltage rise issues and the connection of load customers often causes the voltage to drop. The network is configured such that in a minimum generation, maximum demand scenario, the voltage will remain above the minimum statutory limit. This leaves a limited capacity for DG to connect before the existing transformers can no longer successfully regulate the voltage, for conditions such as minimum load and maximum generation.

Generation also causes changes to the flow power within the network group. As the levels of DG connecting to the network begin to exceed the demand at certain times of the day, reverse power flows occur, which is where power is exported through the 33kV network onto the 132kV system for the instance a generator is connected to the 33kV network. The rating of parts of the upstream network, such as transformers and overhead circuits are increasingly becoming a limiting factor to the connection of DG as the network.

Due to the varying types of demand and generation connected at increasingly disparate points of the network, substations and network groups can have significantly different demand and generation profiles. Often sections of the network with high demand could be physically, or geographically, close to sections with high generation but cannot be connected due to the engineering constraints described. The FPL Method aimed to provide a solution to facilitate the connection between these networks. This would efficiently and controllably transfer active power (P) between the two networks to ensure dynamic and balanced control of the power flows and also facilitate the provision of independent reactive power (Q) on each side of the FPL to provide voltage control to the connected network.

1.4 Principles of the FPL

The main component of the FPL is a power electronic device that utilises two back-to-back Alternating Current (AC) to Direct Current (DC) converters to control the power flows at a normally open point (NOP) between two network groups. The device allows the connection of the networks without many of the negative impacts that would occur if the network groups were operated in parallel without the FPL's inclusion, principally voltage and power stability issues and excessive fault levels.

Through the use of two back-to-back AC-DC converters the FPL is capable of 4-quadrant operation, which enables the FPL to operate with positive or negative P to transfer power from one network to the other whilst injecting or absorbing Q independently on either side. The transfer of P between the networks must be equal and opposite, for example if 5MW is pushed in to the FPL (acting as a load) then 5MW will be pulled out (acting as a generator). However, Q at one side of the FPL is not dependant on the Q requirements of the other and is only limited by the 4-quadrant capabilities of the complete FPL. The basic operation of the FPL is shown in Figure 1-2, where P is transferred from the generation dominated network in Network Group A1, therefore acting as an additional load, to the demand dominated network in Network Group A2. In this example the FPL is also supplying positive Q to both Grid Groups, helping to support the voltage on each group independently.

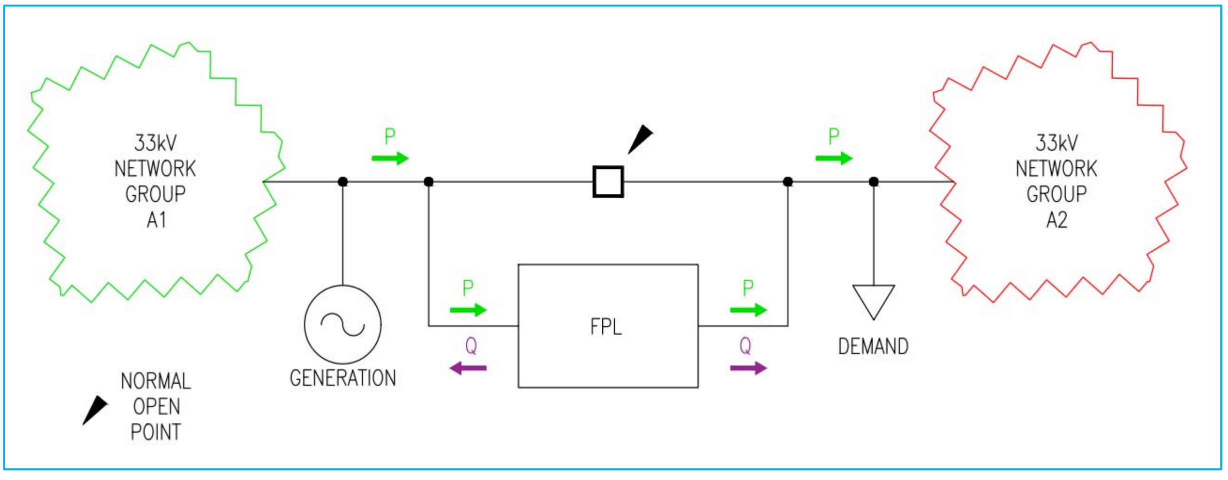

Figure 1-2: FPL Operation

1.5 FPL Trial Area Network

During the initial stages of Network Equilibrium, the network within the trial area was studied to identify the most suitable networks and connection points for the FPL. The conclusion of the studies resulted in Exebridge 33/11kV primary substation being selected as the most appropriate site for the installation of the FPL. This was due to the potential level of power transfer between Barnstaple and Taunton BSPs and the availability of space. A more detailed overview of the selection process is provided in SDRC-3.

Exebridge 33/11kV substation was normally fed from Taunton 132/33kV BSP with an alternative feeding arrangement from Barnstaple 132/33kV BSP via a NOP at South Molton. The installation of the FPL has enabled the connection of these two BSPs through the 33kV network at Exebridge by the closure of the NOP at South Molton. The generation and load profile differences between Barnstaple (generation dominated) and Taunton (demand dominated), maximises the balancing potential of the FPL at this location. A geographic view of the substation locations is shown in Figure 1-3 with Barnstaple BSP indicated on the left, Taunton BSP on the right and Exebridge primary in the centre. A high level indicative single line diagram of the network is also provided in Figure 1-4.

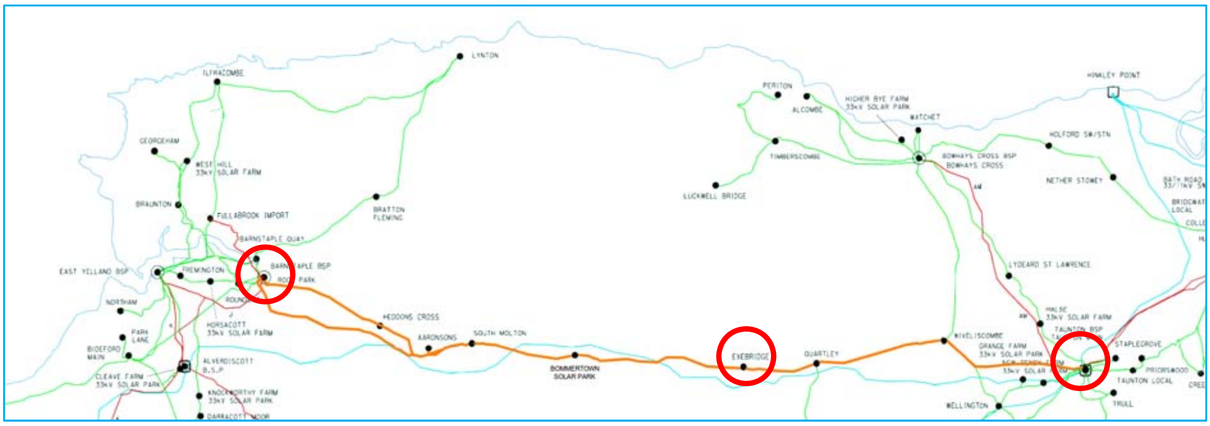

Figure 1-3: Locations of Taunton BSP, Barnstaple BSP and Exebridge Primary Substation

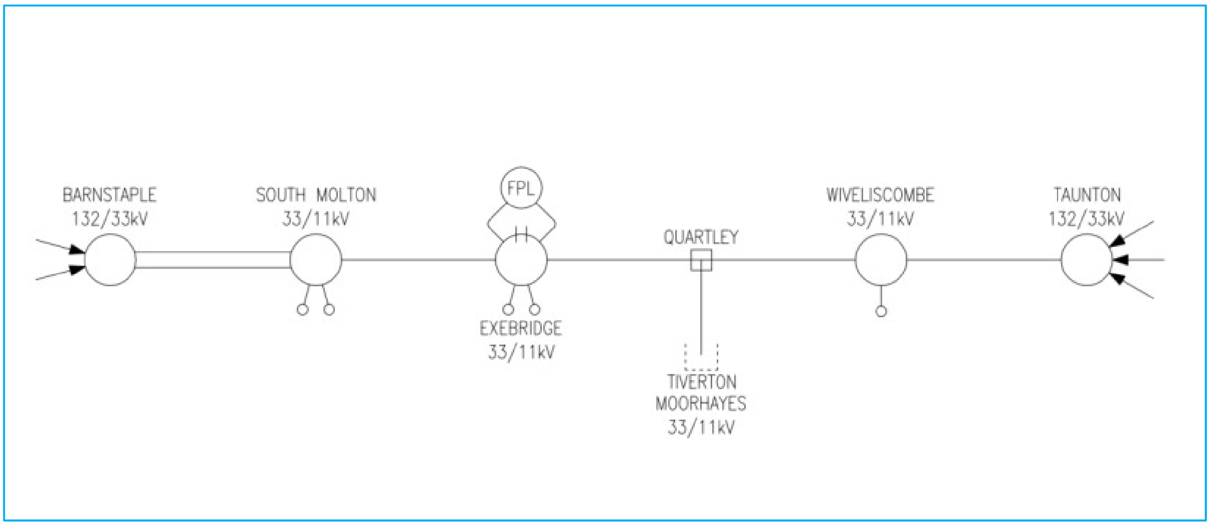

Figure 1-4: High Level Single Line Diagram of 33kV Network between Barnstaple and Taunton BSPs

2.0 FPL Technology

2.1 FPL Overview

The FPL is split into two main elements; the on-site back to back AC-DC converter device installed in the 33kV network along with additional ancillary equipment and a centralised control system that monitors the real-time operation of the network and determines suitable operating points, both P and Q, for the device.

For the FPL device, a functional specification (included within SDRC-3) was developed based on the capability and future needs of the existing network. Following the production of this and the selection of the installation location an open and competitive tender process was carried out. Subsequently, ABB was selected as the device supplier with a technology derived from their PCS6000[1] converter.

For the control system, a centralised system linked to the existing Network Management System (NMS) was specified. Following a competitive tender process, Nortech Ltd was selected to supply the FPL Control Module (FPL CM). An overview of the whole system architecture is provided in Figure 2-1.

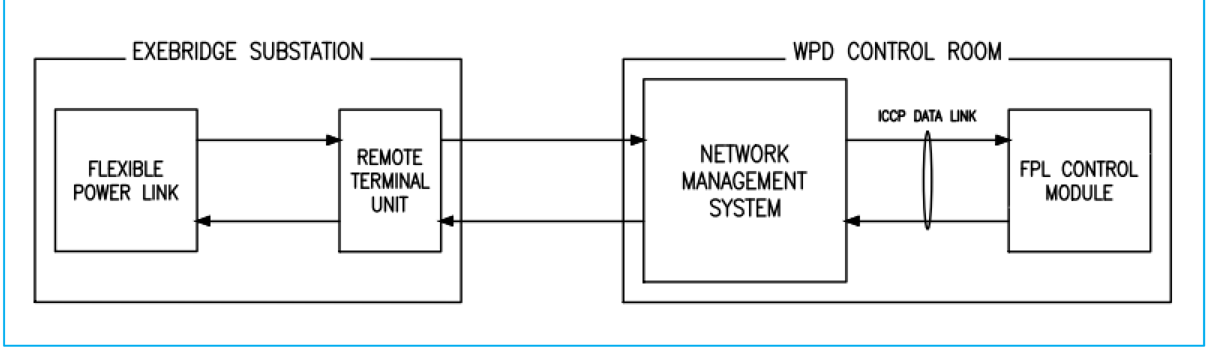

Figure 2-1: Overview of FPL System Architecture

2.2 FPL Device

2.2.1 Specification

The device was required, as per the functional specification at the time of tender, to have an active power capability of ±20MW and a reactive power capability of ±5MVAr. This requirement is shown in Figure 2-2. However, following the tender process and due to the standard design approach by ABB the actual operating capabilities of the FPL are greater than that originally specified; these can be seen in Figure 2-3, where the original operating window is overlaid for reference.

[1] https://new.abb.com/facts/statcom/pcs-6000

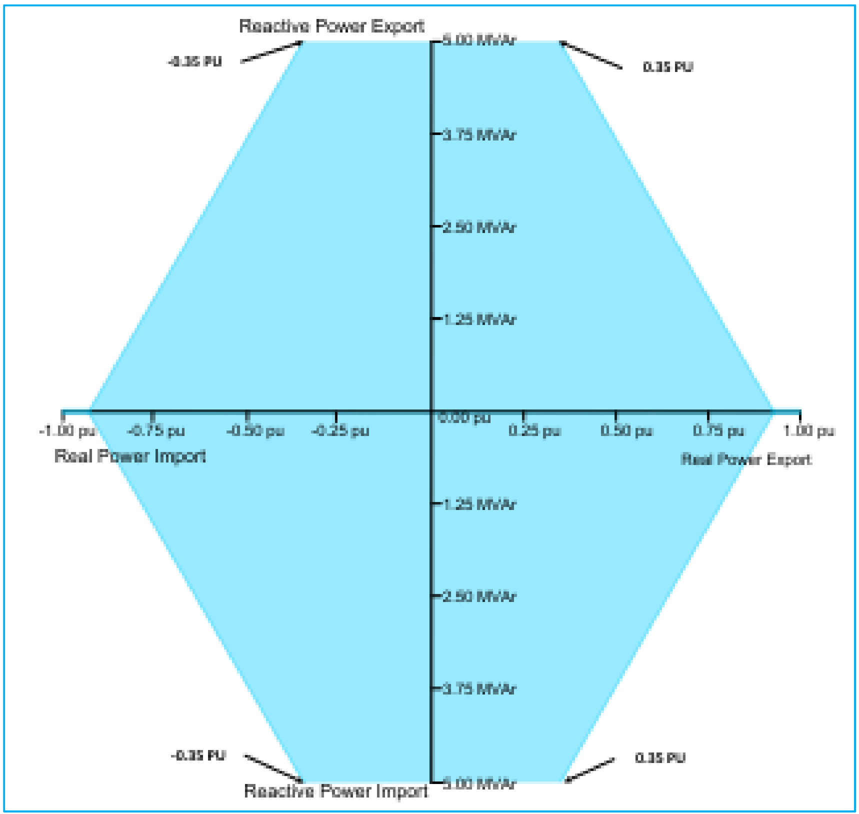

Figure 2-2: FPL Functional Specification Operating Window

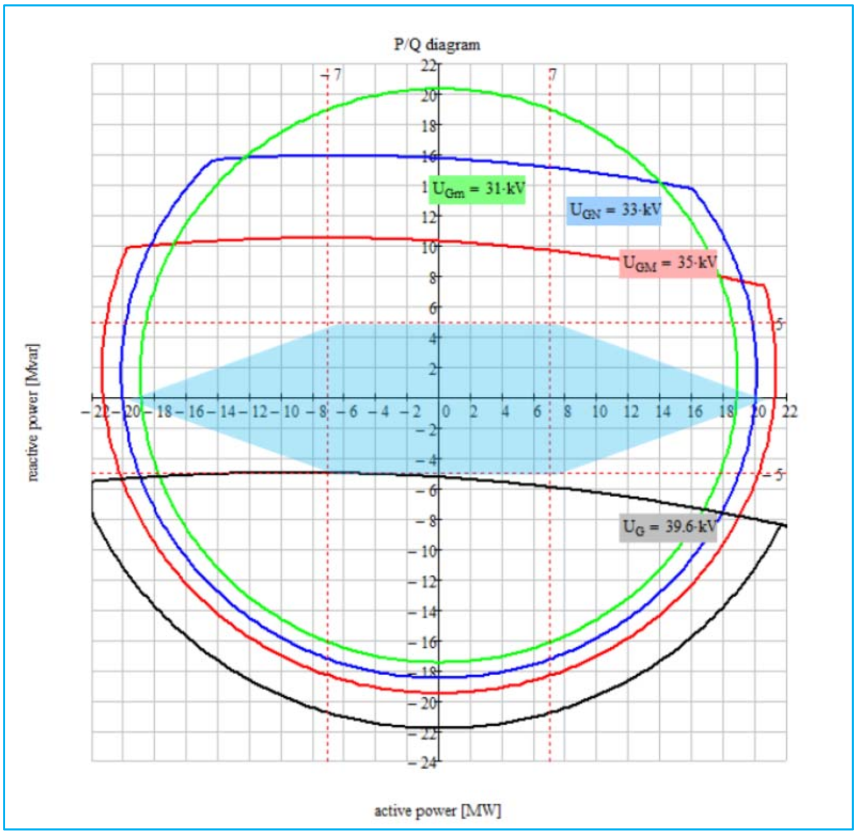

Figure 2-3: ABB FPL Device Operating Window

The overall device was specified with insulation and short circuit withstand requirements as per Energy Networks Association (ENA) Technical Specification (TS) 41-36 and 35-2, which relate to 33kV switchgear and transformers. This ensured the overall device was compliant with the basic requirements for equipment connected at 33kV within the UK. The insulation requirements of the DC element of the device were specified as per IEC60146-1-1, an internationally recognised converter specification, as no existing ENA TS was applicable.

The emissions and power quality of the device were specified to ensure compliance with current UK standards. The maximum sound power level of the device was set at 80dBA for each component and any electromagnetic fields generated at a maximum level of 500µT at 1.5m from each component; this is in line with existing technologies installed on the distribution network, such as transformers. It was also critical that the device complied with the standard harmonic and voltage quality standards, Engineering Recommendation (ER) G5/4 and ER P28 respectively. As well as ensuring that the FPL was suitable for inclusion on the network it was also important to ensure that there was headroom for additional equipment to connect to the network that would contribute harmonic and voltage issues on the system. This is detailed further in the FPL Testing section, 4.0.

2.2.2 Components

The ABB FPL consists of four main components as shown in Figure 2-4:

1. Converter Container;
2. Two 33/3.25/3.25kV Transformers;
3. Two sets of Harmonic filters; and
4. Heat Exchanger.

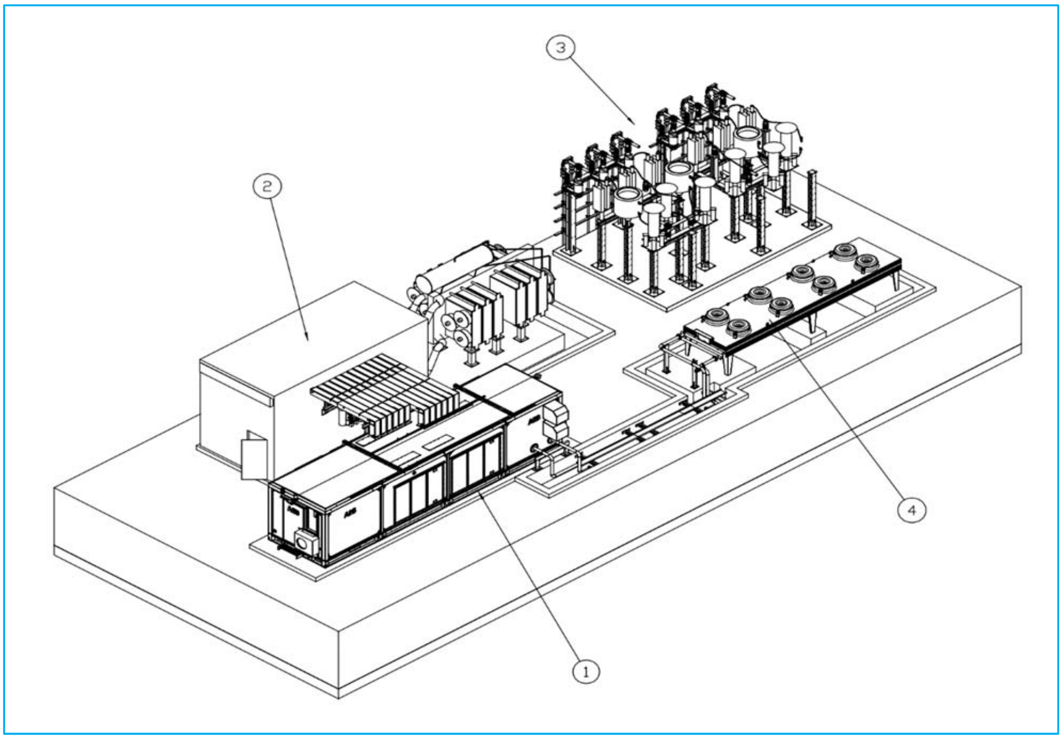

Figure 2-4: Layout of FPL components

Figure 2-5 shows the electrical single line diagram for the FPL device. The incoming 33kV AC supply from Barnstaple BSP is stepped down by the first transformer to 3.25kV AC for use by the first AC-DC converter to create a 2.5kV DC supply. The second converter then changes the DC supply back to AC, with the second transformer stepping the voltage back up to 33kV connected to Taunton BSP. The operation of the converters generates a large amount of heat, especially when the FPL is at its maximum power capability. An active cooling system and heat exchanger is used to cool the converter to maintain a suitable operating temperature.

The operation of power electronic devices on the distribution network, like that of the FPL, caused by their fast frequency switching, produce system harmonics affecting the power quality of the network. To suppress harmonics to within permitted levels (as defined in G5/4) harmonic mitigation was required. This harmonic mitigation was provided in two forms; 33kV harmonic filters were installed at FPL connection points to the 33kV system and the transformers were designed to have two LV (3.25kV AC) windings to enable a phase shift of 30° to be applied, which supports the mitigation of lower order harmonics.

Critical to the operation of the FPL is internal control and protection functionality, which is provided by dedicated control software and a Supervisory Control And Data Acquisition (SCADA) system contained within the converter container. This manages the operation of the device to meet the desired operating points, controls the connection of the device to the network, protection and alarm interface.

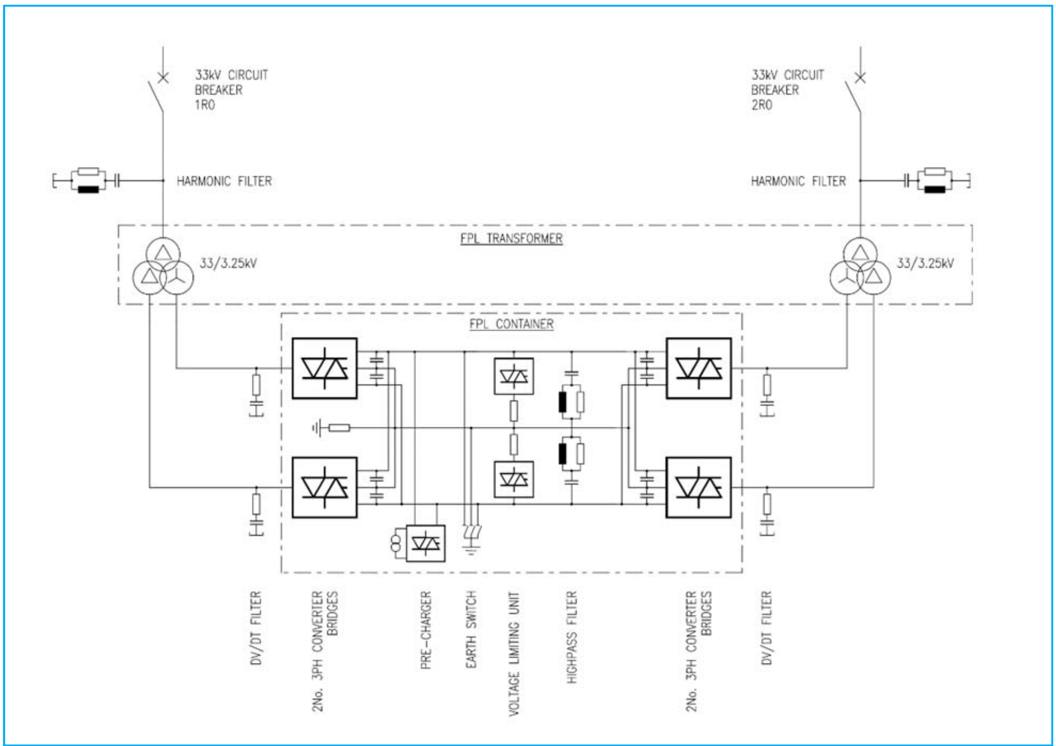

Figure 2-5: FPL Electrical Single Line Diagram

Converter Container

The converter container includes the back to back AC-DC converters, the device's internal control and protection system, human machine interface (HMI) and cooling pumps. The container is split into separate rooms to physically isolate the control systems from the operating converter and the cooling system. Figure 2-6 shows a detailed view inside the container with the partition walls removed for clarity.

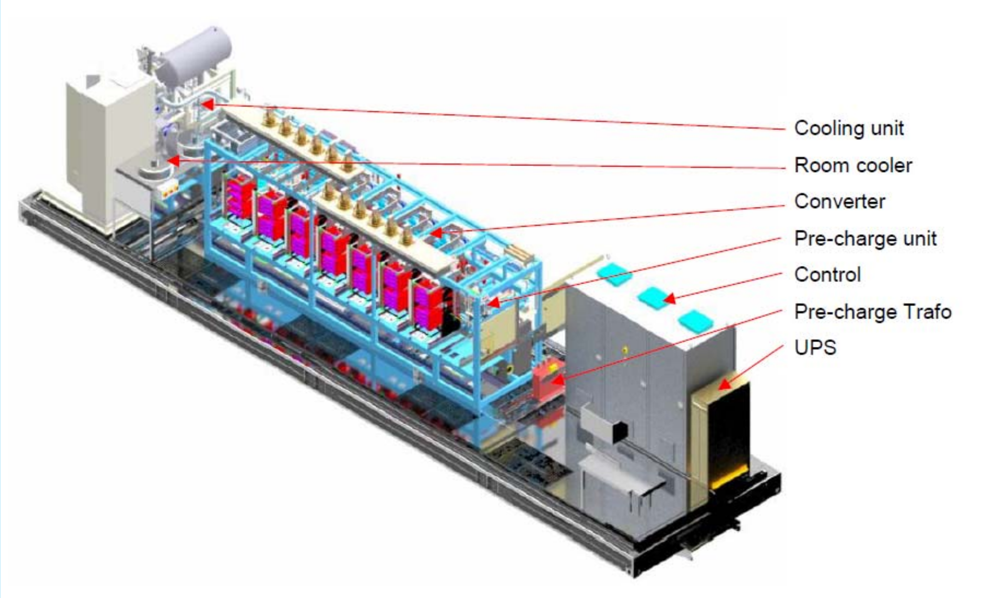

Figure 2-6: Internal view of FPL container

The critical element of the converter container are theconverters, which are an arrangement of Integrated Gate-Commutated Thyristors (IGCT) using three-level phase modules to produce AC voltage from a DC source. An overview of this process is provided in Figure 2-7.

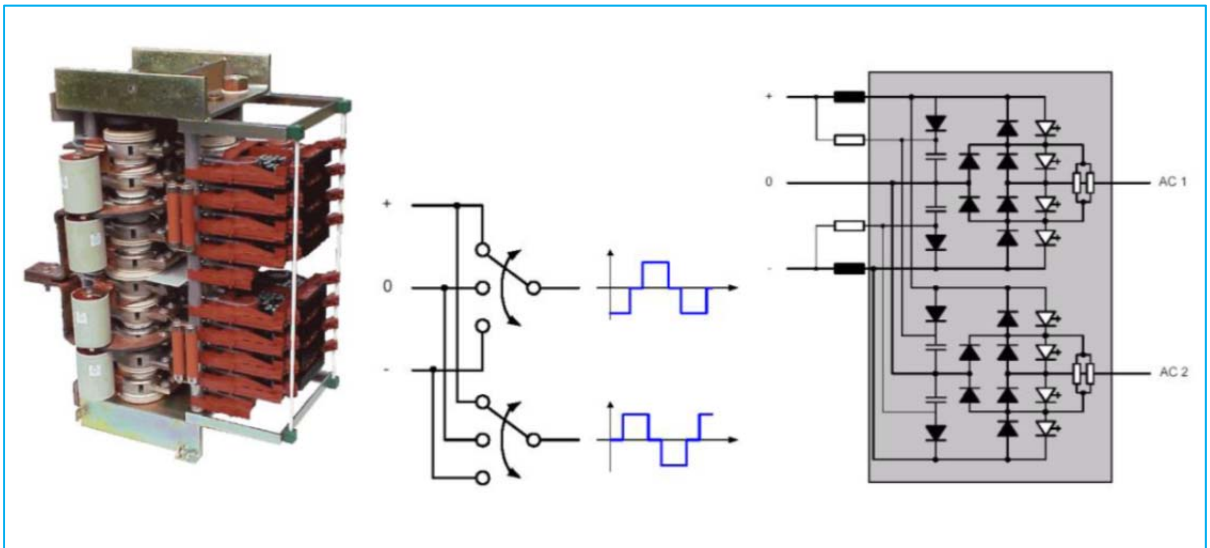

Figure 2-7: Power Electronic AC-DC Conversion

Figure 2-8 to Figure 2-10 show some of the internal features of the converter container.

Figure 2-8: Power Electronic Converters

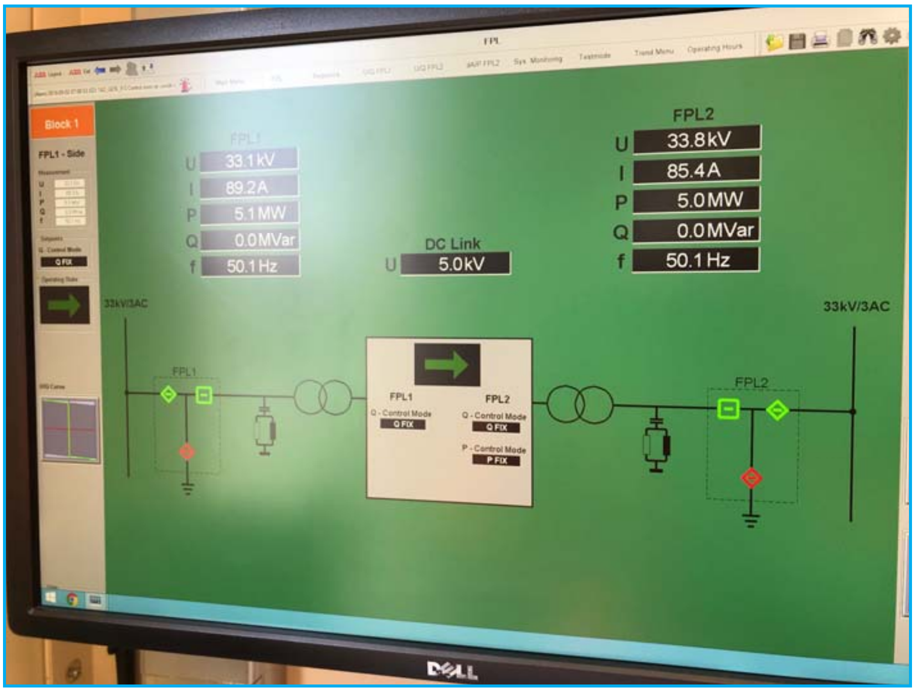

Figure 2-9: FPL HMI

Figure 2-10: FPL Protection and Control

Two key design features of the converter container centre are the earthing requirements and the start-up procedure. To ensure safe operation and access an interlocked DC earthing arrangement, for the converters, was implemented by means of access being restricted to the main converter section of the container, where the door was electrically and mechanically interlocked ensuring safety for access. The start-up procedure was enhanced through the implementation of a pre-charging DC unit, this allowed both the DC system and the transformers to be pre-charged prior to being connected to the 33kV network; this is particularly important on a rural 33kV network to avoid large-scale magnetising currents (often eight to ten times greater than normal load current) that could erroneously operate network protection systems.

Transformer

The FPL requires a transformer on each side for conversion from 33kV down to 3.25kV for use by the AC-DC converters. Both transformers are rated at 14.1/20.2 MVA and are double wound on the LV side. ABB sourced the FPL transformer from Končar DS&T in Croatia who were experienced with providing specialist transformers for this type of application.

To help suppress lower order harmonics generated by the converter, a phase shift of 30° was created between the two LV windings giving a vector group of Dy11d0 for each transformer. The transformer winding configuration is shown in Figure 2-11 below.

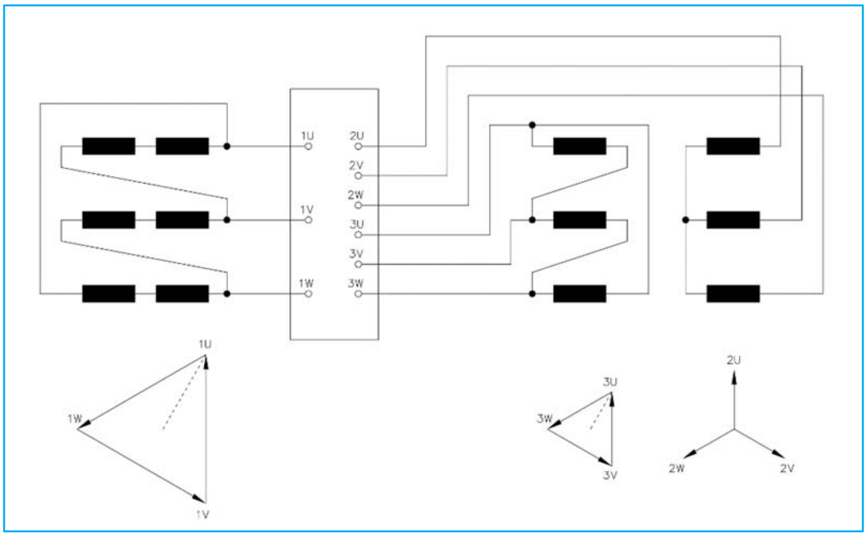

Figure 2-11: FPL winding configuration for Transformer 1

To reduce the size and cost of the transformer solution, ensuring the device would fit within the existing substation it was decided with ABB to place both transformers within a single tank. Separate transformers require individual cooling systems and physical separation for operational and access reasons. A single tank solution meant that the overall installation size for two transformers was significantly reduced and a single radiator bank could be used. The risk of installing two transformers within a single tank was investigated, as typically the need for transformers to be physically separate is for security of supply, whereby if one fails the other can still operate; however, as both transformers are required for the operation of the FPL, for a single transformer failure the FPL system would need to be disconnected. Therefore, the risk was seen as minimal and the space saving and cost advantages were significant.

Due to the high harmonics created by the converters, the pitch and noise generated by the transformer in normal operation would be well above specified and acceptable limits. Therefore, we determined that a noise enclosure around the entire transformer would be appropriate. This was provided through ABB by dBA.

Figure 2-12 shows the front and side elevations of the FPL transformer and Figure 2-13 shows the transformer during testing at Končar's facility.

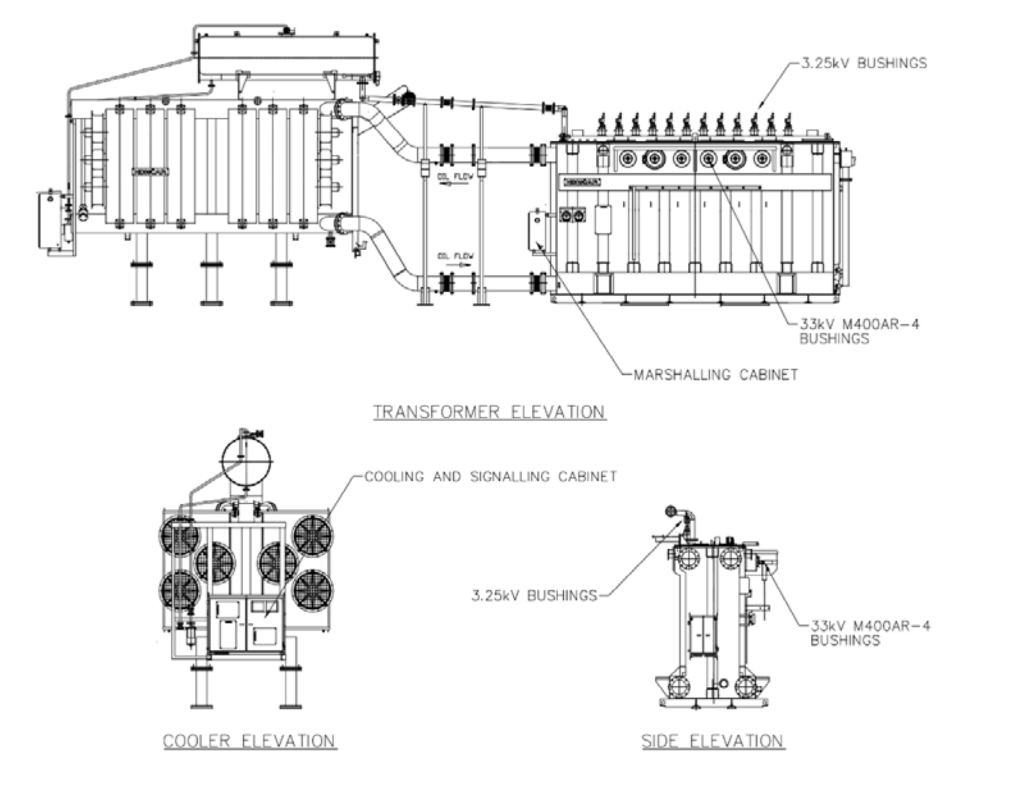

Figure 2-12: FPL transformer elevations

Figure 2-13: FPL Transformer during testing

Heat Exchanger

The converter cooling system is designed to maintain the temperature of the converters below 52°C using de-ionised water as a coolant. In low power conditions, i.e. where the device doesn't generate significant heat, the coolant is circulated within the container cooling system. Only under higher power conditions is the external heat exchanger utilised through the automatic opening of by-pass values within the system. An overview of the cooling system is provided in Figure 2-14.

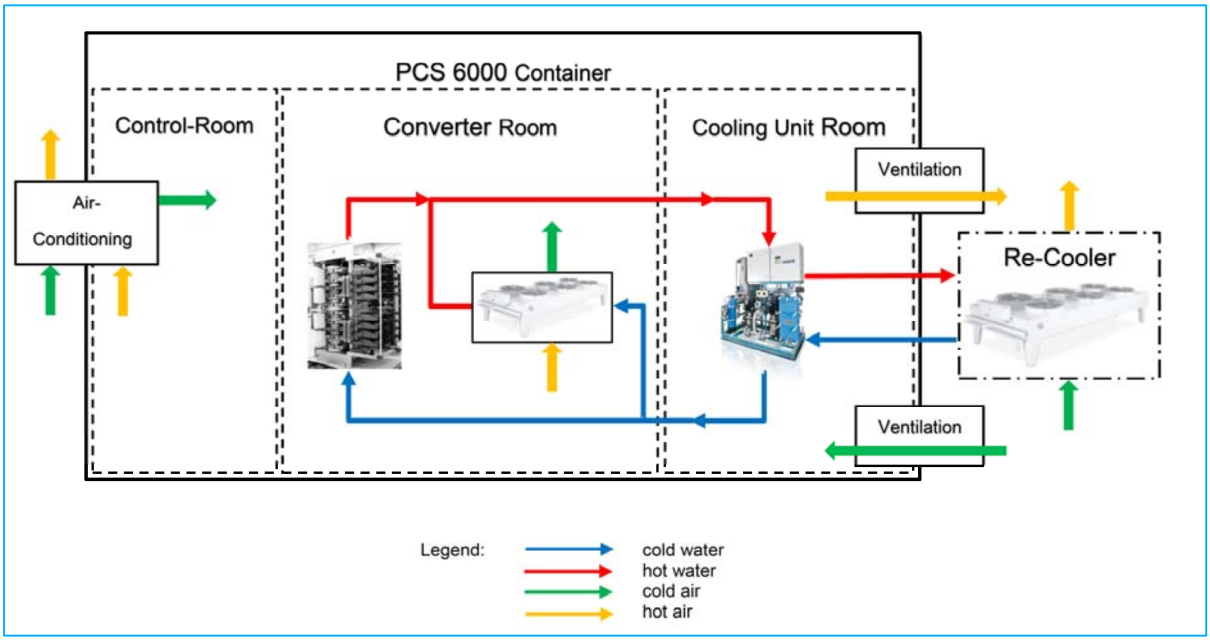

Figure 2-14: FPL Cooling System Overview

An outline of the heat exchanger is shown in Figure 2-15 and it on site in Figure 2-16.

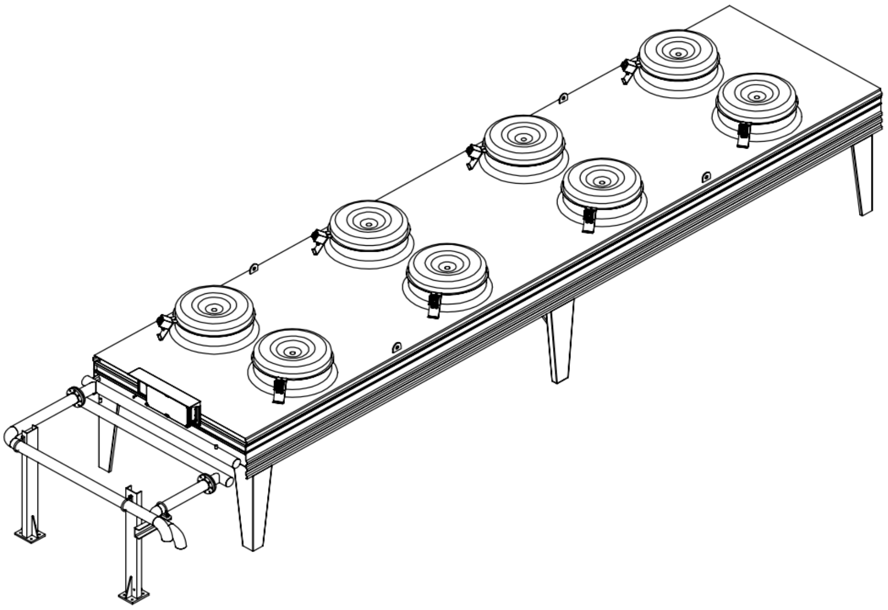

Figure 2-15: FPL Heat Exchanger

Figure 2-16: FPL Heat Exchanger On-Site

Harmonic Filters

Two high-pass (HP) filters are required on either side of the FPL to control and suppress higher order harmonics generated by the converter during operation. Background harmonic measurement data was collected at Exebridge substation and provided to ABB to design a suitable filter. Detailed studies were then carried out by ABB to demonstrate that the FPL, with filters installed, complied with ER G5/4-1 – Planning Levels for Harmonic Voltage Distortion. The design required a standard Resistor, Inductive and Capacitive (RLC) harmonic filtering system. Figure 2-17 and Figure 2-18 show the layout of the two filters comprising reactors, resistors and capacitors.

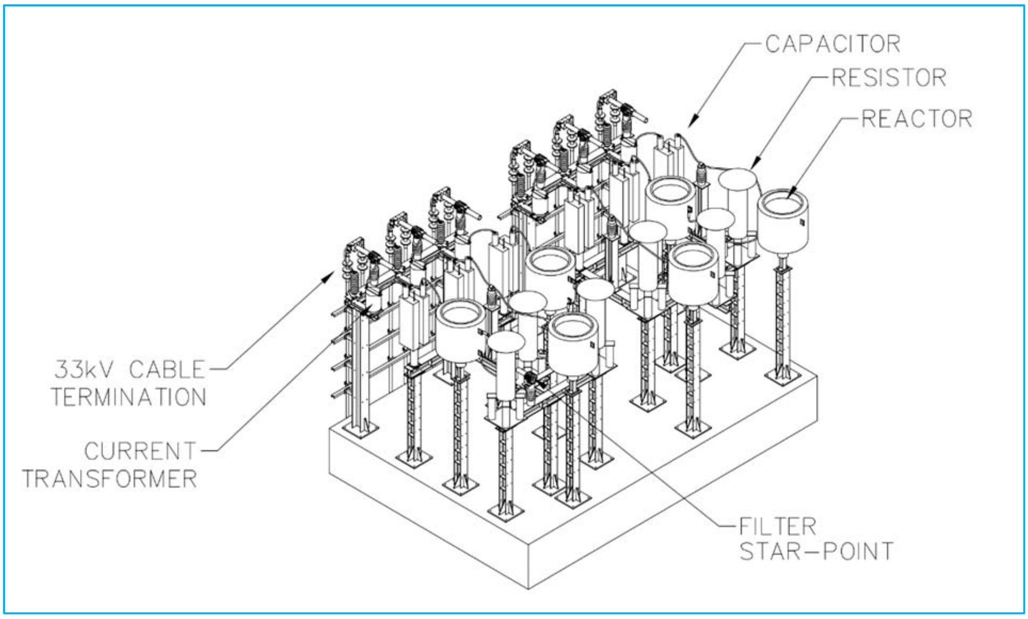

Figure 2-17: FPL harmonic filters

Figure 2-18: FPL Harmonic Filter On-Site

Each filter is teed on to the 33kV circuit between the 33kV switchgear and FPL transformer on each side of the FPL. To provide the tee connection there are two 33kV terminations on each filter; one for the incoming circuit from the 33kV circuit breaker (CB) and the other for the circuit to the FPL transformer.

2.2.3 Software Control System

The FPL converter is controlled by a dedicated software and internal SCADA system. The internal SCADA system is used to manage and monitor the various components within the converter container and provide information through the HMI for diagnostics and local control.

The software is based upon an ABB standard design with modifications carried out to meet the exact requirements for the FPL operation. The basic function of the software is to control the operation of the FPL, determining how the converters should operate to meet the required P and Q set points. The software is also used for the device protection, automatic sequencing of start-up and shut down procedures and auxiliary systems control.

Protection

Typical AC main protection schemes such as unit protection installed across devices do not work with the FPL due to the conversion to DC. Therefore, the main device protection is carried out by the FPL with trip signals sent back to the 33kV CBs to isolate the device. The device protection scheme is complex but can be summarised into four key areas:

- AC protection on both sides – Over and under voltage, Overcurrent and Earth Fault, and frequency protection with multiple measurement points on all components;
- DC Protection – Overvoltage and overcurrent protection;
- Transformer Oil and winding temperature monitoring; and
- Converter air and cooling system temperature monitoring.

The protection scheme within the software is designed such that the device is able to operate the FPL at its maximum capability. Sudden trips of the 33kV CBs causes stress to the FPL converter potentially impacting its operational life and maintenance requirements. The software is designed to modify the converter operation before CBs are tripped to minimise the impacts.

Alarms and Trips

The full overview of all alarms and trip events is available within the FPL SCADA HMI. The list is extensive, therefore to provide a simplified overview onsite and within the NMS, similar indications were combined to just ten alarms and ten trips. Alarms are the first indication that there is an issue with the FPL operation, with the alarm escalating to a trip once critical. The following items are provided as both alarm and trip events:

- FPL Protection Operation;
- FPL Control Fail;
- FPL Temperature;
- FPL Cooling System Fail;
- FPL Auxiliary System Fail;
- Transformer Buchholtz; and
- Transformer Winding Temperate and Oil Temperature.

The following items are provided as alarms only and serve as an indication of issues requiring attention but won't lead to a direct trip of the device if not resolved:

- Transformer Breather Fail;
- Transformer Cooling Fail; and
- Transformer Oil Level.

The following items are provided as trips only with no prior alarms issued to indicate the potential for a trip event. These items are considered critical to the safe operation of the device:

- Transformer Pressure relief fail;
- Fire Detection System Fail; and
- Transformer Protection Operation.

2.3 FPL Control Module

The FPL CM is a centralised control system that monitors and studies, using a Power Systems Analysis (PSA) tool, the Barnstaple and Taunton BSP networks. This is carried out in real-time, with the FPL CM determining P and Q set points for the FPL to solve violations in the network operation. Violations are defined as the voltage or power flow at any point in the network exceeding pre-defined limits or constraints.

The FPL CM is designed to operate on dual servers to provide operational redundancy and is connected to the NMS using the Inter-Control Centre Communications Protocol (ICCP) as defined in IEC 60870-6. The ICCP data link provides a means of sharing data and control actions between two control systems while maintaining their independent operation.

Using real time data, state estimation studies are carried out by the FPL CM with any network violations then ranked by type and severity. Several operating modes are available to define the prioritisation of solving the violations which affects the final set points sent to the FPL.

2.3.1 System Architecture

The FPL CM software runs in the Nortech iHost environment. iHost is Nortech's established centralised data management platform for the receiving, storing and sharing of data. Bespoke operational software, such as the FPL CM, can then be installed within the platform to utilise the data. The platform and FPL CM is installed on dual redundant primary and standby servers connected to the existing WPD IT network.

A further two servers were also used for the development and testing of updates and configuration changes prior to implementing the FPL on the live system. Only the primary and standby servers are connected via the ICCP data link to the NMS. An overview of the system architecture can be seen in Figure 2-19 below.

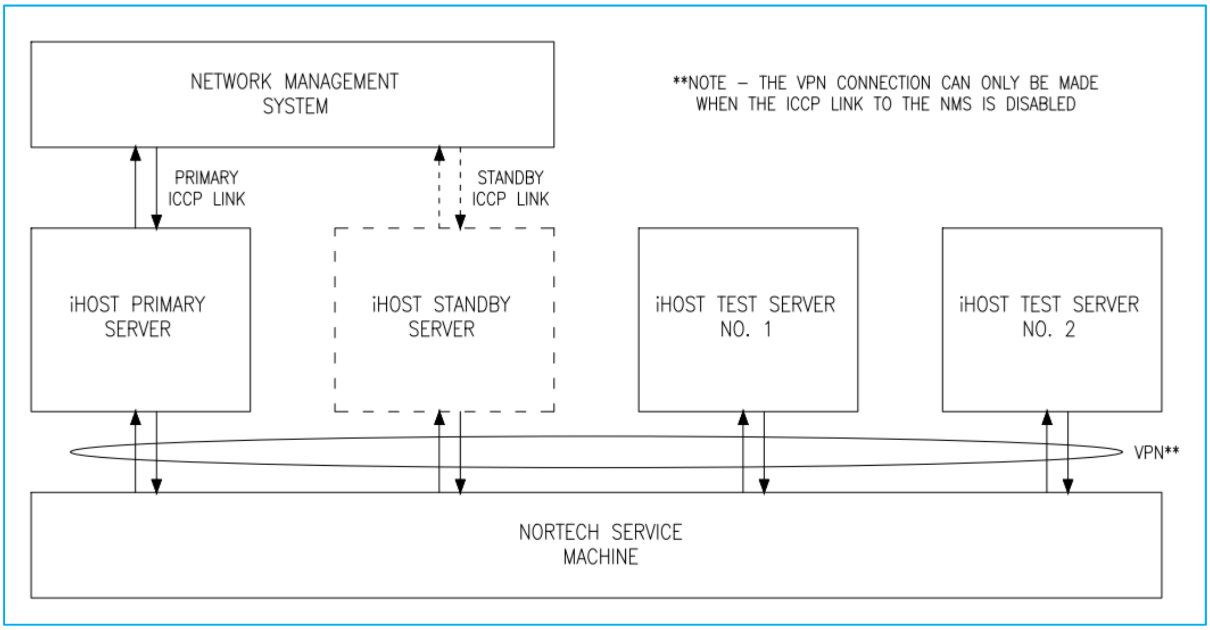

Figure 2-19: FPL Control Module Architecture Overview

Primary and Standby Servers

The primary and standby servers are designed to be exact copies of each other, allowing the standby to become the primary server in case of failure. The system is built around a central database that contains the latest real-time data, historical time series data, system configuration data and the network model. A task manager application is used to oversee the whole system including the FPL CM software operation. The FPL CM utilises the PSA tool IPSA[2] for the completion of real time network state estimation studies.

Other applications within the server are a Communication Server Module (CSM) for the interface with the ICCP data link and a web interface for authenticated users within the corporate network to view real time status, diagnostics and configuration data. Windows Server Desktop is also provided to allow remote access from within the corporate IT network for administration access to the server. This provides the ability to change system configuration settings, operating modes, manage access accounts and update network models. An overview of the internal server configuration is shown in Figure 2-20 below.

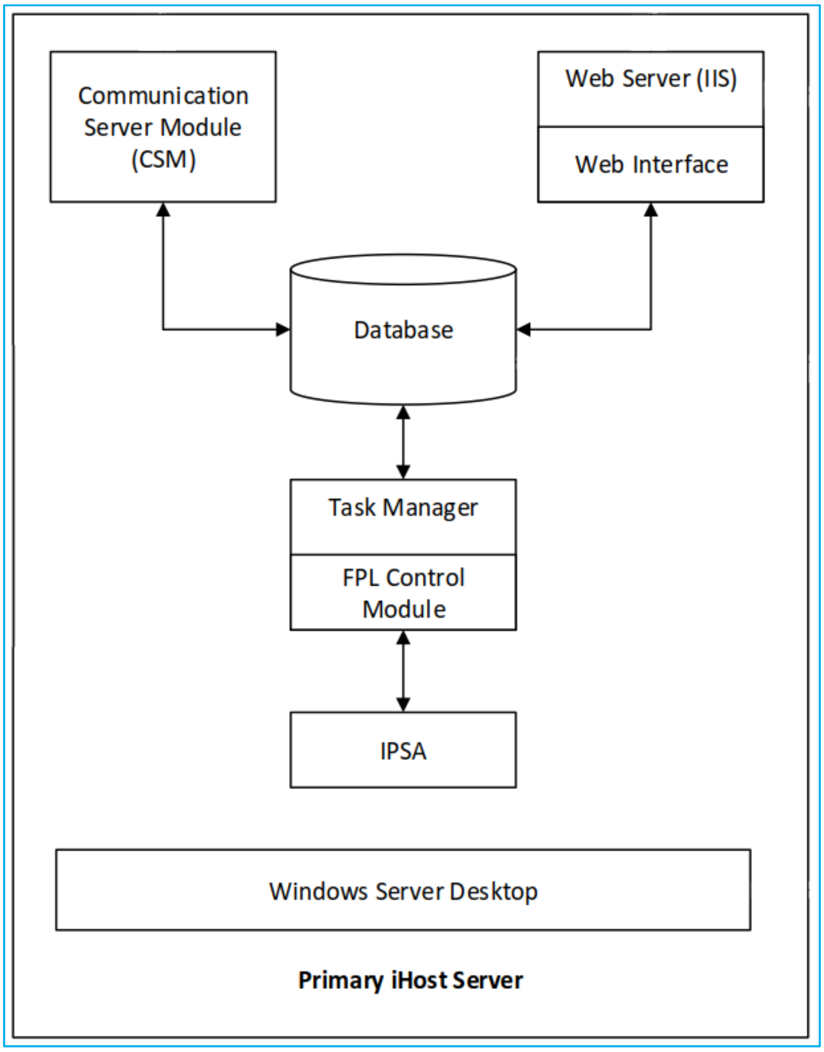

Figure 2-20: Primary iHost Server Configuration

[2] https://www.tneigroup.com/ipsa-software

Virtual Private Network

A Virtual Private Network (VPN) connection has been provided to allow Nortech access to the system, from outside the WPD IT network, to provide support if required. This allows a dedicated machine to remote desktop into any server as required. To ensure the security of operational systems, firewall policies and procedures are in place to only allow VPN connections to the primary and standby servers once the ICCP data link to the NMS has been disabled.

2.3.2 Bilateral Table

A key component of the ICCP data link is the bilateral table. The bilateral table is used to define all data that is passed between the two control systems, with copies of the table held in both systems. Defined network measurement and equipment status information is automatically added to the table by the NMS and sent across the ICCP link to populate the table within the CSM. Set points calculated by the FPL CM are then added to the table within the CSM and sent across the ICCP link for the NMS to transmit to the FPL.

The bilateral table also contains data items for the passing of control information from the NMS to the FPL CM. The FPL CM status and alarm states are passed back to the NMS for display and action, if required, by Control Engineers from within the NMS.

2.3.3 Network Model

The FPL CM utilises the IPSA load flow engine for validation of calculated set points, with a suitable model built for the network. The FPL is designed to influence conditions on a specific section of the network, mainly the 33kV feeders from the FPL back to each BSP and the 132/33kV BSP transformers. To ensure that the models could be set up correctly and provide the required calculation accuracy, the 132kV network from each BSP back to the GSP was modelled. An overview of the 132kV networks supplying both BSPs is provided in Figure 2-21.

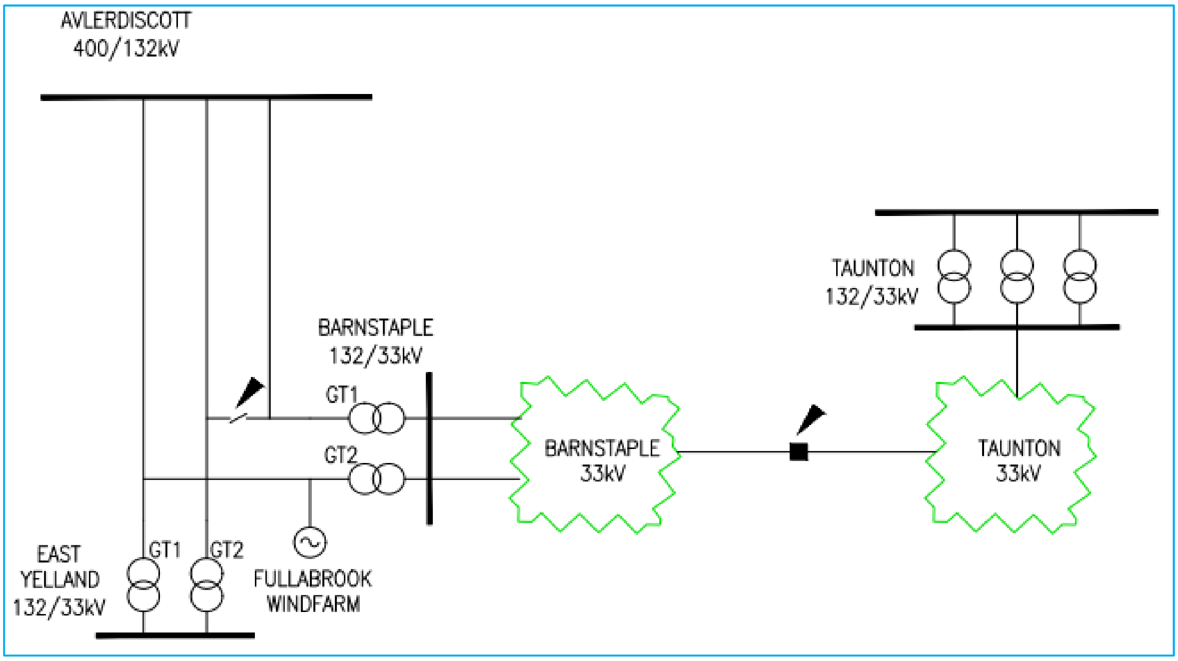

Figure 2-21: FPL CM Modelled Network

The 33kV networks from the BSP to the FPL were modelled along with all 11kV primary substations and 33kV connected generation. An overview of the 33kV network model is provided in Figure 2-22. The primary substations modelled on the Taunton network are Exebridge, Wiveliscombe and Wellington. South Molton and Heddon Cross primary substations are connected to the Barnstaple Network. There are also three generation customers connected on the network at 33kV as well as a demand customer, Arronsons.

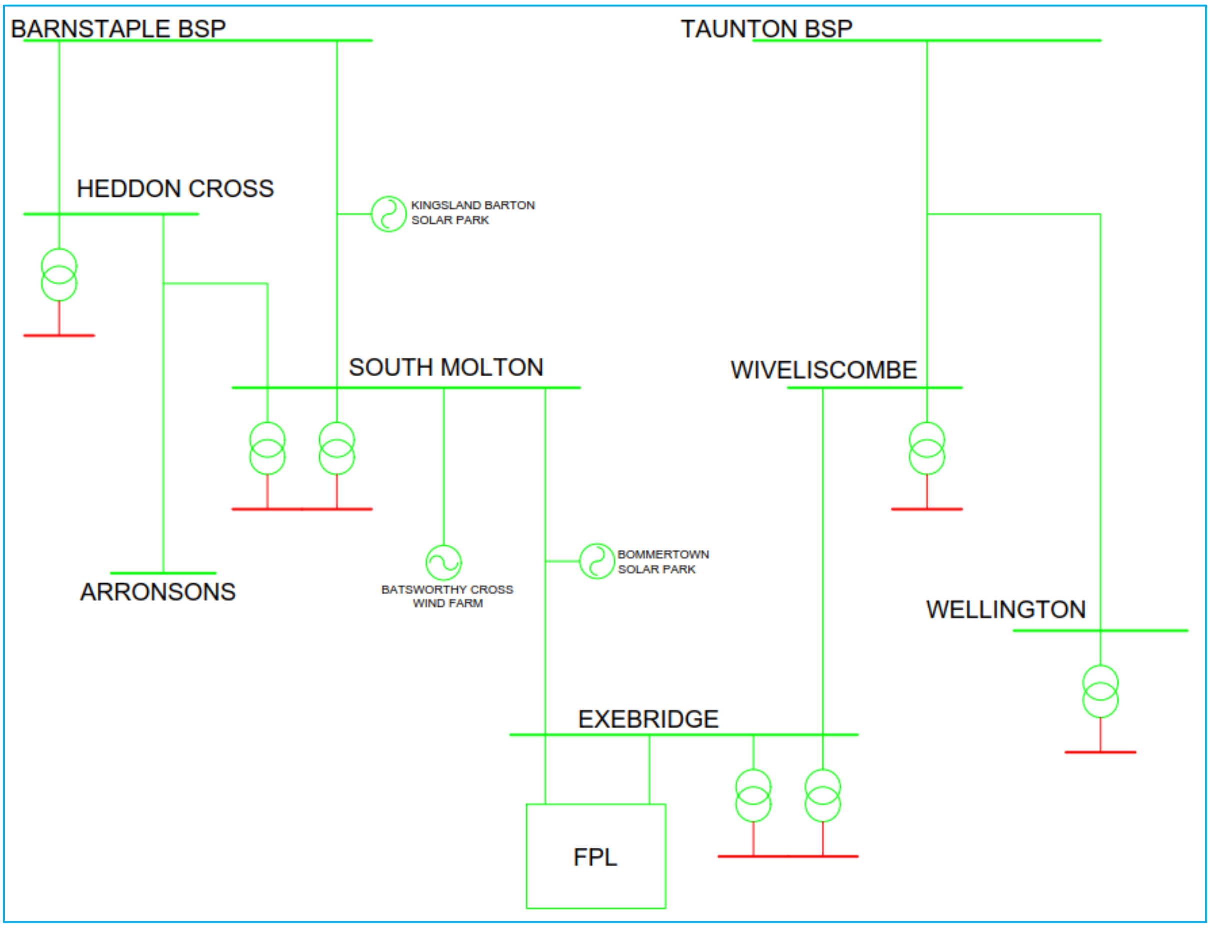

Figure 2-22: Overview of 33kV Network Modelled within the FPL CM

The model included the position of all switches and data measurement points so that the real-time data could be applied to the model and calculated values verified against measured.

2.3.4 Updating Methodology

To maintain the accuracy and safe operation of the FPL, it is critical that the FPL CM model and bilateral table is maintained in line with the actual network and NMS. An updating procedure has been defined to capture all planned and completed changes to the networks to enable the updates to be applied accordingly. A database was created for the capture of all network changes with the modelled area with the population of data carried out by staff maintaining the NMS. The updates are then completed on the network models before uploading to the FPL CM. An overview of the process is provided in Figure 2-23.

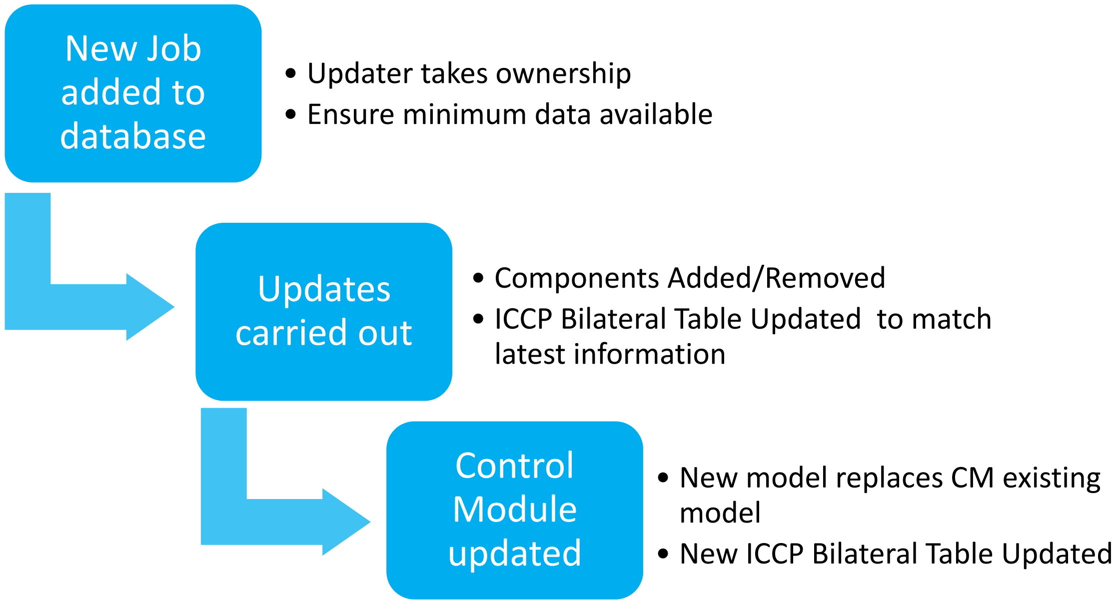

Figure 2-23: Overview of FPL CM Model Update Procedure

2.3.5 Algorithm

The FPL CM algorithm is designed to operate on receipt of updated network measurement or status information. An overview of the algorithm logic is provided in Figure 2-24.

The first stage of the algorithm is to ensure that the FPL is fully operational and the network is in the normal operating condition. The real-time network measurement data is then validated and checks carried out to ensure that a minimum dataset is available for the completion of the state estimation studies. This includes:

- Critical CBs in the correct state;
- Voltage measurements available at both GSPs;
- Power Flow measurements available for all generation; and
- Transformer tap positions available for all transformers.

Once the data is mapped to the network, an initial state estimation study is completed with estimated values validated against measured. If significant variances are found, the FPL CM errors as described by item 4 in Table 2-1. If the data variance is not solved by receiving new data the error will escalate, as described in section 2.3.7, with the FPL being removed from service.

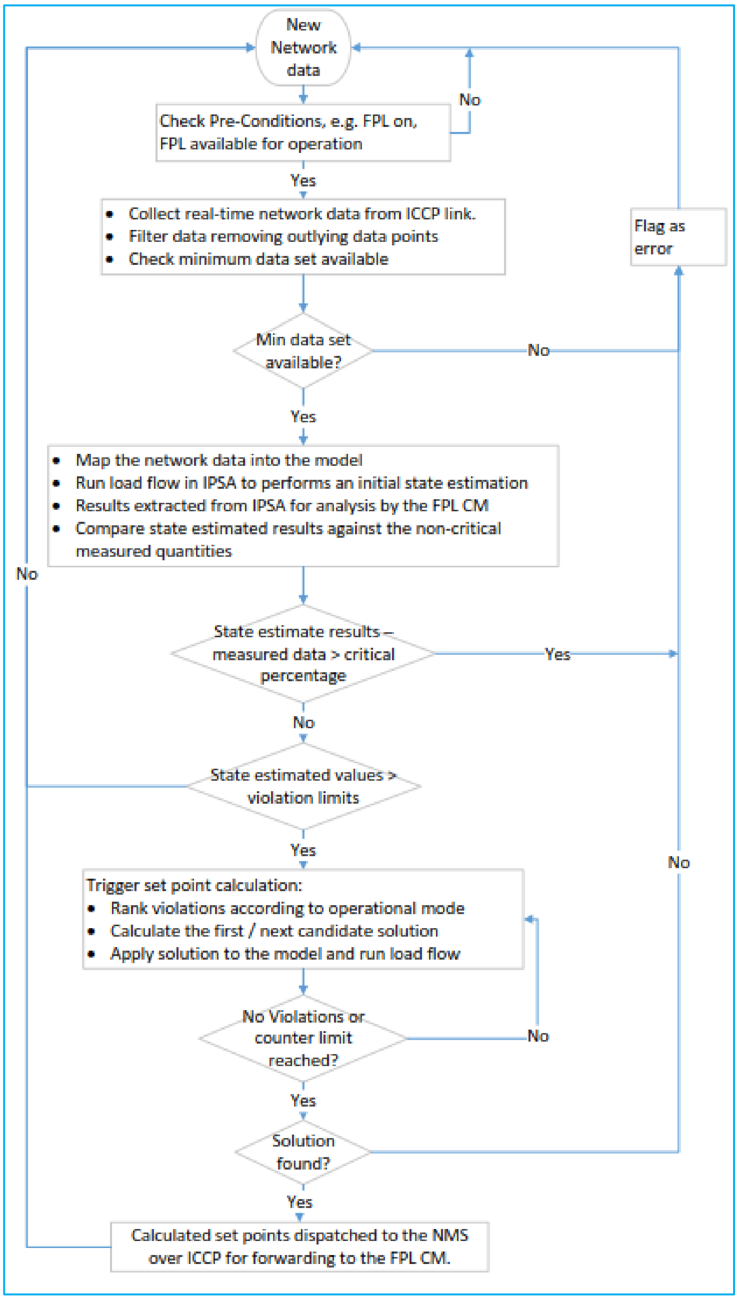

Figure 2-24: Overview of FPL CM Logic Sequence

With the required accuracy achieved, analysis is then carried out to check for network voltage or thermal violations which are then ranked according to their severity and the selected operating mode, described in section 2.3.6. An initial FPL set point is then determined and state estimation repeated to determine if the solution solves the violations. This stage is repeated until a suitable solution is found.

2.3.6 Operating Modes

The FPL CM offers four operating modes that change the ranking of violations and therefore the order in which the algorithm provides a solution. This gives the operator the ability to change the operation of the device to only solve for a certain type of violation or prioritise one type over another. The operation modes available are:

- Active Power Transfer Mode;
- Voltage Support Mode;
- Active + Reactive Power Mode (prioritising Active Power); and
- Active + Reactive Power Mode (prioritising Reactive Power).

Mode 1 – Active Power Transfer

In this operational mode the FPL CM calculates active power set points only with reactive power set at zero on both sides. The FPL CM monitors for violations of the BSP thermal rating and that for feeders connecting the FPL to the BSP. After calculating a suitable active power set point, the FPL CM will then validate that the chosen set point will not cause a voltage violation.

Mode 2 – Voltage Support

In this operational mode the FPL CM only calculates reactive power set points for each side of the FPL and the active power transfer is set at zero. The FPL CM monitors for voltage violations between the FPL and each BSPs providing independent control on both sides. Following calculation of set points, the FPL CM validates that the chosen setting causes no thermal violations.

Mode 3 – Active and Reactive Power Transfer (prioritising Active Power)

In this operational mode the FPL CM calculates both active and reactive power set points prioritising the solving of thermal violations over voltage. Once an active power set point has been calculated to solve a thermal violation, reactive power set points will be calculated to solve any voltage violations present before and after calculation of the active set point. This mode is the default mode for the FPL CM.

Mode 4 – Active and Reactive Power Transfer (prioritising Reactive Power)

In this operational mode the FPL CM calculates both active and reactive power set points prioritising the solving of voltage violations over thermal. Once a reactive power set point has been calculated to solve voltage violations, an active power set point will be calculated to solve any thermal violations present before and after calculation of the reactive set point.

2.3.7 Alarms

The FPL CM has six error codes that are passed to the NMS to provide the user with information about its operation. Depending on the severity of the error, appropriate control actions are either automatically or manually carried out. Alarms are grouped into two categories, Stage 1 and Stage 2.

Stage 1 alarms are pre-cursors to stage 2 alarms and are designed to warn of issues with the FPL CM operation. If a stage 1 alarm remains in place for longer than the predefined time (default of 300 seconds) an alarm will escalate to stage 2 which removes the FPL from operation.

The alarms in Table 2-1 are issued in both stage 1 and stage 2 states.

Table 2-1: Overview of FPL CM Alarm States

Item No.	Stage 1 Error	Description
1	Minimum Dataset Not Available	The load flow analysis cannot take place as there is not enough network data available from the NMS to run a load flow analysis
2	FPL Not in Expected Configuration	The FPL is either: • Not configured in fixed P and Q control; or • The FPL set points are not set correctly according to the FPL CM operating mode
3	State Estimation Failure	This alarm occurs when the load flow analysis has failed to complete. This could be due to the following: • The IPSA module is not loaded; • The IPSA model fails to load; • The load flow analysis fails to converge; or • IPSA returns an error state to the FPL CM
4	State Estimation Mismatch	This alarm occurs if any of the state estimated values does not match the corresponding measured value after the load flow analysis has been completed. The number of state estimation mismatches required to trigger the alarm is configurable in the FPL CM
5	No Solution	This alarm occurs if the FPL CM cannot find a set point solution that is able to remove a violation from the network
6	Set point Control Failure	This alarm occurs when the maximum number of set point control re-try attempts is reached

2.3.8 User Interface

The FPL CM user interface (UI) is a web-based interface based on Nortech's iHost platform and can be accessed by authorised users via a web browser when connected to the WPD IT network. Users are split into two groups depending on their required interaction with the system. The defined groups are:

1. Administration Users – Full rights to the system with the ability to enable/disable the FPL CM, carryout updates and configuration changes; and
2. Operator Users – Read only access to view the current FPL CM status and provide a greater level of detail compared to the NMS.

A screenshot of the front-end dashboard of the FPL CM is shown in Figure 2-25.

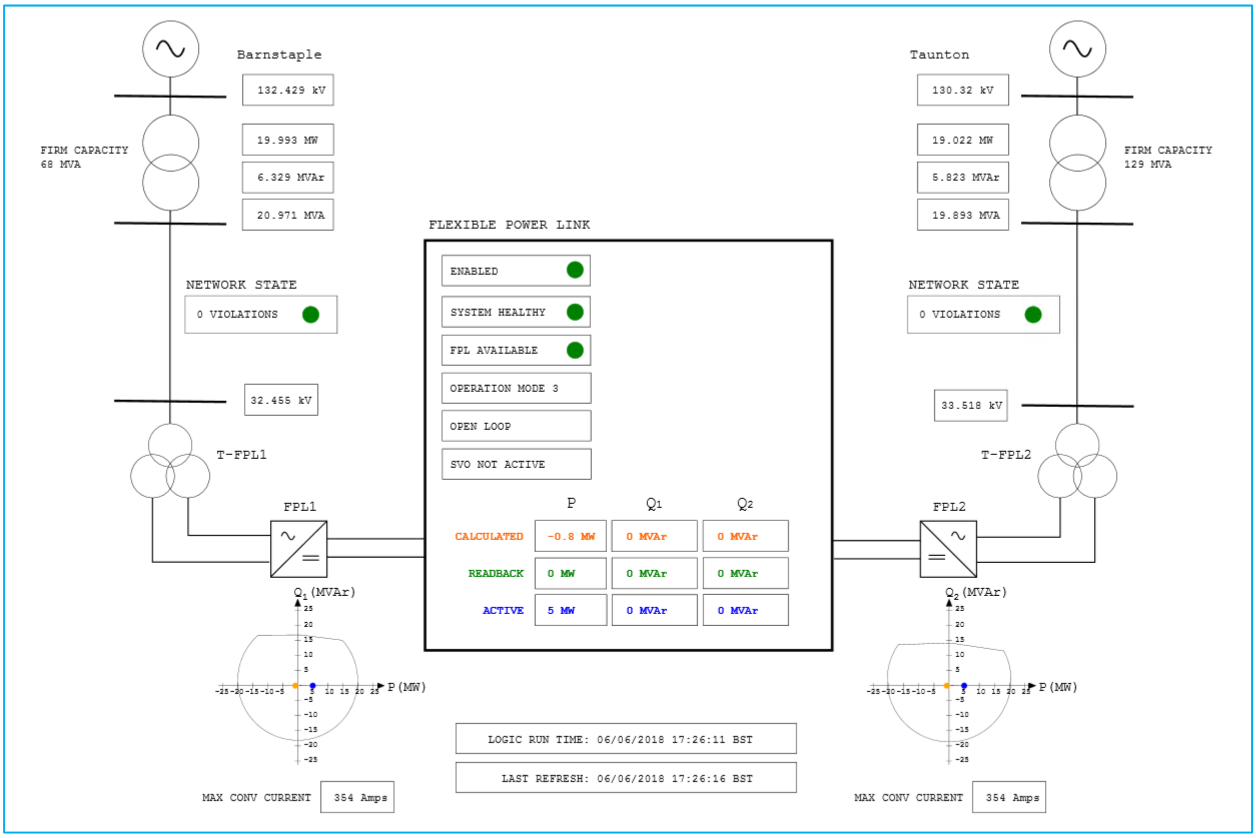

Figure 2-25: Screenshot of the FPL Control Module Dashboard

2.3.9 NMS Interface

The FPL and FPL CM are shown as a combined unit in the NMS interface diagram. The diagram is designed to provide engineers with the most relevant information to assess the health and operation of the whole FPL system. A snapshot of the interface is shown in Figure 2-26.

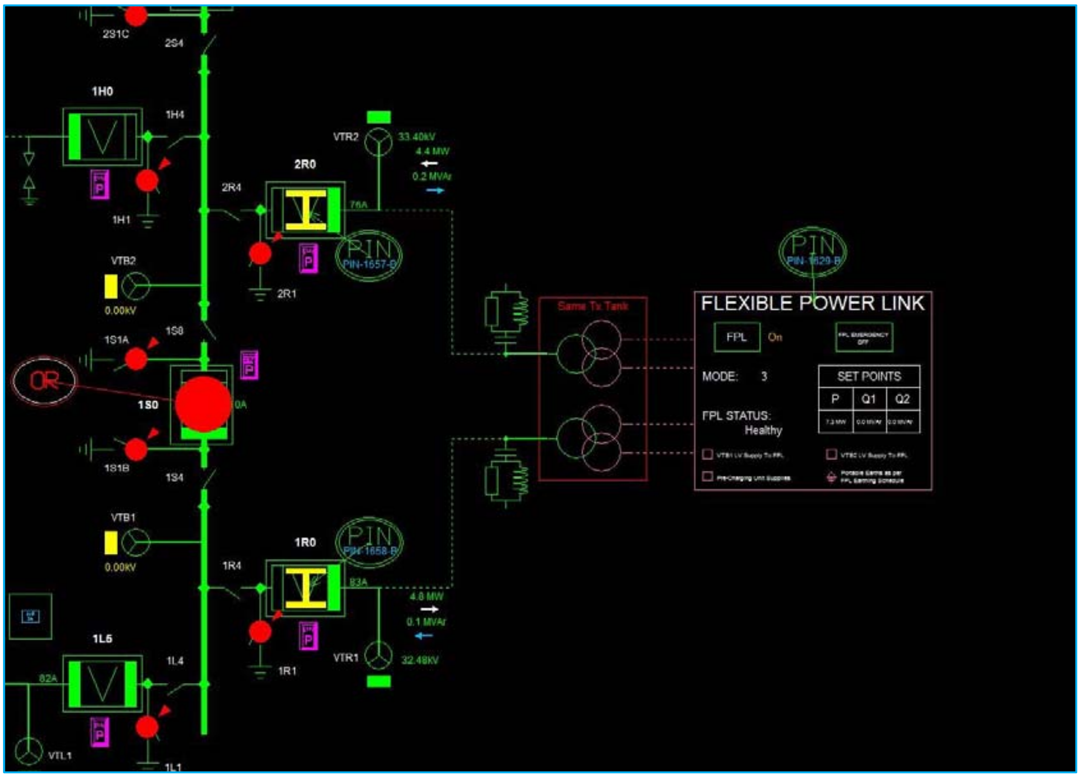

Figure 2-26: Snapshot of FPL within the NMS interface

Actual power flows through the FPL are displayed at the 33kV connection points on each side, with the FPL CM calculated set points shown in the FPL box on the right-hand side of the diagram. The FPL box also contains status information, including any active alarms, the FPL CM operating mode and control actions to enable or disable the FPL as well as perform an emergency off operation. Detailed operational information is available through accessing background alarm and operation screens within the NMS interface.

3.0 FPL Integration Design

In order to integrate the FPL and its ancillary equipment in to Exebridge primary substation a significant amount of civil and electrical work was required to safety and securely integrates the device. This section discusses the original site layout and the processes followed to design the changes required.

3.1 Original Site Layout

Exebridge Substation comprised a 33kV air-insulated switchgear (AIS) compound, two 7.5MVA 33/11kV transformers and a six panel 11kV switchboard. The 33kV compound consisted of a single bus section CB with busbar section 1 connected to Barnstaple BSP via South Molton and busbar section 2 to Taunton BSP. An overview of the substation's original layout and single line diagram are shown in Figure 3-1 and Figure 3-2 respectively.

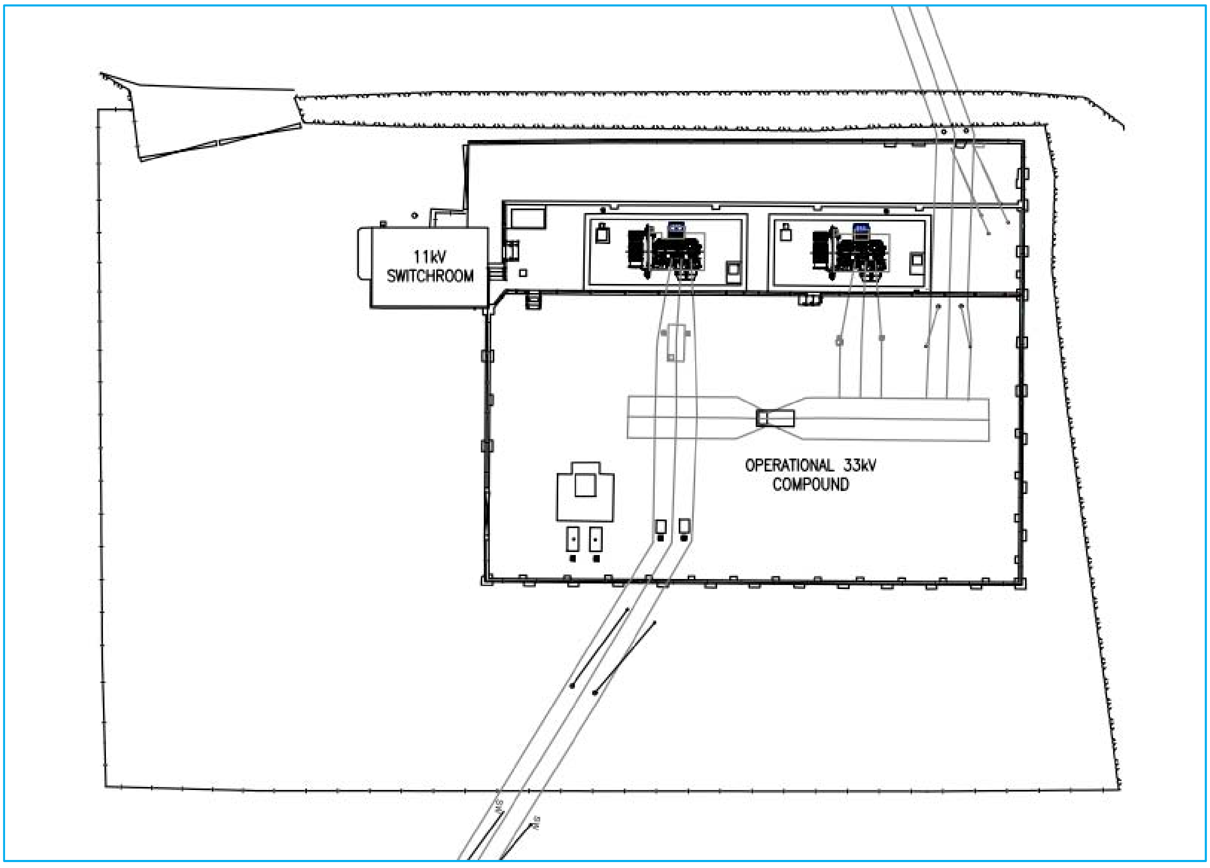

Figure 3-1: Original Layout of Exebridge Substation

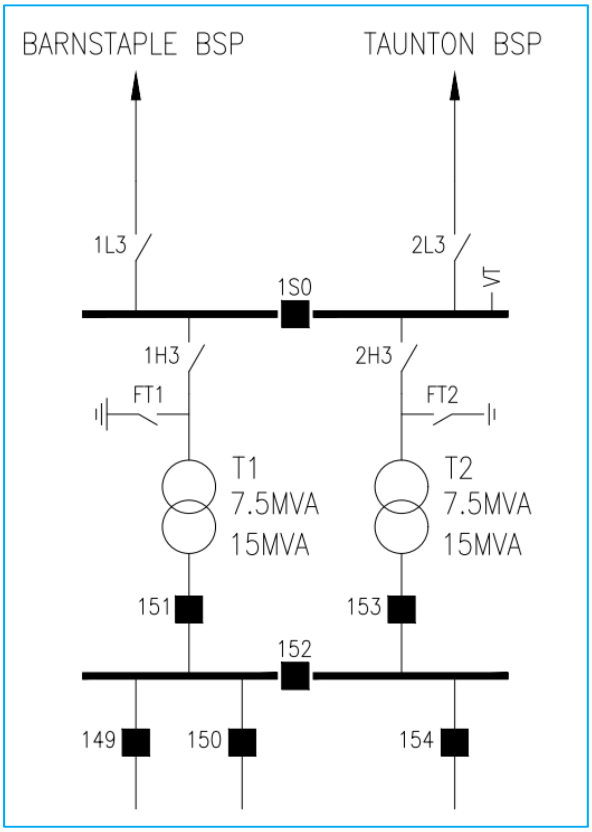

Figure 3-2: Original Single Line Diagram for Exebridge Substation

3.2 FPL Layout

The size of the FPL meant that to install the device within the existing site boundary the 33kV AIS equipment needed to be removed and replaced by a more compact indoor switchboard arrangement. This created a large amount of space, with a new building for the 33kV switchboard positioned outside of the existing compound and AIS busbar terminations changed to cable terminations.

The layout of the FPL was determined in close co-operation with ABB to ensure device functionality while maintaining safe access and egress to all components for operation and maintenance activities. Key considerations for the layout of the FPL were:

- Safe access to all equipment for operation and maintenance;
- Sufficient clearance and lay down areas for installation; and
- Optimal equipment positioning to limit the extent of civil works.

The original equipment layout proposed by ABB was developed in two key areas. Firstly, the harmonic filters were raised in height to provide a minimum safety distance from the ground to all exposed conductors. In other parts of Europe it is standard practice to install the filters at ground level within a separate locked compound for safety; however this was not acceptable for an installation on the UK network. Secondly, being the heaviest item of plant, the transformer location was also changed to be parallel to the compound access to most easily facilitate off-loading and final positioning. The final layout for the FPL is shown in Figure 3-3 below.

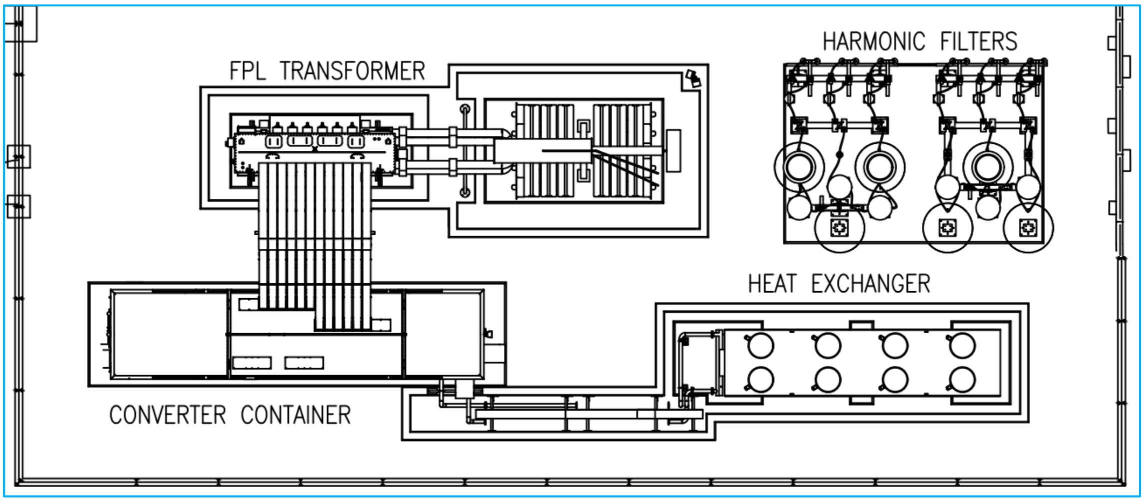

Figure 3-3: Final FPL Layout at Exebridge Substation

Despite efforts to reduce the overall footprint of the FPL, an extension to the compound was required. This was required to provide a suitable access route for the device installation and to provide demarcation between the FPL and other 33kV equipment.

3.3 Exebridge Substation Design

For Exebridge to be prepared for the connection and installation of the FPL the following works were required:

- Replacement of 33kV AIS Compound for a new indoor 33kV switchboard;
- Extension of the existing 33kV compound;
- Modifications to incoming overhead line and transformer connections;
- New LVAC supplies from the 11kV network for the FPL;
- Protection modifications at remote substations and Exebridge 11kV transformers; and
- Modification to existing telecommunication arrangements.

Throughout the design and installation process, works were planned and staged in such a way to minimise disruption to customers and to keep all network outages to the least amount of time possible.

3.3.1 Surveys

Several site surveys were carried out at Exebridge prior to any design work to provide a detailed model of the existing site. This ensured that all design work was based on the latest information, reducing the risk associated with the completion of enabling works and installation of the FPL.

Topographical Survey

The topographical survey mapped and identified the existing equipment, structures, levels and vegetation of the whole substation area up to the site ownership boundary. This survey was used for the basis of overall site layouts and providing information to the civil designers for compound and 33kV building designs. Figure 3-4 provides an overview of the survey.

Figure 3-4: Topographical Survey of Exebridge Substation

Underground Utility Survey

An underground utility survey was carried out map the location and depth of all utilities within the site. It was confirmed that there were no underground services that would impact on the design and installation of the FPL or the new 33kV building. This survey is shown in Figure 3-5.

Figure 3-5: Utility Survey

Geotechnical Survey

The size and specifically weight of individual FPL components meant that geotechnical surveys were undertaken to understand the existing ground conditions and bearing capacity, as shown in Figure 3-6. This was used to inform the foundation design for all new equipment and buildings, plus temporary structures such as crane pads.

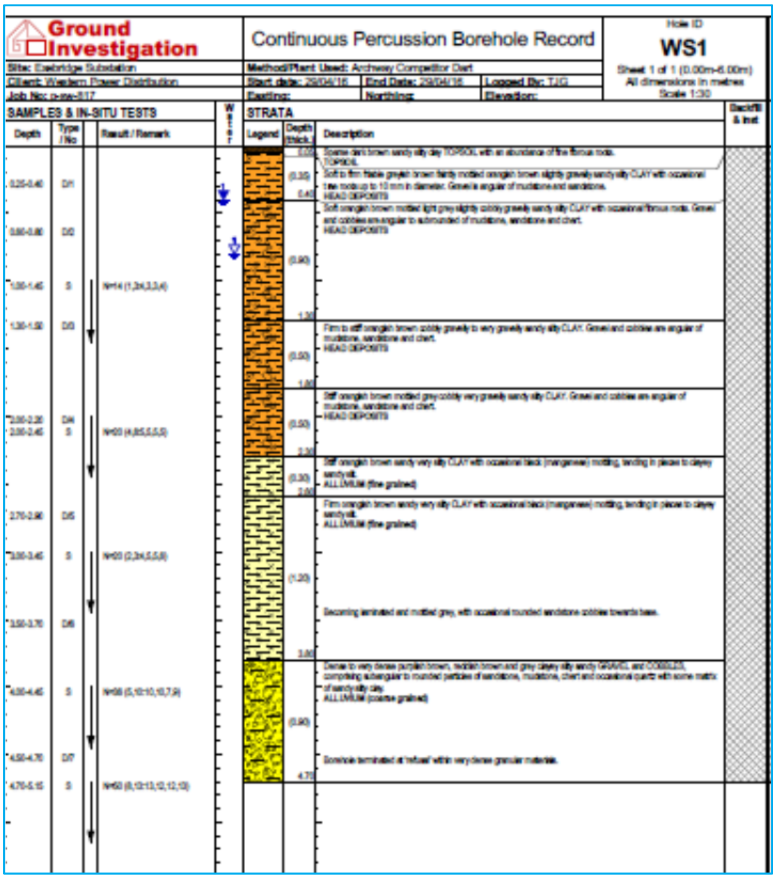

Figure 3-6: Geotechnical Survey

Earthing Survey

Following initial site visits it was identified that there were inconsistencies between earthing records and physical equipment on site. Due to safety concerns, an earthing survey for the whole site was carried out to ensure that the existing earthing arrangements were sufficient before any works began. The survey results recommended that additional earthing be installed for the existing primary transformers and safety handrails, within the compound, be replaced with a Glass Reinforced Plastic (GRP) equivalent. The survey details can be seen in Figure 3-7.

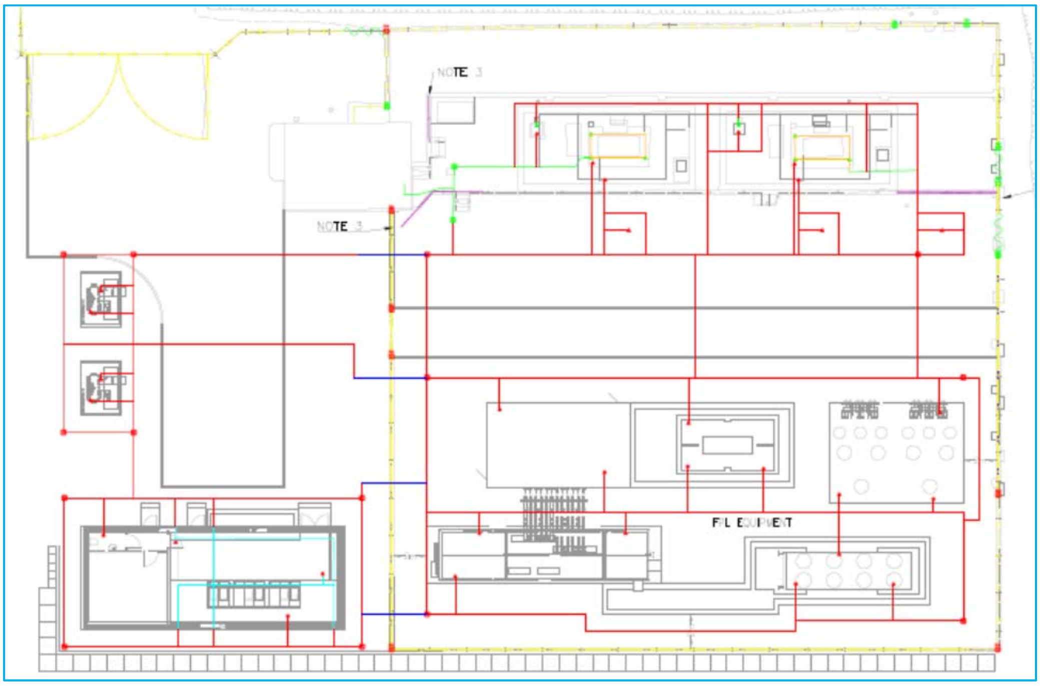

Figure 3-7: Earthing Survey

3D Laser Scan

A full 3D laser scan was completed for Exebridge substation. This provided accurate measurement and positioning information for all existing equipment easing the integration design of new equipment as well as reducing the number of site visits required during the design process. Figure 3-8 shows a sample of the scan carried out.

Figure 3-8: Sample of the 3D Scan

3.3.2 33kV Switchgear Change

New Switchboard Arrangement

The existing substation contained two 33/11kV transformers, both supplied from Taunton BSP. For the instance of a loss of supply at the substation, the 33kV CB would open along with one of the primary transformers, isolating a section of Exebridge from the fault. Once completed the NOP at South Molton would be closed to reenergise Exebridge. It was required to maintain this operational arrangement post FPL installation.

The final single line diagram of the new 33kV switchboard is shown in Figure 3-9. To make the connection to the existing overhead circuits, incoming CBs (1L5 and 2L5) were required at each end of the switchboard. The connection to the FPL was provided from CBs 1R0 and 2R0 on each side of the device to provide protection and a local point of isolation. When the FPL is out of service, the device would be bypassed with the NOP reopening at South Molton, returning the network to the original operational arrangement. This was achieved by the installation of a bus section CB (1S0) between the two FPL CBs. This CB becomes the NOP on the AC network between the two BSPs that the FPL connects across when operational. These three breakers were positioned between the Exebridge T1 CB (1H0) and the incoming CB from Barnstaple BSP (1L5) to ensure that Exebridge remained part of the Taunton BSP network with the FPL operational.

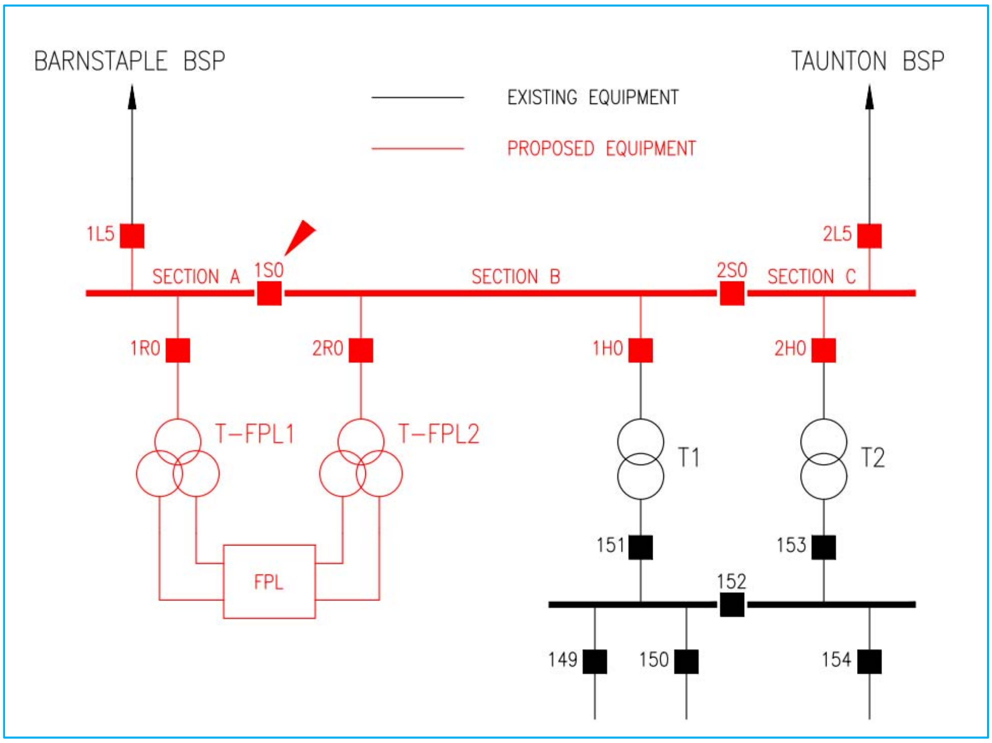

Figure 3-9: Exebridge Single Line Diagram for FPL Installation

Switchgear Specification

All CBs on the switchboard were specified as per the current WPD standards for 33kV switchgear, with minor modifications made to the FPL CBs for the unique connection of the FPL. Modifications made were the addition of an extra voltage transformer (VT) to provide the FPL with measurement of the 33kV busbar voltage on each side of the device.

33kV FPL Protection requirements

The protection requirements for all CBs was as per standard WPD design apart from the two FPL CBs with modifications required to the control wiring and protection scheme. During the FPL start-up procedure, the control of the CBs is critical to ensure they close and open at the correct time in the sequence. Control for the opening and closing of the CB was therefore modified to connect to the FPL rather than directly to the NMS.

Only a backup overcurrent and earth fault protection system was employed on the two FPL CBs as the main protection was provided by the FPL internal protection. A further non-standard modification requested by ABB was the installation of a CB fail protection scheme. Due to the sensitivity of the power electronics it was imperative that under fault conditions the CBs operated within 100ms. If an FPL CB failed to open within this time the bus zone protection would operate to isolate the FPL.

33kV Switchroom Design

A cost verses risk analysis was carried out to determine the most suitable solution for housing the new switchboard between a brick built building or purpose-built container solution. The main risk facing the delivery of the switchroom was the civil works scheduled to take place during the winter. A containerised solution would have minimised the site civil works required to enable the switchgear installation. However, the analysis concluded that the brick built building was a lower cost to build and provided greater flexibility for the configuration of equipment inside, essential for innovation projects of this type.

Within the existing substation boundary, a suitable space in the south-east corner was identified for the building. The overall design was based upon current standards for BSP substations, rather than a primary substation, due to the size of the 33kV switchboard and equipment for the FPL operation. The building consists of a 33kV switchroom with the 33kV switchboard and associated control and protection panels. The building has integral cable trenches within the foundation slab for High Voltage (HV), LV and multicore cables. Welfare facilities are also provided for staff and visitors to site as per the current BSP design philosophy. An overview of the building layout is provided in Figure 3-10.

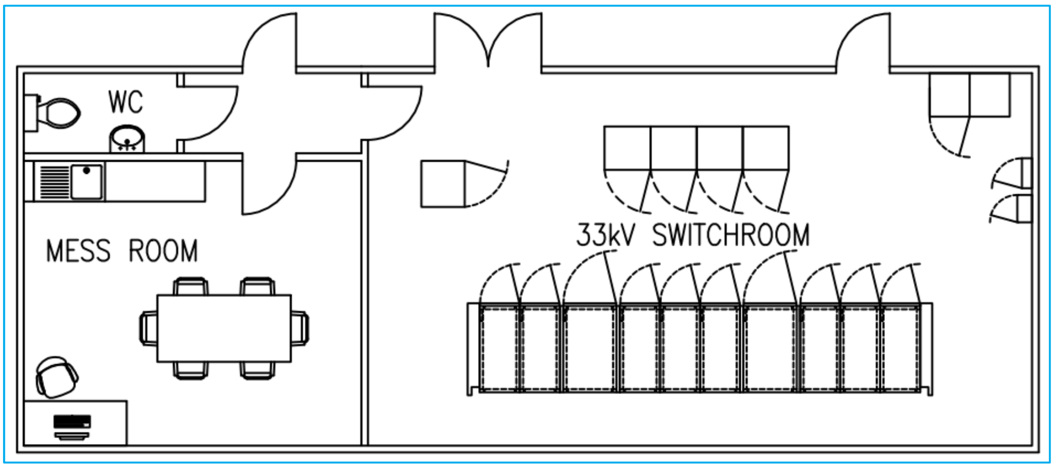

Figure 3-10: Overview of New 33kV Switchroom Building

A selection of photos from the construction of the building and installation of equipment is provided in Figure 3-11 to Figure 3-14.

Figure 3-11: 33kV Switchroom Foundation construction

Figure 3-12: Construction of 33kV Switchroom

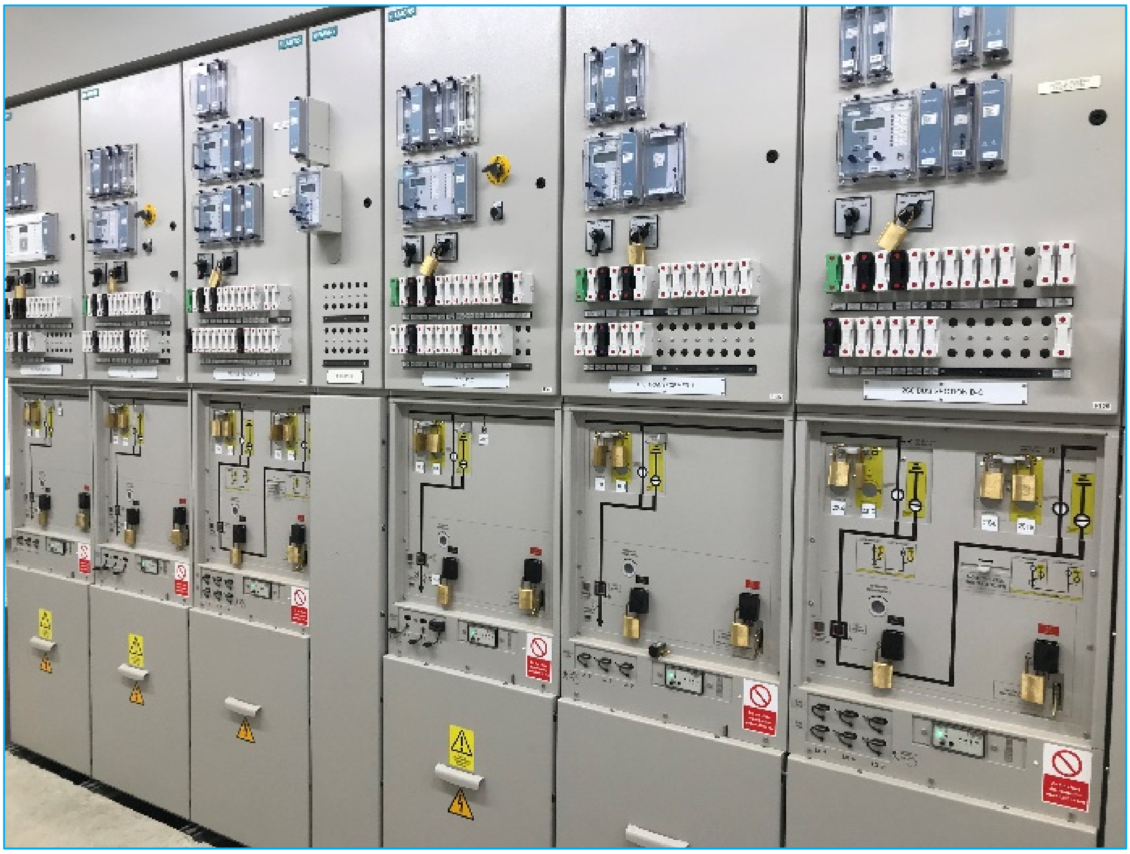

Figure 3-13: 33kV Switchgear

Figure 3-14: Finished 33kV Switchroom

3.3.3 Overhead Line Modifications

The original overhead line circuits in to Exebridge from Taunton and Barnstaple, via South Molton, were terminated onto the 33kV busbars by wooden poles located within the boundary of the substation. The position of the pole for the Taunton line was close to the planned switchgear building and would also impede access to the rear of the site during construction. Therefore, the decision was made to move the terminal pole outside of the site boundary, terminating onto a short cable for connection to the new switchboard.

The overhead circuit from South Molton terminated in the North-West corner of the 33kV compound as seen in Figure 3-1. This termination was changed from an AIS busbar type to a cable sealing end (CSE) during the works to remove the 33kV AIS equipment. The new cable ran across the 33kV compound towards the 11kV switchroom and then towards the 33kV building once outside the compound so as not to affect the FPL installation.

3.3.4 Primary Transformer HV Terminations

The existing primary transformers are connected to the 33kV network via AIS busbars connected to HV bushings on top of each transformer. These connections could not be adapted for cable connections on the transformers themselves. New 33kV cable sealing end structures were installed closer to the transformers, shortening the AIS busbar and maximising space in the 33KV compound. A picture of the new termination during construction is shown in Figure 3-15.

Figure 3-15: Picture of New Transformer HV Termination

Figure 3-16 provides a snapshot of the new CSEs installed.

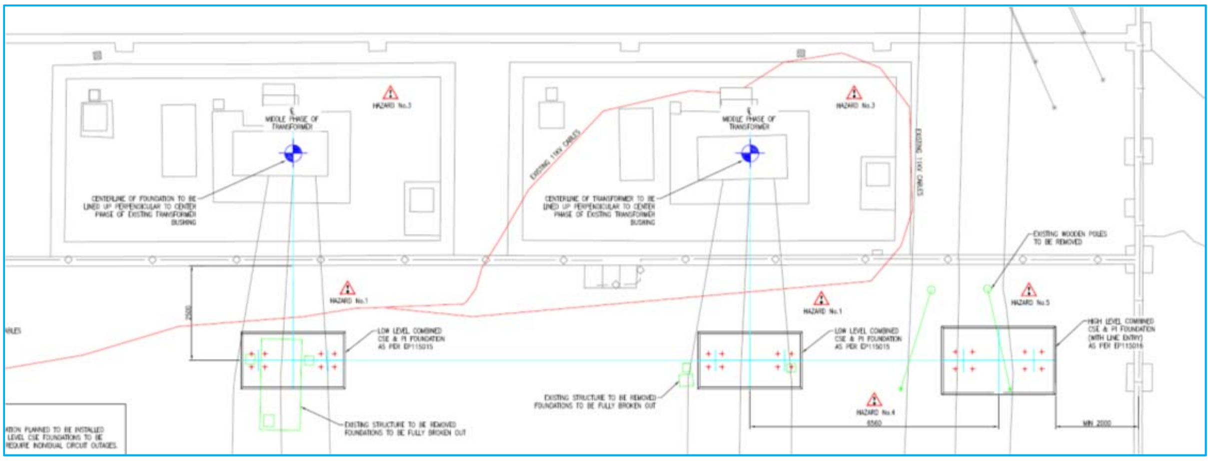

Figure 3-16: CSE Locations

3.3.5 33kV Compound Extension

As discussed in Section 3.2, an extension to the existing 33kV compound was required for the FPL installation. The extension was constructed on the eastern edge of the compound. Due to the topology of the site and weight of the FPL components a new retaining wall was required along the whole eastern edge of the site to support the installation. Pictures from the civil modification works are shown in Figure 3-17 to Figure 3-20.

Figure 3-17: Construction of 33kV Compound extension

Figure 3-18: Finished foundations for FPL Installation

Figure 3-19: New Retaining wall along 33kV Compound

Figure 3-20: New Retaining wall during construction behind new 33kV Switchgear Building

3.3.6 Earthing Design

Following completion of the earthing survey and required modifications discussed, the new earthing design for the substation was developed. The final earthing design is shown in Figure 3-21. All equipment was within the compound was connected at a minimum of two points diagonally opposite each other as per the current design policy. Extra connections were made to some components of the FPL where provided by ABB. The 33kV building and LV distribution substations were also connected to the main earth mat to ensure continuity of earths between equipment. This required the installation of ducts under the compound fence, shown in blue, to ensure there was no touch potential with the compound fence.

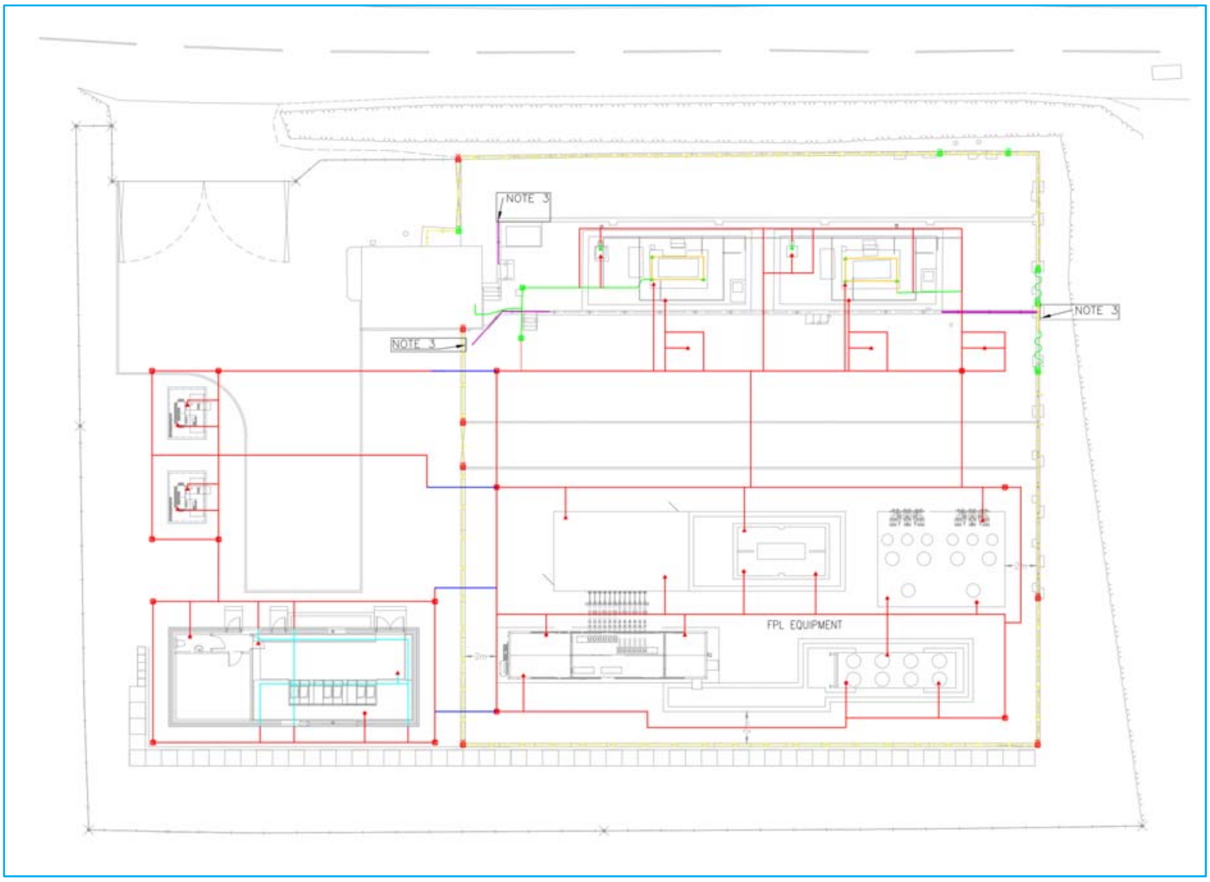

Figure 3-21: Earthing Design for Exebridge

3.3.7 Cable Layout

The design of the cable layout at Exebridge was focused on ensuring any cables did not impact on the installation or future maintenance of the FPL. The overall design is shown in Figure 3-22.

The 33kV cables to the primary transformers and overhead line to South Molton are shown in magenta towards the top of the diagram were installed prior to the civil works starting on the 33kV compound. Therefore, they were run as close as possible to the new structures and then in ducts under the entrance road to the 33kV switchroom so as not to impact on the construction work.

The 33kV cables to the FPL, shown in green, were installed along the back of the device connecting to the harmonic filters. This was a slightly longer route but avoided congestion between the FPL transformer and compound road and avoided crossing over with auxiliary and LV cables shown in blue.

Finally, LV cables shown in yellow from the two distribution substations were run on the edge of the substation compound. These were the first cables to be installed as part of the works and were therefore placed to ensure no impact on construction works.

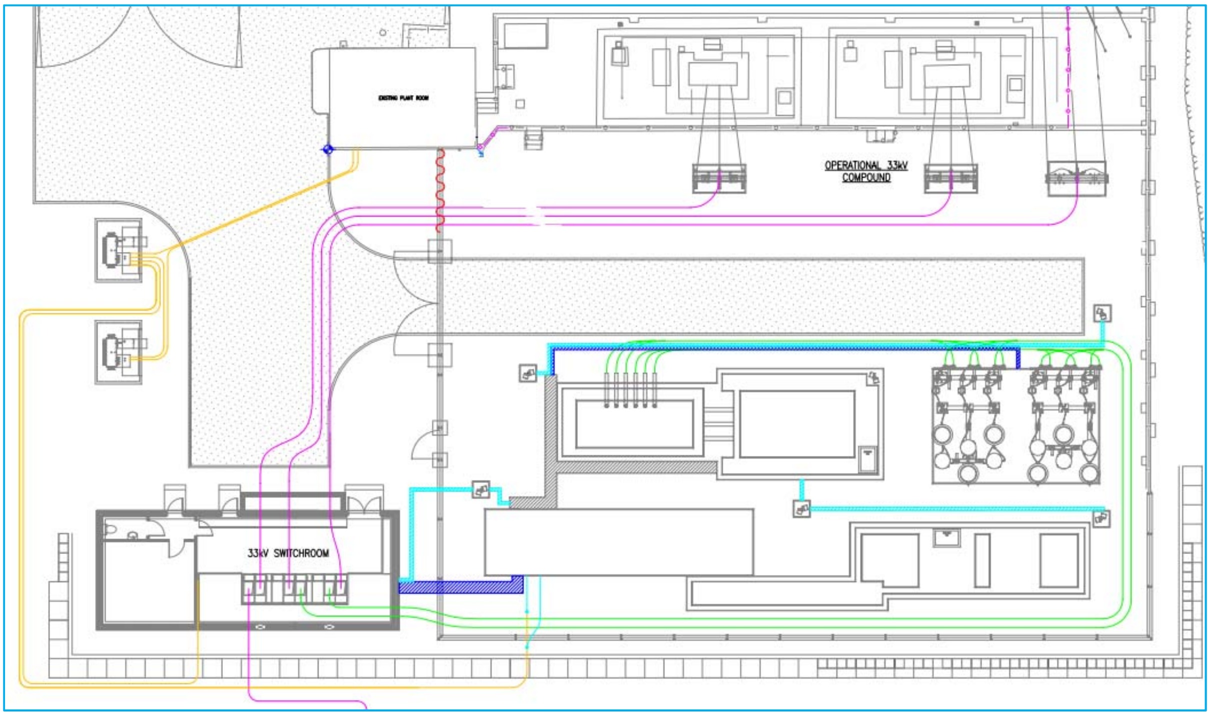

Figure 3-22: Exebridge Cable Layout

3.3.8 FPL Protection Interface

The FPL provides a fully operational HMI located within the FPL's internal control room for control and data logging. To provide a single interface point between the FPL and other WPD equipment, a dedicated FPL Protection Panel was implemented. The panel was located within the 33kV switchroom to provide operational engineers with a summary of the FPL status and current alarms.

The panel is also used to marshal back-up trip signals from the FPL to its CBs providing indication for the operation. All control and indication signals between the FPL and the onsite Remote Terminal Unit (RTU) are marshalled through the panel as well. A picture of the installed panel is shown in Figure 3-23.

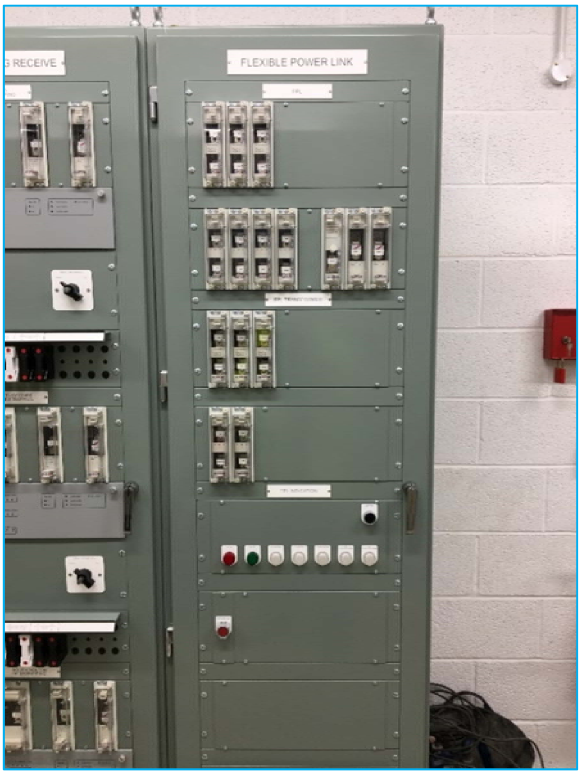

Figure 3-23: Picture of FPL Protection Panel

3.3.9 11kV Protection Modifications

The 33kV switchgear changes to the HV side of the existing primary transformers meant that the 11kV protection schemes on the LV side required modification. The existing LV protection panels contained HV protection relays that were now included on the new HV CBs. The 11kV transformer CB protection was also modified to remove trip circuits to and from the previous 33kV AIS CB and fault thrower and connected to the new 33kV CBs.

3.3.10 LV Supplies

The FPL required two LVAC supplies with a maximum demand of 100kVA for the pre-charge unit and auxiliary systems. The existing substation auxiliary supplies were from two pole-mounted 11/0.415kV transformers located within the site boundary connected to separate 11kV feeders from Exebridge. Both transformers were rated at 25kVA and were therefore not sufficient for the FPL.

The supplies were replaced by two standard 500kVA ground mounted unit substations. A single substation was used to provide LV supplies to the existing 11kV switchgear building, the new 33kV switchgear building and the FPL. The second supply was installed to provide redundancy in case of a network fault. Figure 3-24 shows these substations during the installation phase.

The existing LVAC and DC battery systems in the 11kV switchroom where replaced by new units within the 33kV switchroom with cables installed between the two to maintain supplies. This ensured that a single system powered the whole substation removing potential safety risks to system operation and personnel from operating two interconnected systems.

Figure 3-24: LV Substations during Installation

3.3.11 Final Layout

The final substation layout ready for the FPL installation at Exebridge is shown in Figure 3-25.

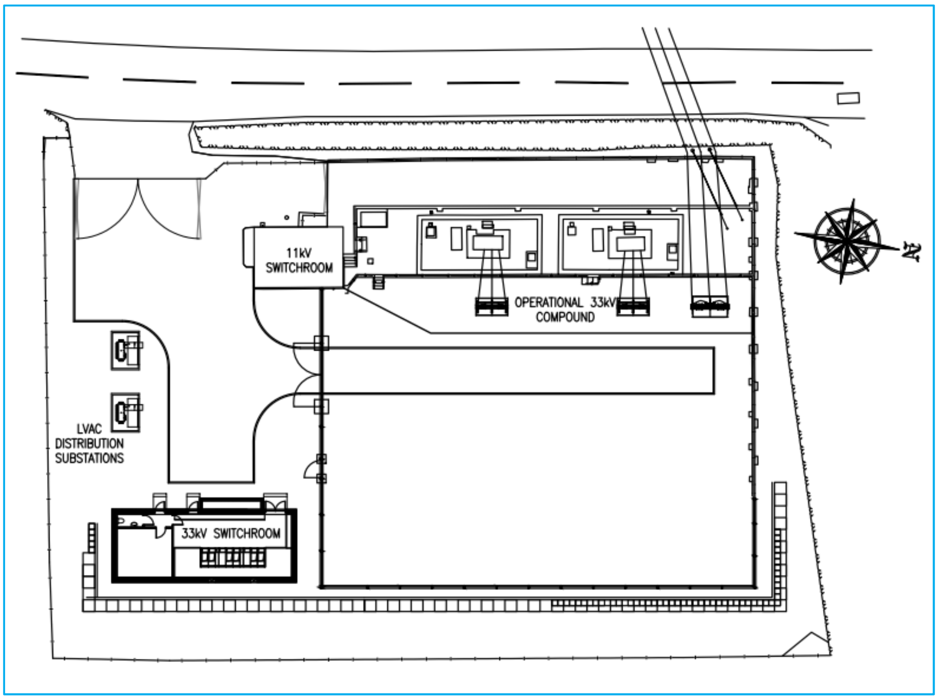

Figure 3-25: Exebridge Substation layout following FPL Installation

3.4 Wider Network Changes

3.4.1 33kV Intertripping

To the wider network protection systems, the FPL appears to operate as either a demand or a generator. When pushing power into either network, the maximum operating window for real power means that, theoretically, the FPL could support sections of the network as an island from the main grid. The built-in protection and monitoring systems of the FPL are designed to prevent this occurrence. However, to ensure network security for customers a back-up intertripping scheme was developed.

The scheme was designed such that a remote protection operation that isolated the FPL from the BSP would lead to the trip of the FPL. Following studies of the network, it was determined that three remote CBs required monitoring for the intertrip protection. These were Taunton 2L5, Wiveliscombe 3L5 and South Molton 3L5. The demand of the network beyond these points was above the maximum power capability of the FPL ensuring the operation of the FPL's main protection systems.

After detailed collaboration with our control and operational staff, it was decided that the scheme would be set so that operation would only occur for protection operations. Manual or telecontrol operation of the CBs would not cause an intertrip and operation procedures at these locations where altered to minimise the risk of human error.

Due to space constraints at all three remote sites, it was decided to integrate the intertrip equipment within the existing protection panels. Due to the age of the existing protection assets, WPD Primary System Design took the opportunity to upgrade the existing protection relays to provide greater reliability. A picture of the combined protection and intertrip panel at Taunton BSP is provided in Figure 3-26.

Figure 3-26: Combined Protection and Intertrip Panel at Taunton BSP

At Exebridge, a single intertrip panel was designed to contain all the equipment for each intertrip circuit. The trip circuits and interfaces were then made with the FPL protection panel for ease of integration and isolation if required. A picture of the installed intertrip panel at Exebridge is shown in Figure 3-27.

Figure 3-27: Picture of Intertrip Panel at Exebridge

3.4.2 Telecontrol

Existing communications from the Exebridge RTU to the NMS were provided via a radio link. Between Taunton and South Molton substations an existing fibre optic cable was installed along the route of the 33kV overhead line; however, it was not terminated into any intermediary substations. The requirement for intertrip protection between substations meant that the fibre optic cable needed terminating at Exebridge and Wiveliscombe substations.

Due to the innovative nature of the FPL and the site modifications, the decision was made to transfer the whole substation communications to the fibre optic network. This provided a more reliable communications system as the fibre optic cable would be less susceptible to issues caused by environmental conditions.

3.4.3 Data Measurements

To provide suitable data for the FPL CM to have sufficient confidence in its calculations, voltage, current and power flow measurements are required at each substation included within its network model, described in Section 2.3.3. Following a review of available data at all modelled substations, additional P and Q measurement data was required at Taunton BSP, South Molton, Wiveliscombe and Wellington Primary substations. This was achieved by installing new multifunction transducers capable of providing the additional measurement data.

Further analysis showed that the quality of data at many points of the network was not at the required quality or granularity. This may have affected the stability of the FPL CM operation as confidence in measured data may be lost. Revalidation and configuration of these data points was carried out prior to energisation of the FPL.

4.0 Testing

The initial plans and preference for testing of the FPL was to complete a full system test for the entire device prior to installation. However, due to the location of manufacturing and the overall size and scale of the device this was not possible. The testing plan was adapted with each component undergoing a Factory Acceptance Testing (FAT) before a completion of a Site Acceptance Test (SAT) to prove the functionality of the device.

For both the FPL and the FPL CM testing specifications where developed and approved in conjunction with the manufacturers prior to commencement of all tests. This ensured that clear testing procedures and success criteria were in place and agreed.

4.1 Converter Testing

The FPL converter underwent a FAT in May 2017 to confirm key parameters of the power electronic modules prior to installation into the main FPL container. Figure 4-1 to Figure 4-3 shows the converter during test.

Figure 4-1: FCL Converter under Test

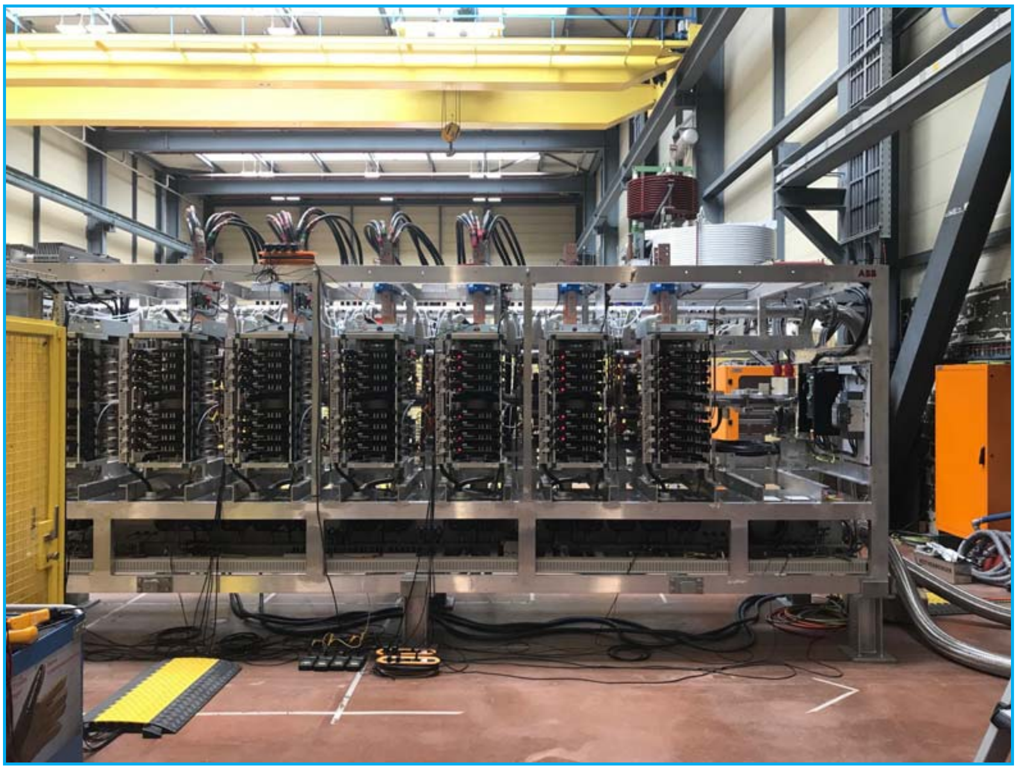

Figure 4-2: FPL Converter in Test Lab

Figure 4-3: FPL Converter Frame

The tests on the converter were successful and the fit out of the FPL container took place over the next two months.

It was specified that the FPL container should be tested in its finished state and therefore all wiring inside the container was completed (including power electronic modules, controllers, protection relays, transducers, small power and lighting etc.) and all the final components were installed (HMI, UPS, cooling system etc.). Carrying out rigorous testing on the completed container meant that any issues could be resolved in the factory rather than on site. Figure 4-4 to Figure 4-6 show the container ready for testing in the ABB's factory in Turgi, Switzerland during August 2017.

Figure 4-4: FPL container in ABB factory

Figure 4-5: FPL cooling system

Figure 4-6: Inside the FPL converter room

The list below details the critical tests that were carried out to verify the performance of the container:

- Insulation Test – this was performed on the 3.25kV AC and 2.5kV DC connections on the converter to ensure there were sufficient levels of insulation following installation into the container. The control cabinets inside the container also underwent insulation tests;
- Control Devices – verification that all the individual control devices operate in the correct manner from protection relays to pump controllers;
- Cooling System – the functionality of the cooling system was tested, included the checking of pumps, controllers, system redundancy, presence of leaks and operation of the by-pass valve;
- Pre-charger – the pre-charger transformer and rectifier that supply the DC link were tested to verify that the correct voltage would appear during energisation; and
- Power loss – the losses associated with the container, including all auxiliaries, were measured and added to the converter frame losses to establish the total figure for the FPL. Additional losses associated with the heat exchanger and transformer would be added to these once tested.

All tests as described in ABB's approved testing specification were passed and witnessed by WPD.

4.2 FPL Device Software Testing

A separate FAT was proposed to verify the performance of the software and this was scheduled to be carried out in parallel with the FPL container testing in August 2017. The main areas that would be tested were the local SCADA system, open loop control, closed loop control and protection functions. The tests were carried out in ABB's test laboratory in Turgi, Switzerland. Figure 4-7 and Figure 4-8 show the ABB test simulator setup used to test the software. The system was configured to simulate the various scenarios that can occur during the FPL operation and was an efficient way to check the performance of the software before finalising and uploading into the container.

Figure 4-7: FPL software on ABB simulator

Figure 4-8: FPL software undergoing closed loop tests

During the initial software FAT in August 2017, it was observed that the software was not fulfilling the test requirements in several areas. The main cause of the issues stemmed from the specific FPL software changes not being fully tested by ABB prior to the FAT occurring. A repeat of the FAT was carried out in October 2017 and all tests were successful.

4.3 FPL Transformer Testing

Initial testing of the transformer was carried out in mid-September 2017. Before placing the windings into the transformer tank and filling with oil, winding resistance tests were carried out to ensure they were symmetric and within the specified tolerances. Following this the transformer was fully assembled a filled with oil.

The transformer underwent a full FAT from 3rd to 6th October at Končar's dedicated transformer test facility in Zagreb, Croatia. The standard procedures detailed in the IEC 60076 suite of standards were used as the basis for testing. Additional modifications were made to account for the special design of the FPL transformer, a single tank for two transformers. The list below details the main tests carried out:

- Impedance Voltage and Load Losses – the LV windings of T1 and T2 were short circuited and current was injected on the HV terminals at three different levels. Measurements were taken to determine the losses and impedances for T1 and T2 at the three levels;
- Sound Level – although the FPL transformer will be installed within a noise enclosure, it was important to measure the sound power level in laboratory conditions so that the noise enclosure design could be verified. Measurements were taken around the transformer tank and cooler to establish the sound power levels at both normal and emergency operating ratings;
- Applied Voltage – the insulation level of the two transformers was checked by applying an AC 50Hz voltage for one minute on each terminal. The HV terminals were subjected to 70kV whereas the LV terminals were subjected to 20kV;
- Lightning Impulse – the basic insulation level (BIL) of the transformers was also tested to ensure that it could withstand a lightning impulse. A test voltage of 170kV in various configurations, as per IEC standards, was applied to each HV terminal to verify that no breakdown would occur;
- Temperature Rise Test – this test involved short circuiting the LV windings and injecting the rated current into each transformer. The transformer top oil and ambient temperatures were recorded and monitored until the temperatures stabilised. The results from the test were used to verify that the maximum hot-spot temperature of the transformers does not exceed the design limits; and
- Induced Voltage with Partial Discharge – the last test in the sequence was an induced voltage test with partial discharge measurement. A test voltage of 66kV at 200Hz was applied to the HV windings to check for any signs of breakdown or variation in partial discharge over a test period of one hour. The partial discharge test can often detect very minor faults in the transformer before they escalate into more serious problems.

The FPL transformer successfully passed all tests on the 6th October but some minor issues, such as paint quality and fixings, were raised during the testing that were rectified before shipping to Exebridge on the 27th October 2017. Figure 4-9 to Figure 4-12 show a range of photographs that were captured during testing.

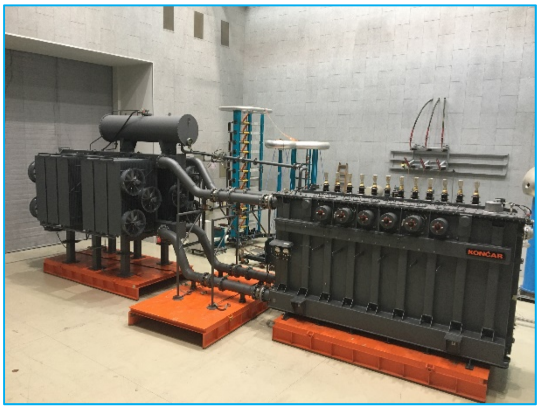

Figure 4-9: Assembled FPL transformer

Figure 4-10: 70kV applied voltage test

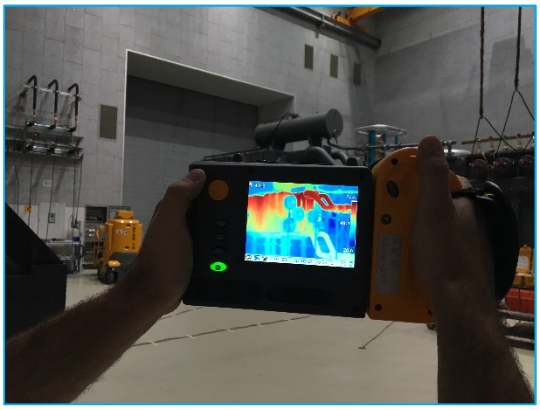

Figure 4-11: Temperature rise test

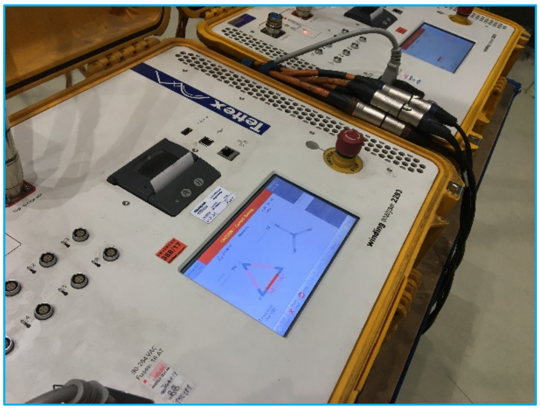

Figure 4-12: Winding resistance test

4.4 Control Module

Three test periods were undertaken on the FPL Control Module prior to commissioning and final testing with the live FPL. First a FAT was completed by Nortech to test the basic functionality of the FPL CM against the agreed functional specification. Next a System Integration Test (SIT) was carried out to confirm the hardware and software were compatible and to test the ICCP data link using the offline NMS test environment. Finally, a SAT was carried out to test the final installation of the FPL CM and its communication over ICCP with the live NMS.

4.4.1 Factory Acceptance Testing

The FPL CM FAT was completed on the 11th and 12th November 2017 at Nortech's Birmingham office. The aim of the FAT was to test the functional requirements of the FPL CM independently with an ICCP simulator operating in place of WPD's NMS. The FPL CM algorithm was tested in stages by sending data for controlled scenarios over the ICCP simulator. This proved the data handling sequences, the operation of state estimation studies, the identification and rating of violations, and finally the calculation of FPL set points.

The user interface was also analysed to test access security and usability. This looked at the FPL CM start up and shut down procedures, the display of real time operating information and the ability to change configuration data and run system diagnostics.

All tests were passed with only minor comments and issues identified. These actions were due for completion prior to SIT and installation of the FPL CM on WPD's hardware.

4.4.2 System Integration Testing

The System Integration Testing was carried out from 11th until the 15th December 2017 at WPD's Tipton office. The aim of the SIT was to install the FPL CM onto two test servers, as shown previously in Figure 2-19 and connect to the NMS test environment. This would provide an accurate representation of the final hardware and live operation data without effecting the live operations. In preparation for the test, a 24 hour snapshot of the live system was taken and loaded into the test environment. Key elements of the test were confirmation of functionality on the server hardware, validation of data being passed over the ICCP data link and the sending and receiving of data from a simulated FPL.

To simulate the FPL operation, Nortech developed a piece of software that was run on a laptop connected to a test RTU. This appeared to the NMS and FPL CM to be the installed FPL. The software could receive set points, simulate the ramp change in power over time and provide full feedback in the same manner as the FPL.

Following installation and basic function tests, a full point by point check was carried out on the bilateral table to ensure all systems were aligned as expected. This identified an issue on seven data points and an issue with the translation of status values between the two systems giving incorrect circuit breaker status information to the FPL CM. Modifications were made during the SIT to correct both these issues.

Simulated running using the snapshot data provided useful feedback on the operation of the FPL CM and ensured that the communications and data transmission could be fully tested. During operation the FPL CM indicated suspect measurement data from four transducers within the network. This information was fed back to the project engineers to carry out validation tests.

All other tests were passed and identified system bugs were actioned for resolution and retest on prior to the commencement of the SAT.

4.4.3 Site Acceptance Testing

The FPL CM SAT was carried out on 5th and 6th of June 2018 at WPD's Tipton office. The aim of the SAT was to install the FPL CM onto the final server hardware and connect via the ICCP data link to the NMS. A full point check was carried out again to confirm that no changes had occurred to the bilateral table on either side following the SIT. The FPL CM logic was operated using the real-time data but set points were blocked by the NMS to prevent operation of the FPL. Simulated scenarios were run to test other operational scenarios and to confirm the alarm processing and display within the NMS.

All tests were passed successfully and the FPL CM left connected to the NMS for soak testing using real time data.

5.0 Installation and Commissioning

ABB UK and their installation contractor HET Hanseatische carried out the installation of the FPL equipment at Exebridge substation. Under the management of ABB, specialist sub-contractors were used for both the transformer installation and transformer noise enclosure.

The FPL commissioning works were overseen by WPD project engineers and was completed according to schedule. Full commissioning of the device took less than four weeks to complete, keeping disruption on the network and to customers to a minimum.

5.1 Site Installation

5.1.1 FPL Container

The FPL container underwent final assembly on site with external fittings and earth connections being completed after delivery. With the majority of components within the FPL container were pre-installed in factory so the time on site for installation was dramatically reduced. Remaining work was mostly associated with pulling, glanding and terminating of multicore and small power cables. Pictures from the installation of the converter container are shown in Figure 5-1 to Figure 5-3.

Figure 5-1: Delivery of FPL Converter Container

Figure 5-2: Picture of Installed FPL Converter Container

Figure 5-3 Picture of FPL Converter Container and connection to FPL Transformer

5.1.2 FPL Transformer

The FPL transformer from Končar was delivered in two main parts to Exebridge; the transformer tank and the radiator bank. Once in place, the connecting pipe work and external oil tanks were installed. The Transformer noise enclosure over the main tank was installed by a specialist contractor, dBA Ltd. A selection of photographs from the delivery and installation of the FPL transformer and noise enclosure are shown in Figure 5-4 to Figure 5-6.

Figure 5-4: FPL Transformer Delivery

Figure 5-5: Installation of FPL Transformer

Figure 5-6: FPL Noise Enclosure

A small amount of remedial work was required following installation due to damage on the noise enclosure sustained during transport to site. This required the removal and repair of paint damage to ensure the transformer was properly protected against corrosion. This work was completed before the connections were made between the transformer and FPL container.

5.1.3 Harmonic Filters

The harmonic filter equipment was mounted onto raised steel support structures using the telescopic crane. Following installation, mechanical checks were made at all fixing locations and connections made to the 33kV network. Once installed, basic electrical tests were carried out to ensure the filter properties, namely resistance and capacitance, were within the designed tolerance. Figure 5-7 and Figure 5-8 shows the installed harmonic filters.

Figure 5-7: Installed Harmonic Filters

Figure 5-8: 33kV Terminations to Harmonic Filters

5.1.4 Heat Exchanger

The FPL heat exchanger is connected to the FPL converter cooling system via a run of external pipework. This was then inspected to ensure flange connections and steel supports were properly tightened and earthed. The cooling system by-pass values were mechanically tested to ensure transition from the internal to external cooling system. A picture of the installed heat exchanger is shown in Figure 5-9.

Figure 5-9: Picture of Installed FPL Heat Exchanger

5.2 Commissioning

In accordance with WPD's Safety Rules, the commissioning programme comprised of two parts; Cold (or Pre) Commissioning and Hot Commissioning.

The cold commissioning tests involved equipment checks and tests using low power and standalone test equipment. This testing commenced on 6th March 2018 and was completed by 20th March 2018.

The hot commissioning tests were conducted over a nine-day period. The first six days to undertake the standard tests mandated by ABB for the FPL equipment and three further days to demonstrate the full performance of the FPL (i.e. active and reactive power transfer capability). Following this, a series of measurements were taken relating to audible noise, harmonics and Electromagnetic Field (EMF) to ensure compliance with the functional specification.

5.2.1 Cold Commissioning

During cold commissioning tests the FPL was completely isolated from the 33kV network via the two FPL CBs (1R0 and 2R0). The cold commissioning process consisted of routine installation checks and integrity tests that would be carried out for all equipment installed on the distribution network. This included visual checks and proving of auxiliary wiring and earth connections to all equipment.

ABB under witness by WPD, carried out further tests on the FPL converter and transformer as detailed below.

FPL Converter

The following tests were carried out by ABB as part of the cold commissioning of the FPL converter:

- Overcurrent protection commissioning;
- Energisation of the DC link with ±25V_{DC} to test integrity;
- Check of all IGCT operations at low voltage;
- Measurement of FPL Transformer Voltages; and
- Energisation of the DC link and measurement of frequency spectrum at the harmonic filters using a Rogowski coil.

All tests were passed successfully.

FPL Transformer

The following tests were carried out on the FPL transformer during cold commissioning:

- Sweep Frequency Response Analysis (SFRA);
- Insulation Resistance testing;
- Transformation ratio test to ensure it is within ±0.5% of design in accordance with IEC 60076-1; and
- Magnetising current measurement at low voltage.

All tests were passed successfully.

5.2.2 Hot Commissioning

To carry out the hot commissioning tests, connection to the live 33kV network was required. Several network configurations were agreed by all parties for the tests aiming to eliminate any disruption to customers. For much of the testing, a ‘bypass’ configuration was used allowing power to circulate from one side of the FPL to the other without significant impact to the live network. In this configuration CB 1L5 to South Molton was opened and CB 1S0 closed as shown in Figure 5-10.

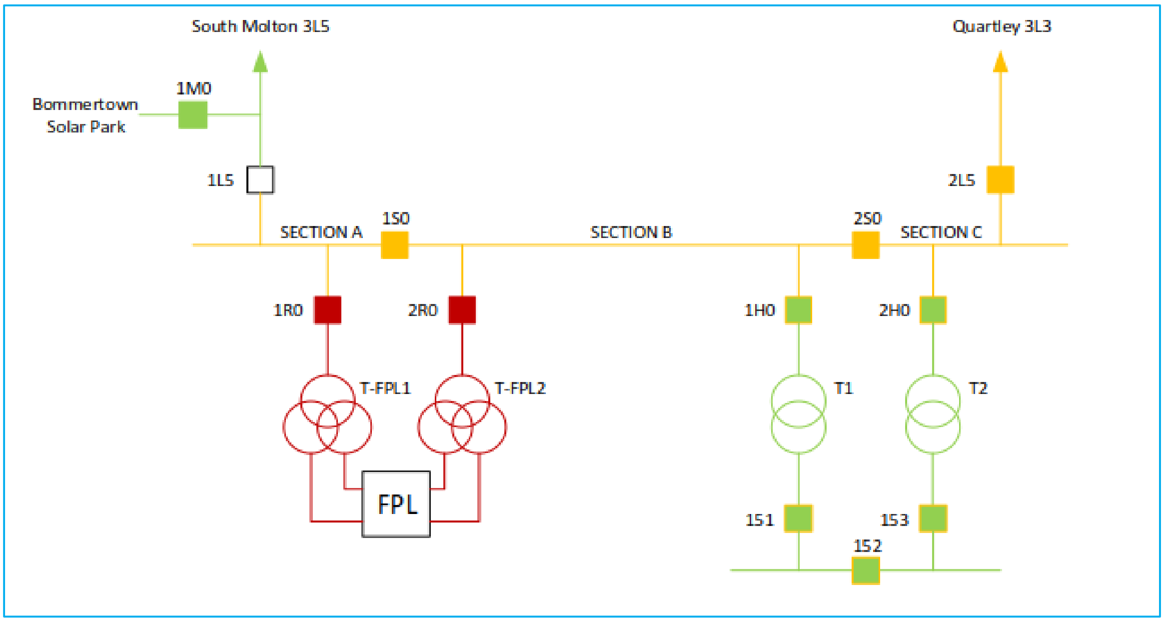

Figure 5-10: Bypass network configuration used for hot commissioning tests

Other special configurations were developed for conducting voltage measurement tests during the energisation of the FPL onto the live network for the first time.

Once all main circuit components had been energised and synchronised to the 33kV network, the local and remote-control inputs were tested before a full load test was carried out for 30 minutes. For this test the FPL was operated at its maximum power transfer capability with the power cycling between each side of the FPL through the 33kV network. Figure 5-11 shows a screen shot from the FPL HMI during the hot commissioning with the FPL transferring 20MW from one side to the other.

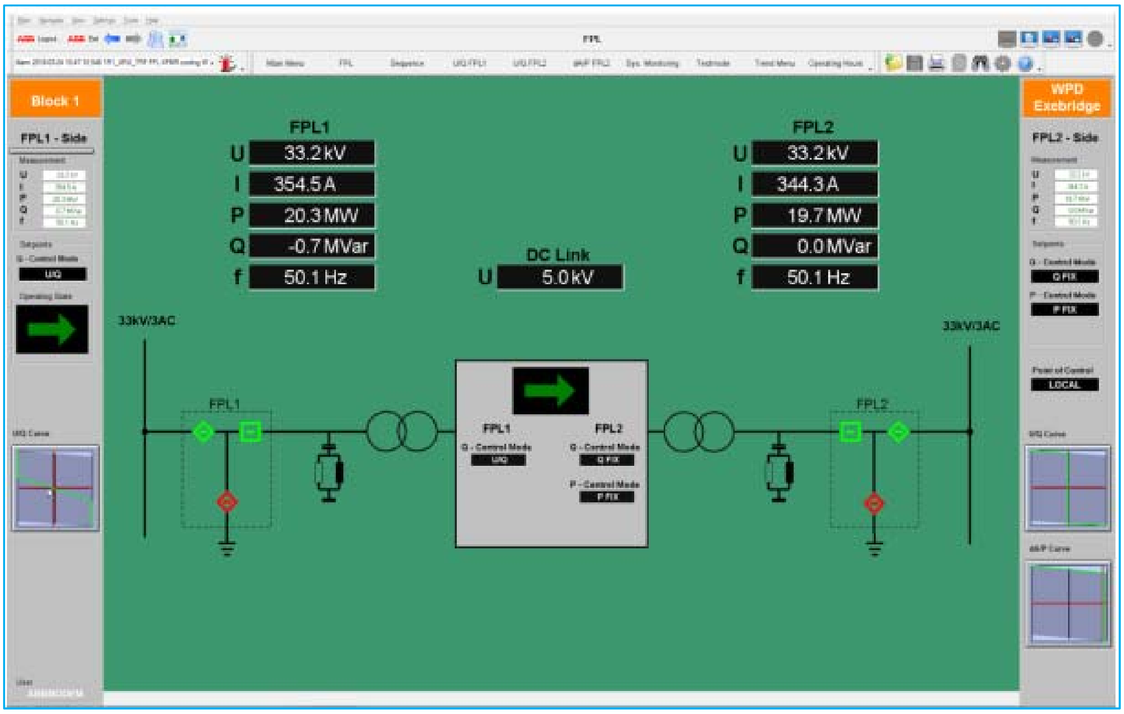

Figure 5-11: Screen shot of FPL HMI during Hot Commissioning

All hot commissioning tests were passed successfully without incident and a formal SAT was carried out.

5.2.3 Site Acceptance Tests

Each FPL component was subjected to an FAT to ensure compliance with the functional specification and planning limits. Due to the size of the FPL and technical limitation of the test facilities, a FAT of the complete FPL was impossible to undertake. To fully demonstrate the performance of the FPL, a set of contractually agreed SATs were completed post installation.

Functional tests carried out were:

- A heat run to test final cooling and auxiliary systems;
- Full power loss determination tests; and
- Maximum active and reactive power capability.

Heat Run Test

The heat run test was run for a period of four hours with no issues identified and no reduction in the FPL performance due to limitations of the cooling or auxiliary systems. A graph of the heat run test is shown in Figure 5-12.

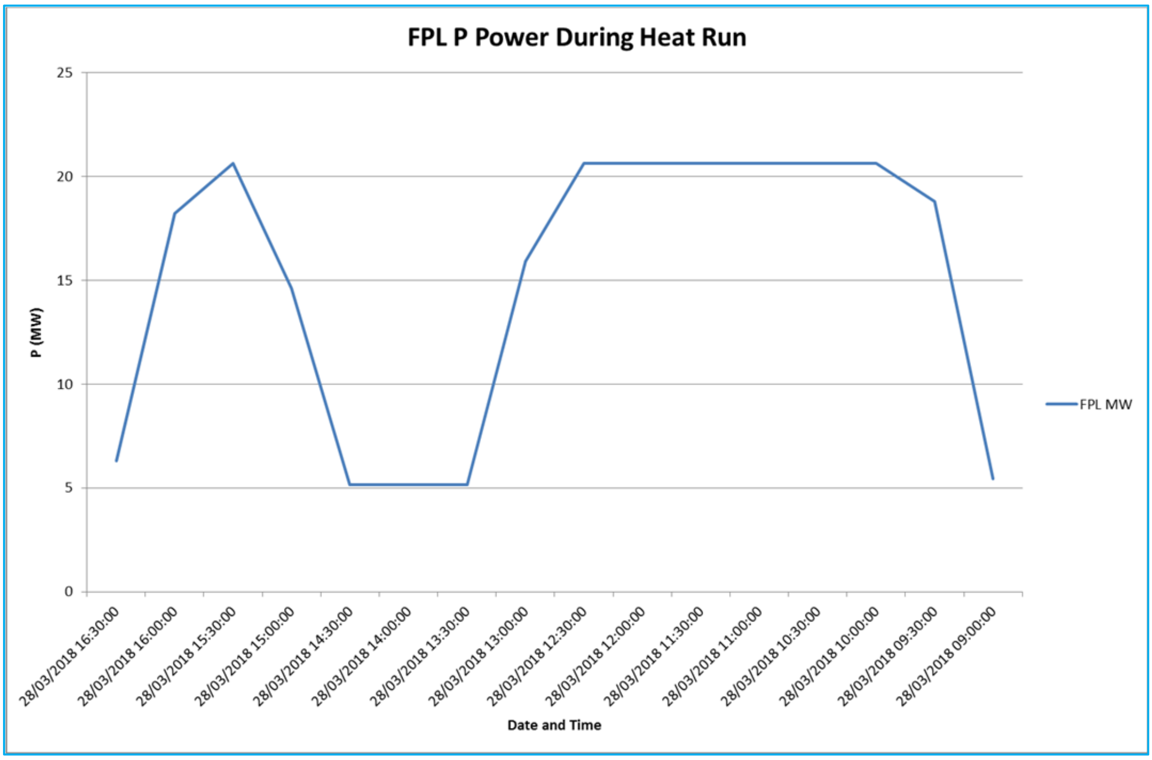

Figure 5-12: FPL Heat Run P Power

Power Loss Determination

The FPL power losses were calculated on site by transferring power through the FPL in both directions and then taking an average of the two results. This method, proposed by ABB, was reviewed and approved prior to testing.

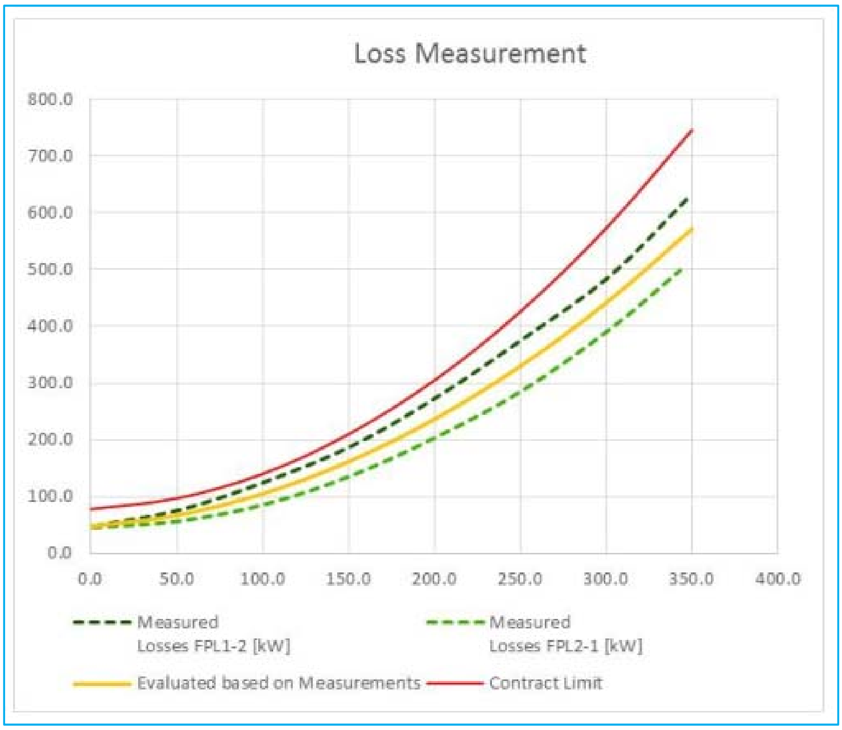

Figure 5-13: FPL Loss Measurement Test Result

Figure 5-13 shows the results graph for this test. The red line was the limit of losses as contractually agreed. The green dotted lines show the measured losses as power is transferred in each direction with the yellow line being the average of both measurements. This shows that the total FPL losses are within the contracted limit and in line with calculated results from the FAT.

Active and Reactive Power Capability

Figure 5-14 was produced from data measured during the whole SAT process to ensure that the 4-Quadrant operational on-site met the requirements of the functional specification and ABB's preliminary design work.

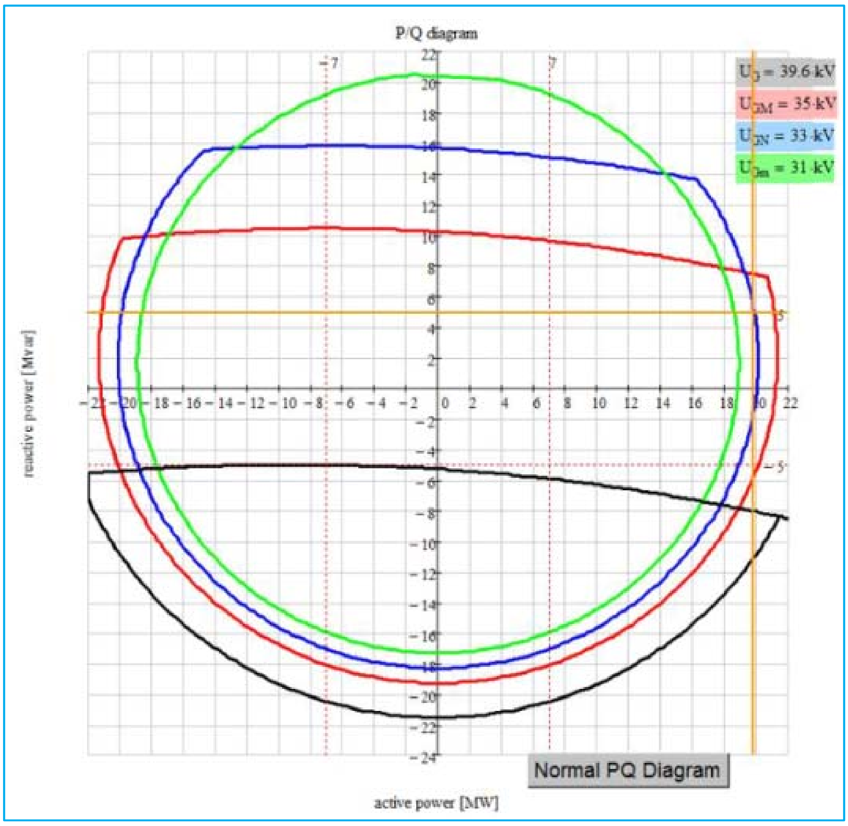

Figure 5-14: FPL Power Capability Graph from Site Acceptance Testing

The blue line shows the device active and reactive power capability at the nominal operating voltage of 33kV. The contractual P and Q capability of the device is 20MW and 5MVar at nominal voltage; this is successfully demonstrated by the intersecting of the two orange lines and blue curve in the upper right quadrant.

Emissions Testing

The following emissions tests were completed to ensure that the system was operating within planning and safety limits.

Electromagnetic Field

The device EMF emissions were tested to ensure that levels were below 500µT, which is a safe level for occasional access personnel with medical implants. Measurements were taken at various points around the complete FPL to ensure compliance. Figure 5-15 shows the EMF test results for the FPL with a maximum recorded field of 391µT.

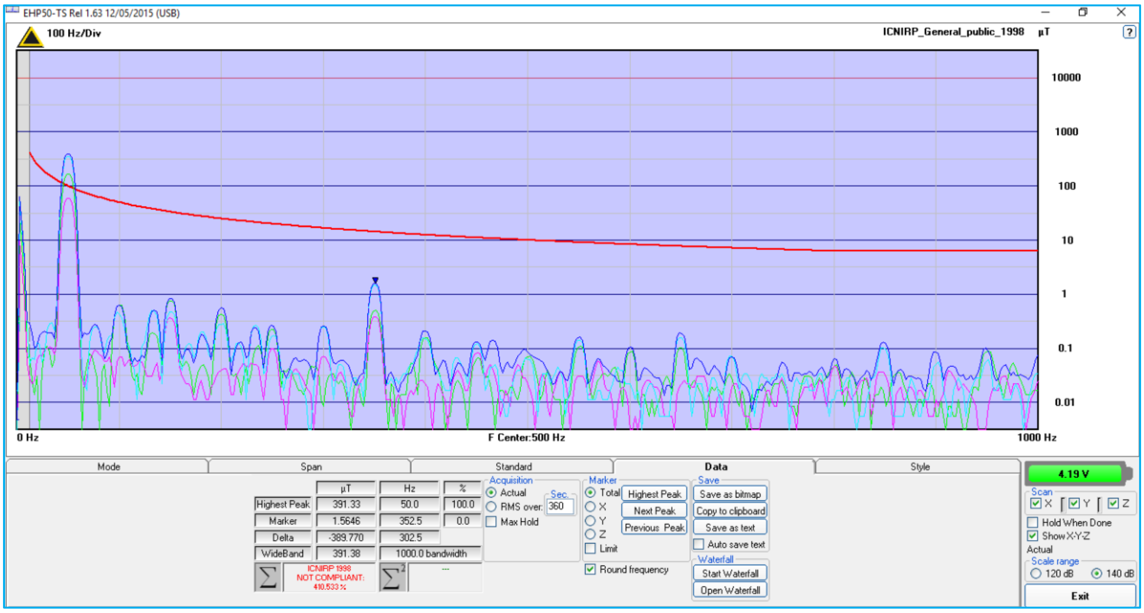

Figure 5-15: EMF Test results for the FPL

Sound Power Levels

Noise measurements were carried out with the FPL operating at maximum power transfer capability to ensure that at 1.5 metres from all equipment the sound power was within the 80dB limit. Figure 5-16 shows the results from the sound power assessment completed at Exebridge.

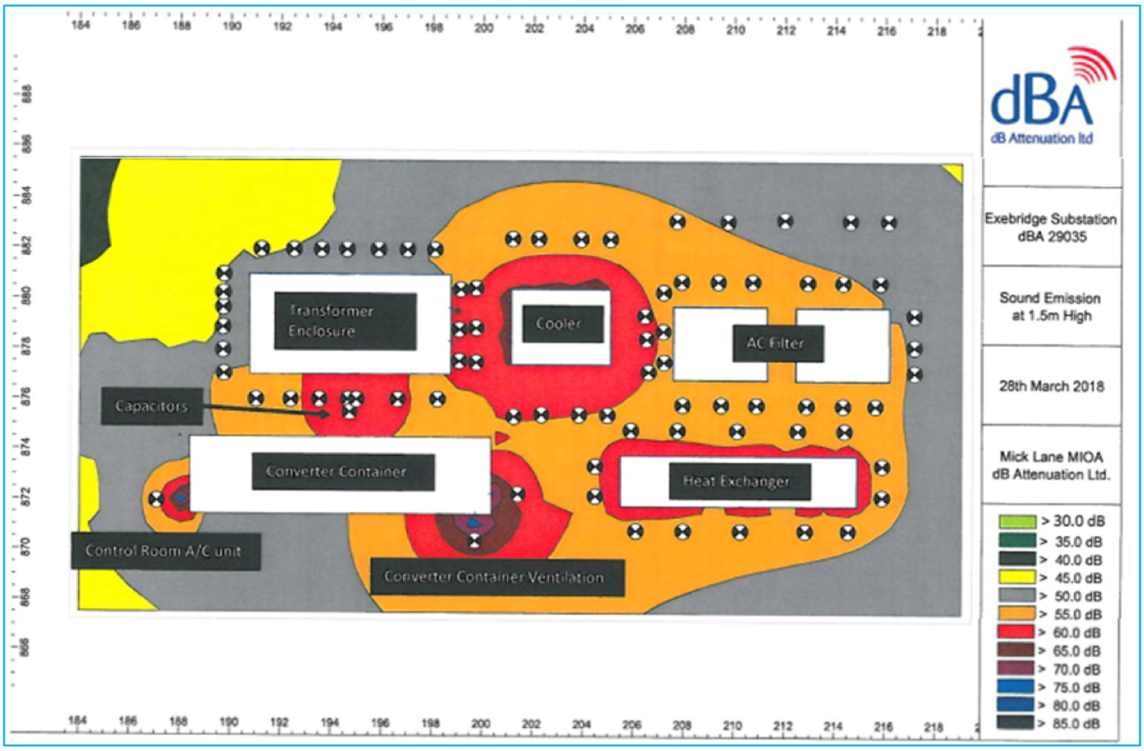

Figure 5-16: Sound Emissions with FPL Operating at Maximum Power Output

Harmonic Distortions

To ensure the harmonics produced by the FPL remained within planning levels according to the methodology in ER G5/4, harmonic measurements were taken on site with the FPL in operation. The results from the survey are shown in Figure 5-17 with the blue line showing the planning limits and the red lines the measured total harmonics at the 33kV connection point of the FPL.

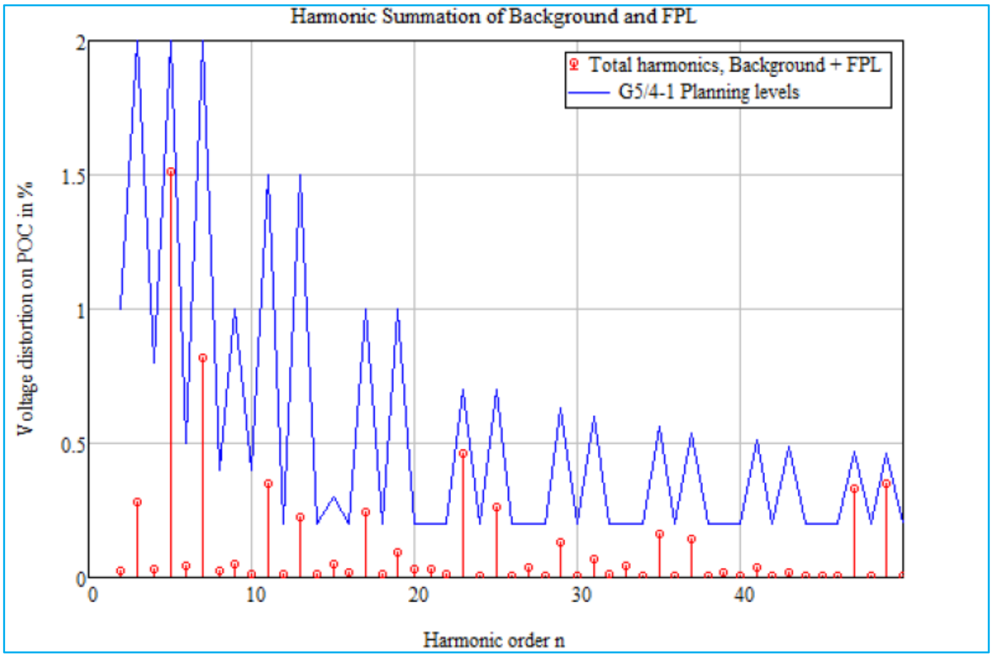

Figure 5-17: Harmonic Survey Results post FPL installation

All tests were passed with the device operating within the agreed planning and safety limits.

5.3 Initial operation

Operation of the FPL was split into two periods of time; open-loop and closed loop testing. Open loop testing set the FPL output at a fixed value and the FPL CM calculated set points but did not send these to the FPL. This provided a long term “soak” test of both systems, testing the resilience of the FPL device to network events and the stability of the FPL CM and ICCP data connection. Operation of the FPL in the mode, where P was fixed at 5MW is shown in Figure 5-18.

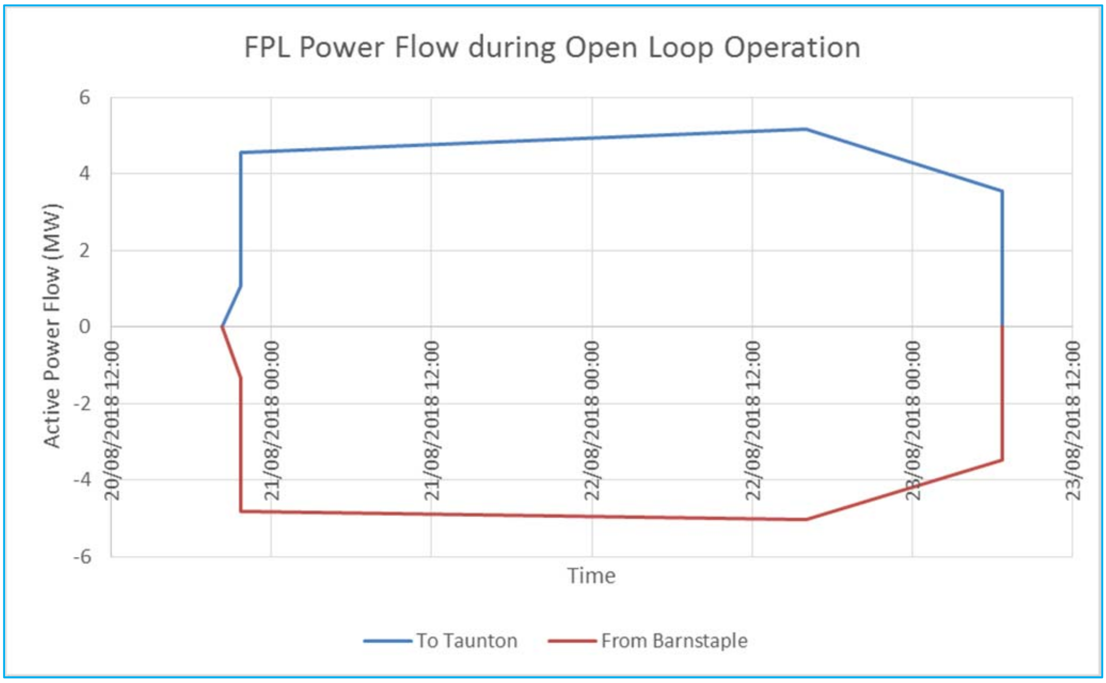

Figure 5-18: FPL Operating at Fixed P

Closed loop testing placed the operation of the FPL under the automatic control of the FPL CM. Closed Loop operation began on 10th September 2018 following a final commissioning process and confirmation of the Operation and Control Policy. The first set points from the FPL CM were sent that afternoon when a thermal violation was identified on the grid transformers at Taunton BSP. This violation was being caused by an increase in demand and was repeated each day with the FPL supplying power (acting as a generator) to assist with this daily peak.

6.0 Evaluation of the Performance and Capacity Released

6.1 Overview

The FPL device and FPL CM were monitored during the long term open and closed loop operation to evaluate their performance and effect on the network. This analysis focused on the effect of the power transfers, P and Q, on each BSP network, the reliability and availability of both systems. Power System studies using network and FPL operation data were completed to estimate the additional generation capacity that has been released by the FPL.

6.2 FPL Performance

In order to fully test the operation of the FPL the system violation limits of the network assets have been reduced compared to what they would be on a business as usual implementation; this has allowed us to drive the FPL in to operation and present the following information.

The operational performance seen from the FPL has predominately focussed on the real power (P) transfer. This is principally due to the volume of generation located on the Barnstaple side of the FPL network and the load dominated network on the Taunton side. Due to this the transfer of real power has generally aligned with large load utilisation of the system; Figure 6-1 shows the performance of the FPL. It can be seen that the utilisation of the FPL centres on morning and evening peak demands when considering the loads at both Barnstaple and Taunton BSP as indicated in Figure 6-2 and Figure 6-3.

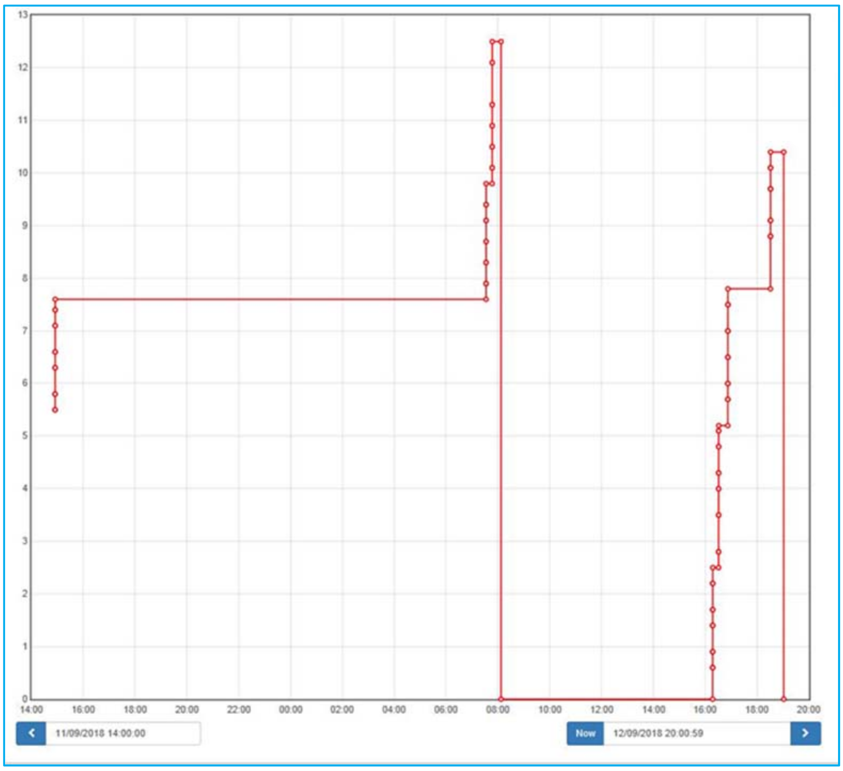

Figure 6-1: Real Transfer Performance of FPL (MW)

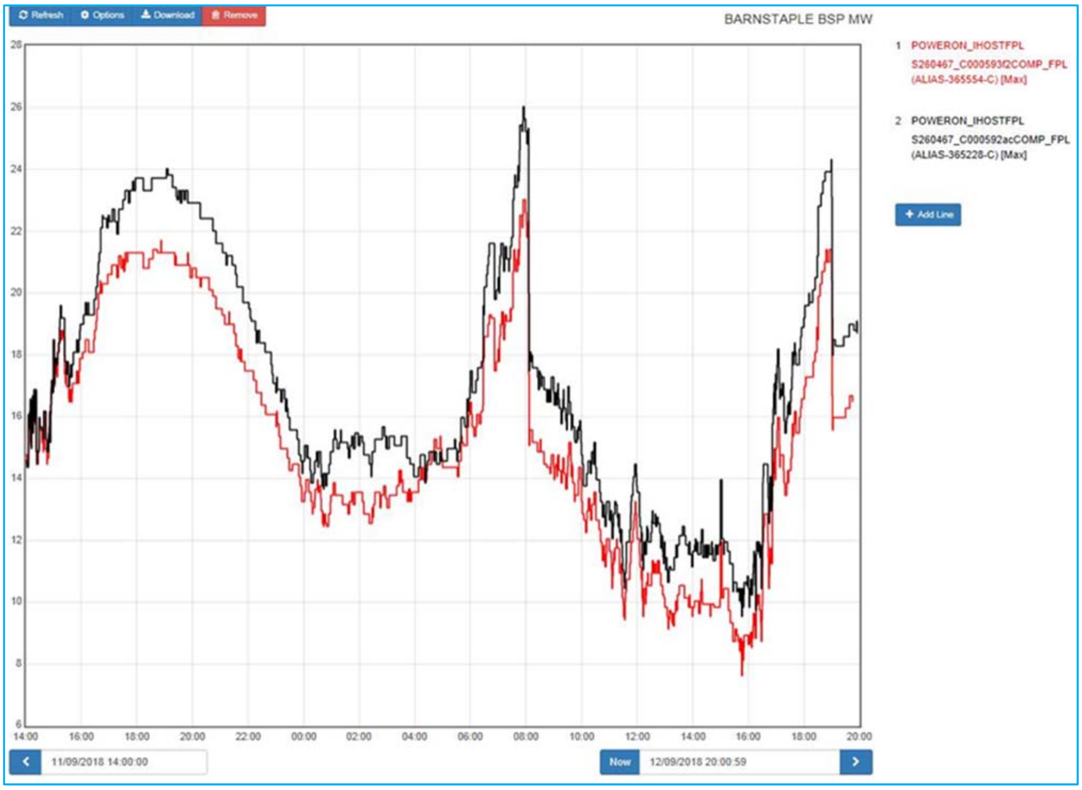

Figure 6-2: Barnstaple BSP Power (MW)

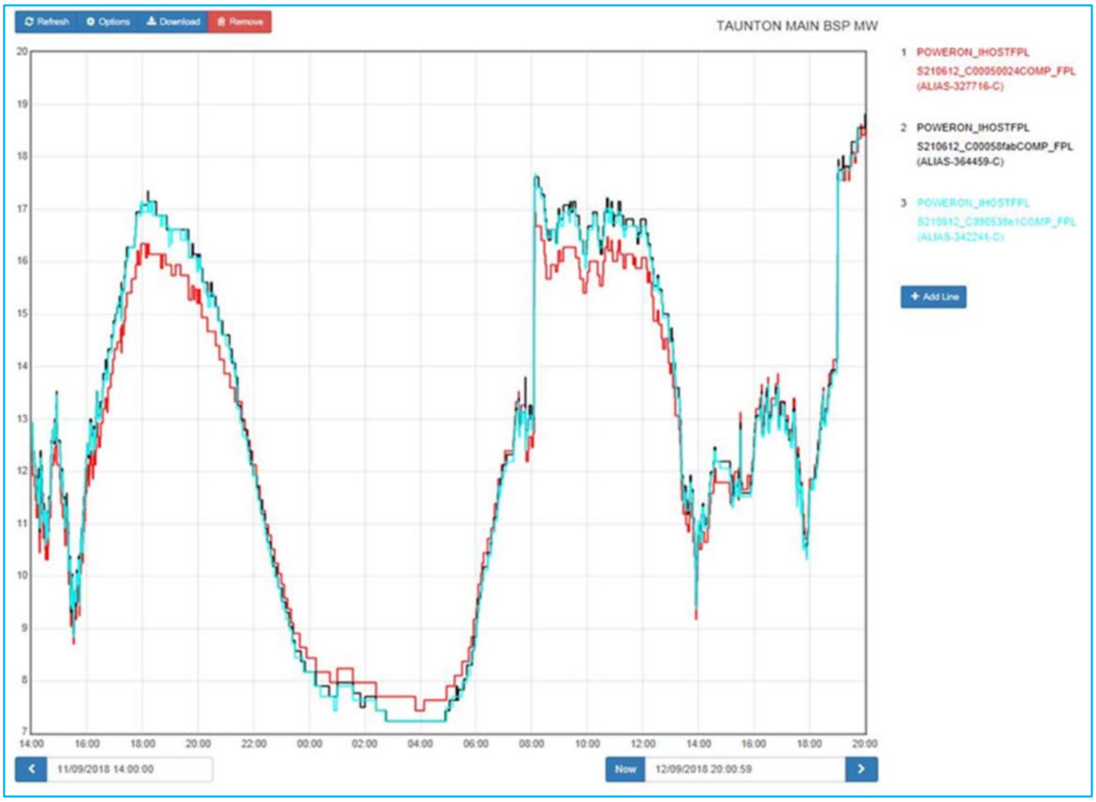

Figure 6-3: Taunton BSP Power (MW)

The graphs show that at times of high load on Taunton BSP, the FPL transfers between 10.5MW and 12.5MW from Barnstaple BSP.

Throughout both open and closed loop testing the FPL device proved reliable with no periods of unavailability caused by issues with the device. On several occasions the device automatically shut down for a short period of time. Following analysis of the FPL, FPL CM and NMS data logs the issue was identified as being caused by the trip operation and auto reclose of the 11kV switchgear. This caused the loss of the LV supply to the FPL auxiliary systems including the cooling system. Further analysis showed that the trip events were a regular occurrence on the breaker supplying the LV substation for the FPL.

Modifications were made the to the LVAC connections to transfer the critical FPL supplies onto the other distribution substation supplied by a section of network with a greater reliability. Since the change there has been no further period of unavailability of the FPL device.

The FPL CM was available and operational throughout the open and closed loop testing period. On two occasions during open loop testing, due to maintenance activities on the network, the FPL CM triggered a stage 2 alarm caused by the closure of a remote normally open point. Following this, further guidance information was produced for control and operational engineers to ensure that switching operations at defined locations are completed within a defined time, or ensures the FPL is disabled prior to starting work.

Figure 6-4 provides a snapshot of the FPL CM interface. The availability for the project team and wider support staff to visualise the status and operational performance has been particularly useful, especially the capturing of data at 10 second internals for the purpose of detailed analysis.

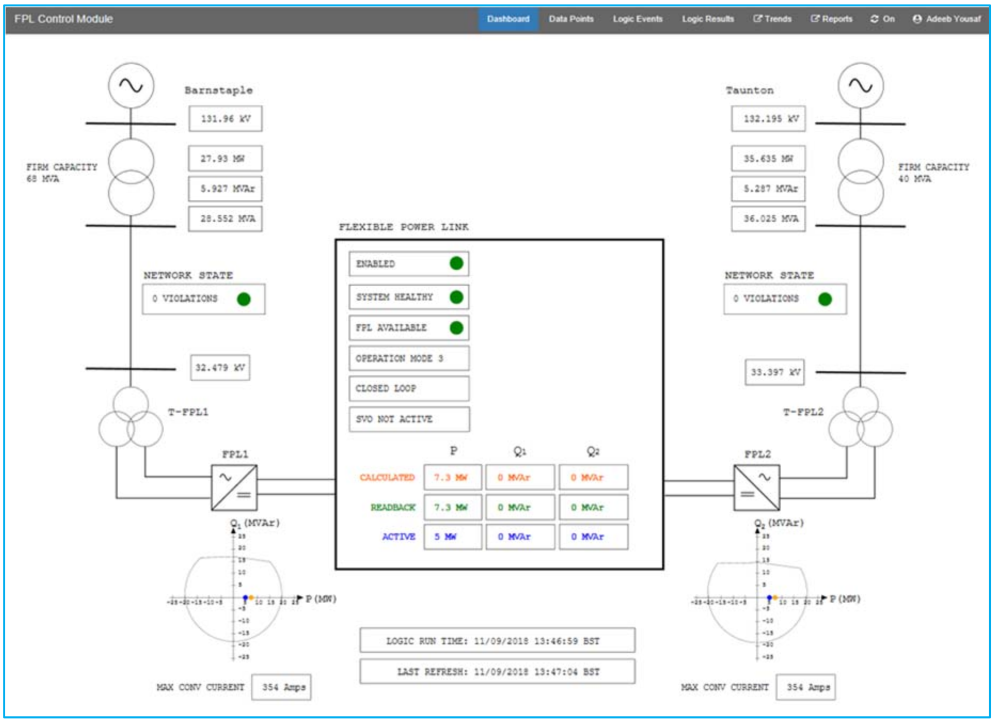

Figure 6-4: FPL CM Screenshot

6.3 Capacity Released

Previous analysis of the capacity released from the implementation of an FPL was presented in SDRC-4, whereby for the specific implementation between Barnstaple and Taunton was completed. Figure 6-5 shows the analysis carried out in SDRC-4, specifically Barnstaple-Taunton 2 relates directly to the FPL install at Exebridge primary substation.

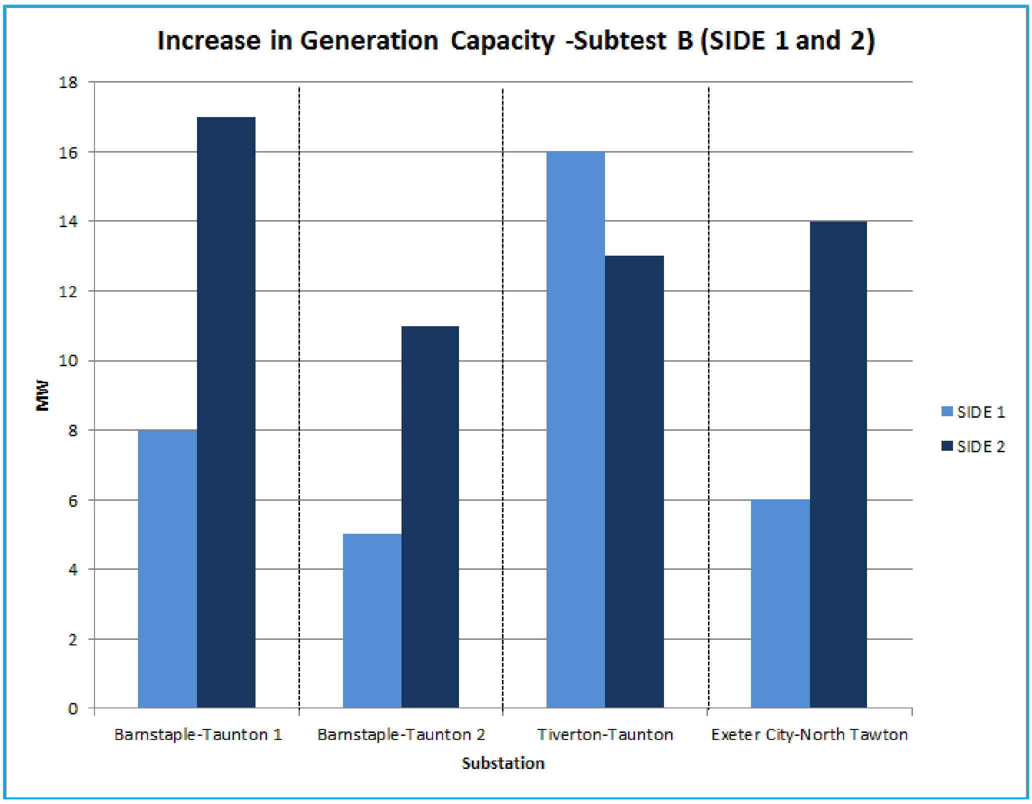

Figure 6-5: Increase in generation capacity flexibility using FPL

Following the implementation of the FPL and the development of a PSA FPL tool updated capacity release figures have been generated. The figures presented in SDRC-4 have now increased from 5MW to 6.5MW and 11MW to 13.5MW; these values represent a transfer between Barnstaple and Taunton and Taunton and Barnstaple respectively.

The operation of the FPL will continue to be monitored and analysed, which will provide the opportunity to further understand the performance characteristics and capacity release capability of the device.

7.0 Guide to Implementation and Use of the FPL

Building on the detail regarding the implementation and use of the FPL captured in the Technology and Integration Design sections, this section summarises the information to inform on a further FPL implementation.

7.1 Connection Arrangement

As the FPL is fundamentally designed to connect across a NOP between two networks following detailed design analysis captured in SDRC-3 and the implementation of the FPL at Exebridge substation, the recommended connection arrangement is shown in Figure 7-1.

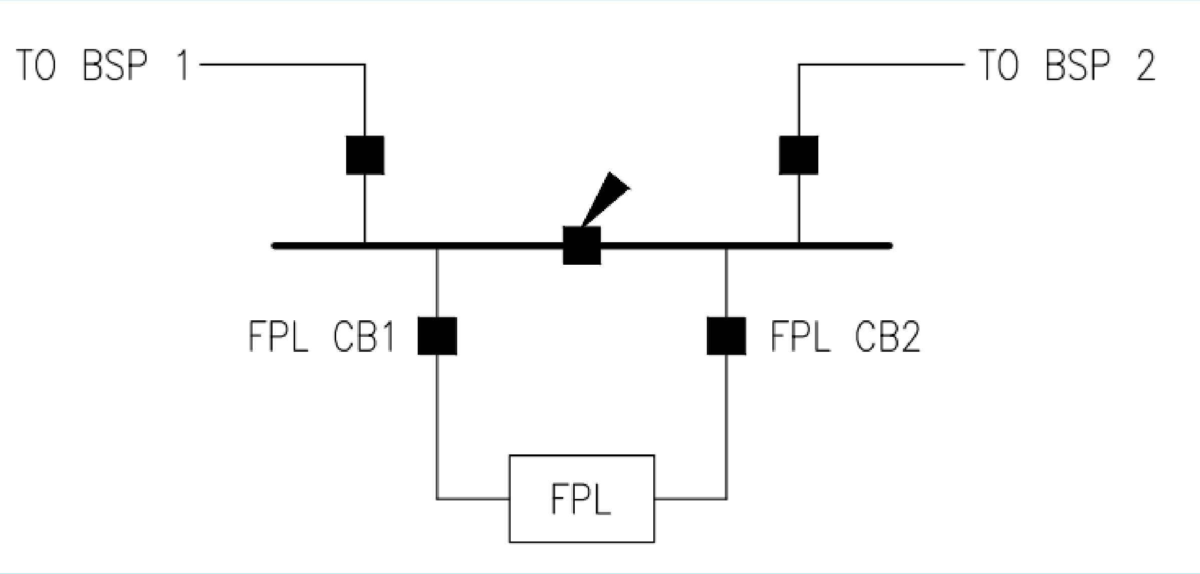

Figure 7-1: Proposed FPL Connection Method

This five-panel switchboard arrangement maintains the NOP between the two networks with the FPL operating in parallel across it. The two incoming CBs from the BSPs provide backup isolation capabilities for the device in case of an FPL CB failing to open. This is particularly useful as the operation of the FPL on the distribution network is still in its infancy; however, following greater operational experience the need for additional circuit breakers may be removed.

It is possible to position the FPL at a different location to the existing NOP while maintaining the existing operational functionality. Any change to the NOP location should be studied to ensure that any there is no detrimental effect to customers from connecting to a different BSP.

7.2 Network Considerations

When determining the suitability of an FPL installation, the effect on the wider network must be considered. The FPL power transfer capability is limited by the thermal capacity of the connected network, most likely of the cables and overhead line circuits. Maximum benefit of the FPL is achieved when the adjoining networks have a large discrepancy in available generation capacity. Studies should be carried out to determine the maximum device capability with detailed analysis using historical time series data completed to show the actual device performance.

For the wider network, the FPL will alter the power flow within the network and is likely to be of a capacity to support large demand groups. Existing network protection schemes should be reviewed to account for the change in power flow and potential islanding. This would require intertrip schemes to be developed with the installation of communications networks to carry protection signals.

To provide a high level of accuracy in the FPL operation, network measurement data is required at the 33kV connection points of all primary transformers and of 33kV connected customers. The quality and availability of measurement data should be analysed to determine if the installation or upgrade to existing measurement devices is needed to meet requirements. Data is also required from the 132kV network supplying the BSP transformers to provide suitable data for state estimation studies to be run.

7.3 Use of the FPL

The FPL transfers real power from one network to another while controlling reactive power on both networks independently. Real power transfers have the effect of increasing generation headroom on one network while reducing demand on the other. This allows increased generation connection or output on networks that are thermally limited while reducing total demand on the BSP transformers on the adjoining network.

The ability of the FPL to independently control reactive power on both sides enables the device to provide voltage control support on both networks. This has the effect of assisting with the management of voltage drop on long radial feeders and reducing the voltage rise caused from the connection of generation. This removes some of the reliance at a local level on the control of voltage by the BSP transformer.

The FPL creates parallel connections between two networks without the passage of fault current. Many NOPs between BSP networks occur at primary substations with customers often supported by a single transformer from either the splitting of the transformers or by opening the HV circuit breaker leaving a transformer on “hot standby”. The installation of an FPL on an incoming 33kV circuit enables the substation to operate in parallel increasing the security of supply to customers and maximising the available capacity through the full use of installed assets.

8.0 Key considerations for incorporating FPLs across 11kV networks

8.1 Overview

The trial of an FPL as part of Network Equilibrium has demonstrated significant benefits and yielded valuable learning on how to integrate and operate these devices on the 33kV distribution network. The trial has also increased the Technology Readiness Level (TRL) of the FPL technology and has given DNOs the tools to consider 33kV FPLs as part of their system offering. As a result of the trial, it has been identified that the FPL technology could be adapted and applied for use on the 11kV distribution network, unlocking significant additional benefits for DNOs and their customers.

This section describes the key technical considerations for developing and integrating an FPL on the 11kV distribution network and the benefits that could be achieved by utilising this technology on the 11kV system. The sections addressed are as follows:

- Need Case;
- Connection Configurations;
- 11kV FPL Technology;
- Integration Design; and
- Testing.

8.2 Need Case

Section 1.4 of this report detailed the advantages of installing an FPL on the 33kV network. Additional network capacity and network optimisation were able to be realised through the device to control real and reactive power flows between load dominated and generation dominated BSPs. Although the topology of the 11kV network is somewhat different to the 33kV network, similar advantages can also be realised when connecting an FPL to this lower distribution voltage level.

In the same way that the 33kV FPL allowed two distinct network groups to be connected together, installing an 11kV FPL to connect two network groups together would:

- Allow 11kV networks with differing vector groups to be connected together;
- Release capacity by balancing load and generation between two network groups;
- Provide voltage support at the network boundary points; and
- Control the passage of fault current during network events.

These advantages will provide DNOs and Distribution System Operators (DSOs) with a network which is more flexible, avoiding the need for traditional reinforcement to release capacity. With the distribution network becoming more active, alternative solutions which can offer dynamic control of the network, such as the FPL, will become commonplace.

It is also worth noting that the trials planned for UKPN's Active Response Network Innovation Competition (NIC) project will aim to establish the benefits of a back-to-back AC-DC converter on the 11kV network (using similar technology to the FPL).

8.3 Connection Configuration

8.3.1 Overview

The following section details the considerations when choosing how to connect an FPL to the 11kV network. As discussed in Section 8.2, the topology of the 11kV network is different to the 33kV network where the FPL was trialled. Initial studies have indicated that there are three main connection configurations that could be implemented to connect the FPL to 11kV network. These connection configurations are:

- **Configuration 1** – Interconnector between two primary substations;
- **Configuration 2** – Across a NOP between two circuits or two primary substations; and
- **Configuration 3** – Across the bus-section of a primary substation.

For each connection configuration there are a number of design factors that need to be considered to tailor the design of the FPL and control system and ensure the correct level of performance is achieved. Table 8-1 provides a list of the design factors that need to be considered.

Table 8-1: Design factors for 11kV FPL connection configuration

Item	Description
Rating	The continuous current rating of the FPL has to be chosen to coordinate with the rating of the circuit it is connected to. The ratings of circuits and equipment often reduces further downstream on the 11kV network. For instance, the busbars at the 11kV primary substation will rated to match the incoming transformers (typically 1250A or 2000A) with outgoing circuits rated at 630A. Downstream circuits typically carry less load and can be rated at 300-400A depending on circuit type and the seasonal load profile. Hence, the 11kV connection point of the FPL needs to be considered to ensure that the device rating is not over or under specified.
Vector Group	It is important to understand if the FPL will be connecting across different vector groups for the purposes of synchronising and ensuring there is a suitable interlocking procedure. 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). In this instance it is important that there is a recognised procedure and synchronisation process to ensure that the FPL can be safely connected and disconnected from the network.
Network Complexity	The successful operation of the FPL depends upon the accuracy of control system to calculate the optimum set-point. As such, the control system should aim to use as many real-time data points as

	possible to ensure the calculations are accurate. Connecting the FPL on a complex network with many variable data points will require a network model which is equally as complex. State estimation can be used to calculate values where measurement points are not available; however, this can create instability (especially if there are too many unknowns). Connecting an FPL directly to the busbars of a primary substation would not require such a complex control system as the network model would not need to include the downstream network. However, a complex control system would be required for applications where the FPL is embedded within the downstream network.
Voltage Support	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. Therefore, it is prudent to ensure that the FPL has sufficient levels of reactive power capability if connected downstream on the 11kV network.
Fault Current	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. paralleling between two adjacent busbars at a primary substation or across an interconnector between two primary substations). 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.

The following sections provide an overview of each of the three connection configurations for an 11kV FPL. Each configuration has been assessed against the factors above to give an indication of FPL capability as detailed in Table 8-2.

Table 8-2: FPL capability requirements

Factor	Description	Options
Rating	What rating is required for the FPL	Low Medium High
Vector Groups	Will the FPL need to work across different vector groups	Yes No
Network Complexity	How complex is the network the FPL is connecting to	Low Medium High
Voltage Support	What level of voltage support will the FPL have to provide	Low Medium High
Fault Current	Importance of the FPL to limit fault current	Low Medium High

8.3.2 Configuration 1 – Interconnector

Typically, primary substations are interconnected through NOPs which allow for the transfer of load in the event of an outage. In some instances, interconnection is relied upon for the restoration of demand for compliance with Engineering Recommendation P2/6 - Security of Supply. As such, a number of interconnectors with larger than average ratings can be found connecting primary substations to allow this transfer of demand.

Figure 8-1 shows an FPL connected within an interconnector between two separate primary substations. In this configuration, the FPL is designed to balance the load and generation between two primary substations.

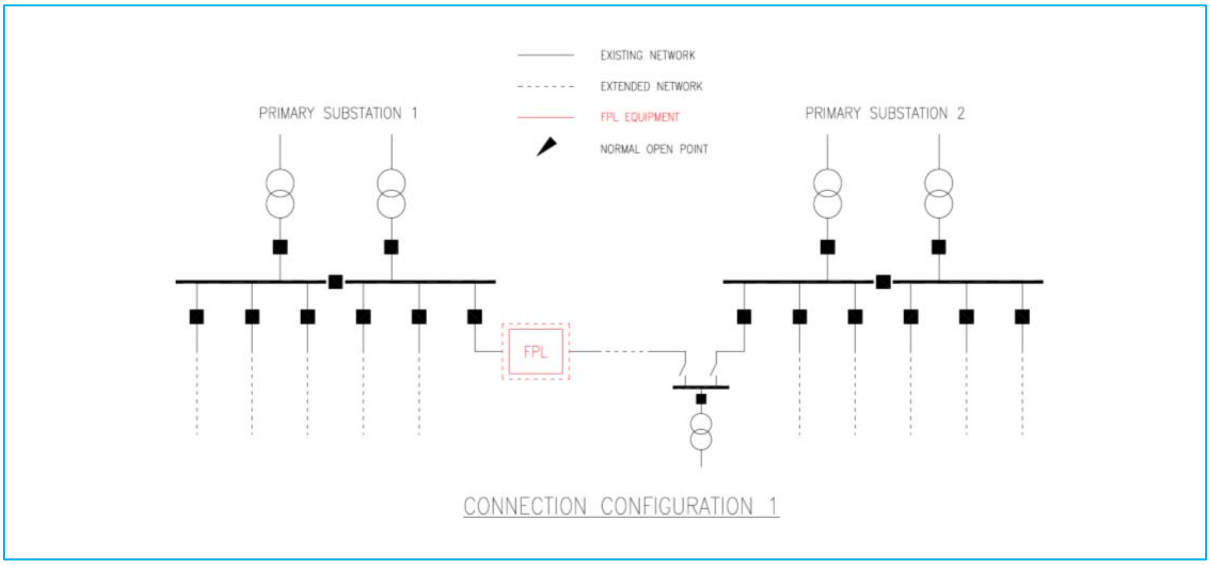

Figure 8-1: Connection Configuration 1 SLD

FPL Rating	Vector Groups	Network Complexity	Voltage Support	Fault Current
High	Yes	Medium	Medium	Medium

8.3.3 Configuration 2 – Normal Open Point

The distribution network is designed to have interconnection through NOPs to provide the required levels of flexibility for maintenance and fault events. The 11kV network supplied by a primary substation normally has several NOPs that provide separation between two circuits fed from the same primary substation or between circuits fed from different primary substations.

The diagram in Figure 8-2 shows an FPL connected between two circuits fed from the same primary, whereas Figure 8-3 shows the connection between circuits fed from different primary substations. For both configurations, the FPL provides a balance of load and generation across feeders.

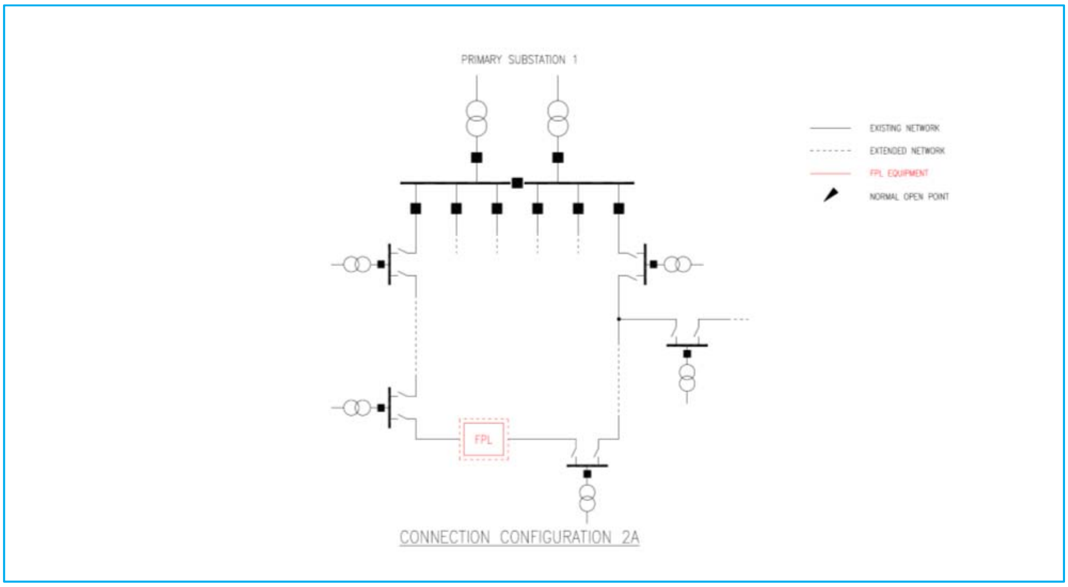

Figure 8-2: Connection Configuration 2A SLD

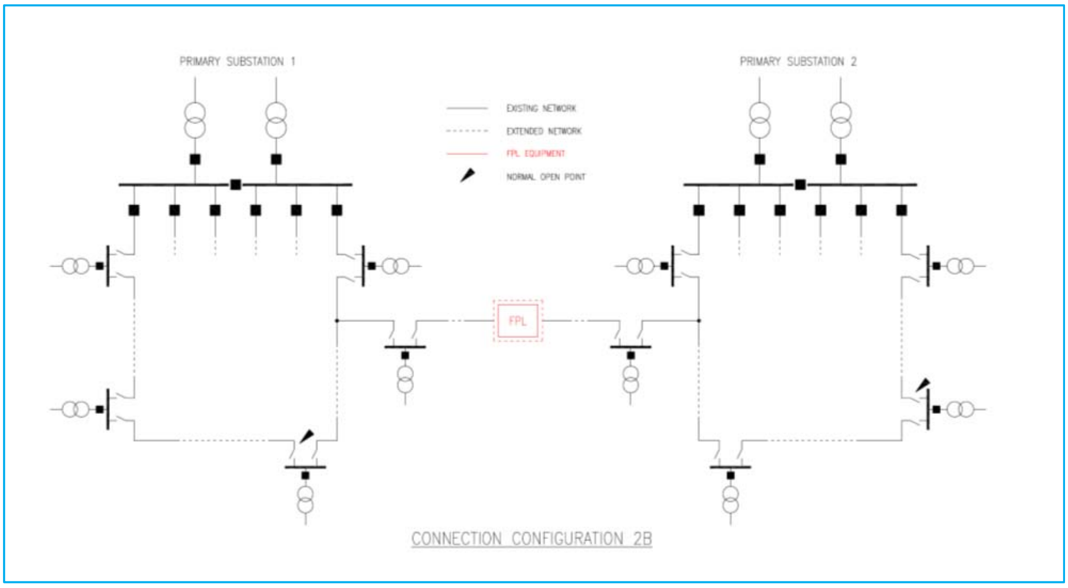

Figure 8-3: Connection Configuration 2B SLD

FPL Rating	Vector Groups	Network Complexity	Voltage Support	Fault Current
Medium	Yes	High	High	Medium

8.3.4 Configuration 3 – Across a bus-section

Most primary substations have two or more transformers to provide security of supply during outages. Parallel operation of transformers through a bus-section circuit breaker can occasionally result in fault levels exceeding equipment ratings. In these instances the bus-section circuit breaker is operated “normally open” to limit the fault level contributions. However, the operation of substations in this configuration can lead to an imbalance in load between transformers resulting in higher losses and accelerated ageing of assets.

Figure 8-4 shows an FPL connected across a bus-section of an 11kV switchboard at a primary substation. The FPL has been integrated within an interconnector between each side of the 11kV switchboard. In this configuration the FPL ensures there is an equal balance between power flows on each transformer without exceeding fault levels.

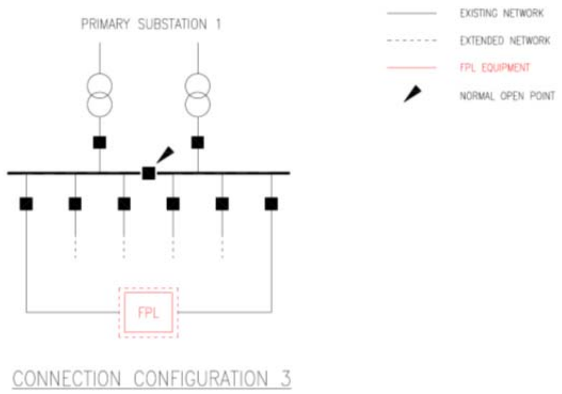

Figure 8-4: Connection Configuration 3 SLD

FPL Rating	Vector Groups	Network Complexity	Voltage Support	Fault Current
High	No	Low	Low	High

8.4 FPL Technology

8.4.1 Overview

It is likely that there would need to be significant modification to the FPL technology in order to design a compact and cost effective solution for the 11kV distribution network. The rating, system architecture and protection/control philosophy would need to be studied and specified carefully in the new design to tailor them for the 11kV system.

The extent of the modifications will be dependent on which connection configuration is selected, the rating of the device and to what degree the device is required to be re-designed to become cost effective whilst still providing the required performance.

It is important to stress that the FPL technology will need to be re-specified and re-packaged to produce an 11kV FPL design. Therefore, studies 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.

8.4.2 Rating

The rating of the 11kV FPL will differ based on the connection configuration that is employed. In Configuration 1 (interconnector between two primary substations) the FPL will be located close to the primary 11kV busbars and therefore it is advisable that the rating of the device isn't lower than the 11kV switchgear rating in the primary substation. This is usually 630A for a standard 11kV feeder circuit breaker (but could be higher depending on the individual application).

In Configuration 2 (at the 11kV NOP) the FPL will most likely be located a large distance from the 11kV primary substation. In this instance, it may be possible to have a rating below 630A; however, care is to be taken to avoid ratings that match the rating of the adjacent circuits. This is to avoid the removal/replacement of the FPL if these circuits are reinforced with higher capacity conductors in the future. It is recommended that the rating of the FPL is to be no lower than 400A.

In Configuration 3 the FPL will be connected across the 11kV bus section of a primary substation. Therefore, the rating of the FPL will need to be no lower than the rating of the 11kV primary bus section circuit breaker. This is usually 2000A for a standard bus section circuit breaker.

8.4.3 Network Interface

The 33kV FPL required 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 the 11kV voltage level it may be possible connect the FPL directly to the 11kV network 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.

The technology that could facilitate this architecture is the multilevel converter. The multilevel converter is a scalable modular converter architecture. The converter modules are able to be stacked to provide the required voltage rating. This architecture is discussed further in Section 8.4.4 .

8.4.4 Converter Architecture

As discussed in Section 8.4.3, it may be possible to adapt the converter architecture to remove the need for a bulky transformer by interfacing the FPL directly to the 11kV network.

The multilevel converter architecture which facilitates this connection interface typically has a reduced power range when compared to other solutions; therefore an investigation is recommended to understand if this technology can be utilised for 11kV FPL current ratings identified in Section 8.4.2. An outline of the multilevel converter design is shown in Figure 8-5.

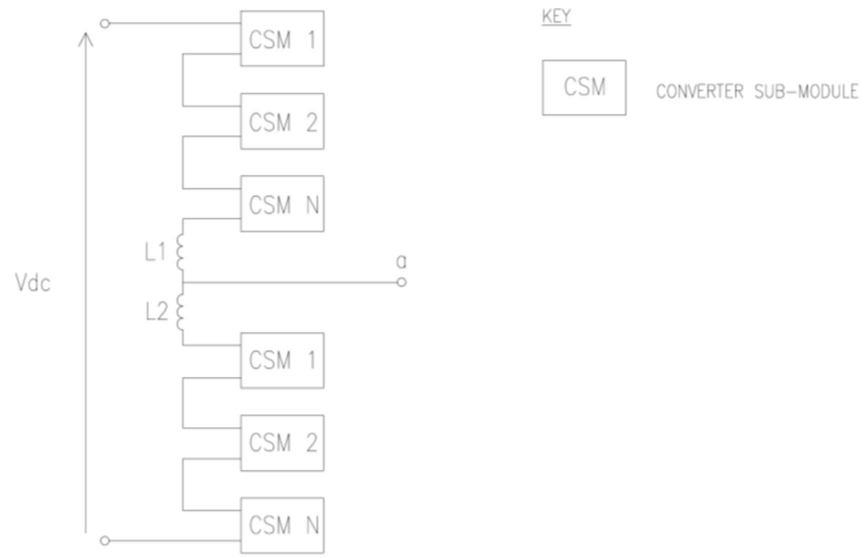

Figure 8-5: Multilevel converter architecture

If the converter transformer is kept as part of the design philosophy it is not anticipated that converter technology will change fundamentally from the 33kV FPL. There will be scope to miniaturise system components for the 11kV FPL based on the lower voltage level.

The 33kV FPL converter power electronics were controlled by dual redundant control units. In the 11kV unit it would likely be sufficient to have a single converter control unit to reduce the converter cost and aid with space efficiency.

It is recommended that a detailed evaluation of the converter architecture is implemented as a basis for informing the optimum design of an 11kV FPL.

8.4.5 Harmonic Filtering

If a multilevel converter architecture is adopted, it is possible the external harmonic grid filters similar to the ones used on the 33kV FPL could be omitted from the design. The multilevel converter provides an inherent smoothing of the waveforms via the capacitive components in the system. 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 each 11kV FPL rating (400A, 630A and 2000A) that would provide the required minimum voltage rating and harmonic performance. A cost benefit analysis would then have to be implemented to compare the costs of any additional modules with the space and cost saving of removing the external grid filters.

8.4.6 Thermal Management

The 33kV FPL utilised a large and complex water cooling system to ensure the converter temperature was maintained within safe limits at the devices rated current. The 11kV FPL will have a lower rated power level than the 33kV FPL therefore there may be opportunities to utilise forced air cooling systems to reduce the size of the installation. However, the 11kV

FPL will still have higher levels of current flow through the device when compared to the 33kV FPL. As such, air cooling may not generate the level of heat dissipation that is required. A further consideration with air cooling systems is that they are likely to generate more noise than water cooling.

It is recommended that a detailed study is implemented in conjunction with the converter architecture selection process. This will ensure that the optimum cooling solution is achieved to give sufficient thermal performance in the smallest physical footprint.

8.4.7 Switchgear

It is recommended that the 11kV FPL follows the same switchgear philosophy as the 33kV FPL. As described in Section 8.5.3, the device will have two 11kV feeder circuit breakers and a bypass circuit breaker. This configuration provides the appropriate level of control and flexibility for the operation of the FPL.

8.4.8 Housing

One of the key design principles for successful deployment of ground mounted equipment on the 11kV network is standardisation of the associated housing. A standardised 11kV FPL housing should be a key aim for the development of this device. It should be developed and sized to include the 11kV FPL switchgear. This will be key for connection configurations 1 and 2 where the FPL is installed remote from the 11kV primary substation and hence the switchgear cannot be installed locally at the primary substation.

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. The housing shall be designed to facilitate this optimum layout and ensure the equipment is suitably protected from the external environment.

8.4.9 Interlocking

The 11kV FPL shall be fitted with an interlocking system to ensure that the device is isolated and earthed prior to an operator being granted access to any exposed 11kV conductors or converter parts.

8.4.10 DC Link Pre-charging

The 33kV FPL had an integrated pre-charger unit that ramped the FPL dc link voltage up to nominal dc voltage prior to the energisation of the FPL to the grid. This device was supplied from the local substation LV supply. This process energised the windings of the FPL transformer to avoid large magnetic inrush currents when the FPL circuit breakers are synchronised to the network.

It is unlikely that magnetic inrush will be a major consideration for an 11kV FPL as any interfacing transformer will be much smaller in size and will draw a much smaller magnetising current when compared to the 33kV device. 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.

8.4.11 FPL Control Module

The FPL Control Module is a key element of the 33kV FPL system. Its purpose is to generate set-points for the FPL to remove voltage and/or thermal violations that are either measured or estimated on the network through the use of a power systems model of the network area.

There would be significant challenges to replicate the 33kV control architecture on the 11kV FPL. These are as follows:

1. An accurate power systems model of the 11kV network would have to be produced and maintained for each FPL installation. At 11kV this becomes more difficult as the network is significantly larger and more interconnected; and
2. The 33kV FPL Control Module was able to receive circuit breaker statuses as well as reliable voltage, current and real/reactive power analogues from the NMS. The 11kV network has much less monitoring and as such the system may rely more heavily on state estimation.

A simplified control architecture would be recommended for the development of an 11kV FPL which would also be tailored for the connection configuration of the device:

Configuration 1 – In this configuration a basic network model is required. Select binary and analogue measurements from the switchgear and transformers at the primary substations could be acquired directly and used as inputs to the control system which could be located locally at the FPL. The interface with the NMS would be used for basic control, alarm and trip signals via the station RTU. This architecture is described visually in Figure 8-6.

Configuration 2 – In this configuration the FPL is installed at the NOP and is remote from the primary substations. A centralised FPL Control Module is best suited in this configuration. A model of the surrounding 11kV network would be required to be produced and maintained as part of the Control Module. The boundaries of the network model will have to be carefully defined to ensure that the FPL behaves in a stable fashion. This architecture broadly similar to configuration 1 and is described visually in Figure 8-6.

Configuration 3 – This will be the simplest configuration to control. The FPL is balancing load across busbars whilst acting as a fault current limiter. Therefore the Control Module shall be situated locally to enable the appropriate speed of operation. The system will only need binary and analogue inputs from the local substation to perform its function. This architecture is described visually in Figure 8-7.

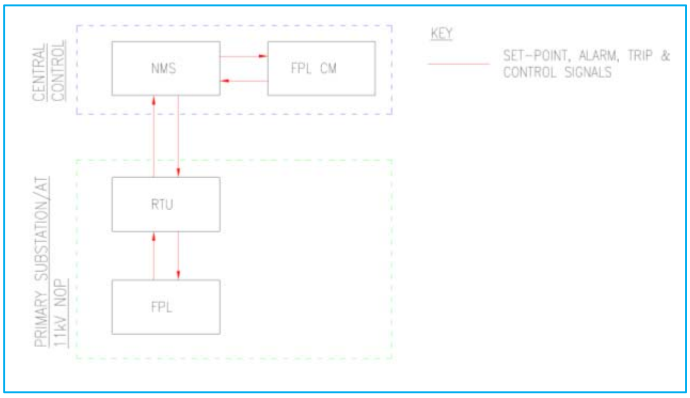

Figure 8-6: FPL Control Module interface - Configurations 1 and 2

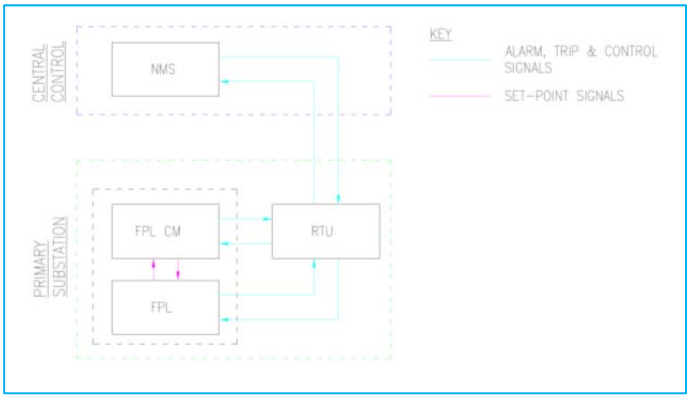

Figure 8-7: FPL Control Module interface - Configuration 3

8.5 Integration Design

8.5.1 Overview

The next consideration after a choosing the desired connection configuration is how to integrate the FPL with the surrounding network. There are a number of parameters that need to be considered to ensure that the FPL can be physically installed and ensure optimum performance.

The following sections describe the high level areas that need to be considered.

8.5.2 Site location

Having a suitable location for the FPL is critical to ensuring safe installation and ongoing operation / maintenance of the device. Selection of the site will follow the same principles that were considered for the 33kV FPL as detailed in SDRC-3.

The learning from the installation of the 33kV FPL has shown that selecting an existing site with adequate spare space is a preferred solution as the device can be readily integrated with the surrounding network. In addition, the following factors should also be considered:

- **Access** – providing suitable clearance around the device for maintenance and operation is paramount to ensure safe working conditions. It is also important to carefully consider the access and space arrangements required during the installation and commissioning phases (i.e. off-loading of equipment, storage of tools, equipment and spares etc.).

- **Surrounding area** – the additional noise generated from the FPL and ancillary equipment could be intrusive for surrounding neighbours (even if sound levels are within specified limits). If the FPL is located in close proximity to a built up area, consideration should be given to measuring background noise levels and installing acoustic enclosures if necessary. In addition, the visual impact of a new FPL installation could have a detrimental impression on surrounding neighbours. Therefore, consideration should be given to making the installation to improve visual amenity.
- **Future Projects** – a key consideration when selecting a suitable site for the FPL is the potential for the installation to impact on future works. For example, if the FPL were to be installed within a primary substation there could be a possibility that transformers at this site may need to be replaced in the future. Therefore, it is important to ensure that the FPL installation is planned to allow future works to be safely carried out with minimal impact to the network.

8.5.3 Network connection

Another key consideration for integrating an FPL is the physical connection to the 11kV network. The integration design should ensure that the FPL can be fully controlled both locally and remotely via the FPL controller or NMS. The connection shall also be designed such that the FPL can be bypassed for maintenance activities.

The FPL requires a number of different interfaces with the network to ensure full operation and control can be achieved. These interfaces are:

- **HV connection** – the physical 11kV connections to the network;
- **HV control** – circuit breakers are required at both sides of the FPL to allow for automatic synchronisation and protection;
- **Voltage references** – voltage reference points are required at both sides of each FPL circuit breaker to ensure that the FPL can synchronise and for monitoring purposes;
- **Current references** – the FPL relies upon measurements of current for control and protection purposes; and
- **Status** – the FPL requires information on the status (open/closed) of circuit breakers and/or switches to inform the automatic control and protection systems.

There are also a number of interfaces with the protection and control systems which are covered in the following sections.

Figure 8-8 provides an outline SLD of the physical requirements for an FPL network connection. In the example, circuit breakers have been used to control and bypass the FPL. An alternative solution could involve using Ring Main Units (RMUs) which are prominent on the 11kV network. However, the number of interface points and the speed of operation may mean that network connections using RMU are difficult to achieve in practice.

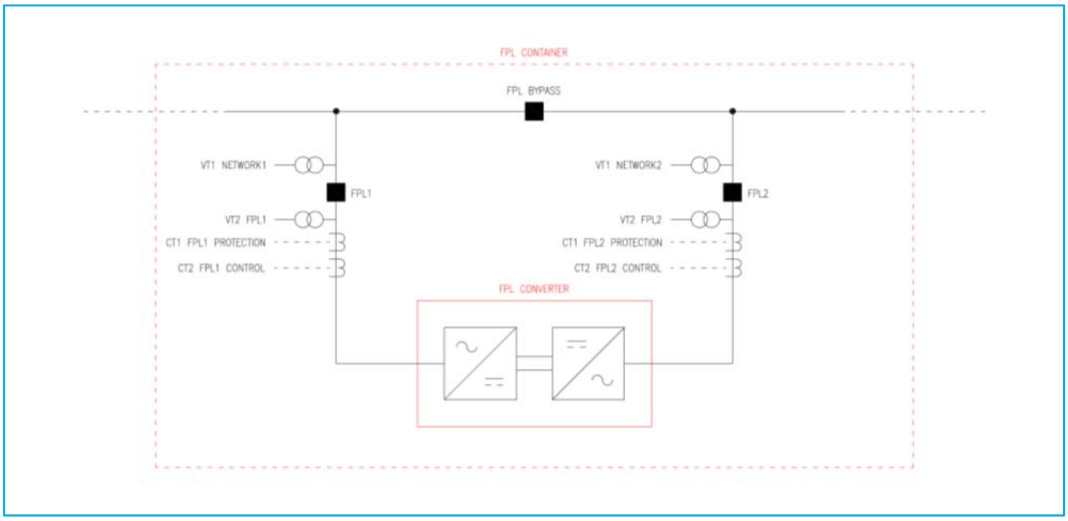

Figure 8-8: Outline SLD of 11kV FPL

8.5.4 Protection

The connection of the 33kV FPL at Exebridge required a number of protection modifications to be made to ensure that performance of the network was not compromised. The two key elements with regards to protection were:

1. Ensuring that the 33kV network was protected from events associated with the FPL; and
2. Ensuring the FPL was protected against events associated with the surrounding network.

These two elements are also applicable to an 11kV connected FPL. To achieve the first element, the FPL will have its own discrete protection which monitors the device and issues a trip signal to the FPL circuit breakers if it has to be disconnected from the network. The protection system will also interface with the NMS to ensure that all alarm and trip events are seen by operatives and action can be taken if necessary. The alarm and trip indications for the 33kV FPL protection system were consolidated at the device to limit the volume of information being transferred to the NMS. For the 11kV FPL further consolidation could be applied to reduce this information further.

The second protection element for the integration of the 33kV FPL involved an intertrip scheme as discussed in Section 3.4.1. This intertrip scheme ensured that the FPL would be disconnected for faults which would result in the FPL supplying an islanded network. Similarly, an equivalent intertrip scheme would be required for the 11kV network. In this instance, if the circuit breakers at the 11kV source were to trip, a signal would be sent to disconnect the FPL to ensure the network was not operating as an island. Figure 8-9 shows an example of how this would be achieved.

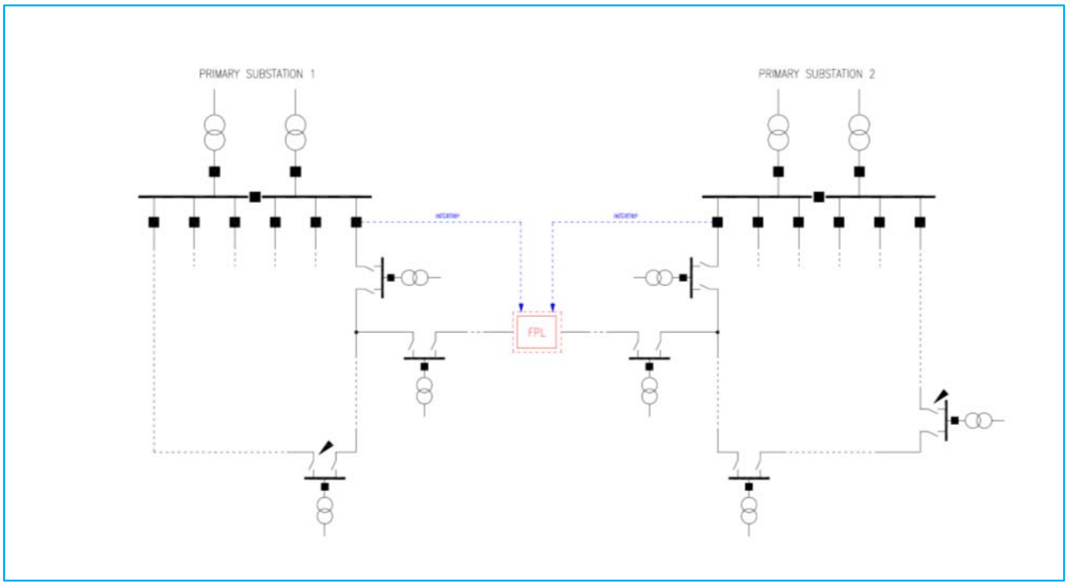

Figure 8-9: Example of intertripping for 11kV FPL

8.5.5 Communications

The 33kV FPL was connected at an existing primary substation which had established communications with the NMS. A new RTU was installed at the site due to the switchgear replacement that was carried out to integrate the FPL and this RTU was specified to communicate with the FPL over DNP3.0. In addition, the communication channel was upgraded from radio as there was existing fibre telecommunication infrastructure which passed immediately adjacent to the site. These upgrades provided the required level of reliability for 33kV FPL communications.

An 11kV FPL will also require a communication channel to the NMS and a similar interfacing protocol to an RTU. It is likely that for installations downstream on the network a new RTU will need to be installed, however, for installations at an existing primary substation the RTU may already be suitable (or require an upgrade). The level of reliability required for an 11kV FPL may not dictate the need for a fibre connection as was the case for the 33kV FPL trial. However, studies would need to be performed to ensure that the chosen communication channel provided a sufficient level of reliability to avoid the FPL from frequently disconnecting due to the lack of communications with the NMS.

8.5.6 Other interfaces

There are a number of other interfaces that should be considered to ensure the FPL operates correctly on the 11kV network. These are:

- **AVC scheme** – the FPL can actively control real and reactive on the 11kV network which will have an effect on system voltage. Similar to a large embedded generator, consideration should be given to integrating the output of the FPL with the primary substation automatic voltage control (AVC) scheme. This will ensure that both systems are working together, rather than against each other.
- **Switching scheme** – 11kV networks typically have automated switching schemes which aim to restore supplies in the event of a fault. As the FPL is likely to have an

impact on the performance of these schemes, it is imperative that the scheme is amended to include the FPL.

- **ANM scheme** – the FPL could be integrated with local active network management (ANM) schemes to help prevent curtailment of embedded generation during system events. For instance, if an ANM scheme existed to prevent reverse power flow on a primary transformer, the FPL may be able to prevent curtailment by changing the set-point to transfer power and avoid the reverse power flow issue.

8.6 Testing and Commissioning

8.6.1 Overview

This section describes the testing and commissioning requirements for an 11kV FPL based on the learning that has been generated from the 33kV FPL trial.

8.6.2 Factory Testing

The 33kV FPL could not be tested as a complete unit in the factory due to the size, complexity and the number of different components which made up the entire device. This required significant testing to occur on the live network after the device had been installed at site which should be avoided where possible. It is anticipated that the 11kV FPL would be much smaller in size and therefore it is more amenable to implement the testing on the complete system in the factory prior to delivery to site. This will reduce the risk of technical issues being discovered post-installation and hence reduce the likelihood of cost and programme impacts to the project.

Any 11kV FPL will require the following tests as a minimum:

- Temperature rise (soak test);
- Voltage withstand test;
- Converter output symmetry test;
- Power losses test;
- Harmonic distortion test;
- Control system tests;
- Protection function tests;
- Auxiliary system tests; and
- Clipping test (if required to check the fault limiting performance of the FPL).

8.6.3 Site Testing

The majority of the testing activities will be undertaken in the manufacturer’s facility and therefore there will be minimum site testing of the 11kV FPL. Specific tests should be implemented to ensure that the control and set-point signals are correctly interfaced with the local/remote control system. In addition, it is advisable to test the emergency off functionality of the FPL to ensure that it safely disconnects.

8.6.4 FPL Control Module

Factory Testing

The control system that instructs the FPL to reach a target set-point and takes control action to connect/disconnect the device from the network requires rigorous factory testing separately from the FPL factory testing. However, there needs to be coordination between the FPL and FPL control module design teams to ensure that the system behaves according to the design specification.

System Integration Testing

There will need to be interface testing between the various subsystems in the control chain to ensure that the correct control signals are sent/received to/from the FPL at the right time and in the correct format to enable stable operation of the FPL.

It is recommended that the System Integration Testing is broken down into functional tests of each subsystem (i.e. each subsystem in isolation and the inputs/outputs simulated to test for the correct response) and point-to-point tests between subsystems to test that the signals are configured correctly. The system integration testing shall be undertaken, as much as possible, on an offline system to avoid directly impacting the live operational network.

Any 11kV FPL Control Module will require the following tests as a minimum:

- Point-to-point signal tests from control module to NMS; and
- Point-to-point signal tests from NMS to FPL.

Site Testing

The site testing will involve end-to-end tests from the Control Module to the FPL to ensure the set-point and control/trip signals are correctly sent/received by the FPL. This will initially be completed with the Control Module in open loop mode i.e. with the Control Module manually triggered into sending signals. When the open loop behaviour has been confirmed the FPL can be connected to the network and the Control Module switched into closed loop mode i.e. it is calculating set-points automatically based on network measurements.

8.7 Summary

The learning generated from the connection of the 33kV FPL at Exebridge substation is very relevant for developing a similar application at 11kV. The device characteristics would be broadly in line with that of the 33kV FPL, however, it is likely that the overall FPL could be miniaturised using alternative technologies at the lower system voltage.

The protection, control and safety systems are equally critical for the 11kV FPL and would have to be demonstrated through a thorough design, build and testing process.

9.0 Policies

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

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

For Network Equilibrium a suite of new policies were developed to assist engineers with the connection and on-going operation of the FPL. The following section provides an overview of each of policies developed.

9.1 FPL Specification

The key technical and functional requirements for the FPL are captured in the new policy "Engineering Equipment Specification – Flexible Power Link (FPL) for use on the 33kV Network". This provides details on the required performance, design, construction and testing of the device. This document is principally designed to be used for the procurement of additional FPLs, either by WPD or another DNO.

9.2 FPL Application and Connection Guide

During the design stages of the project, work was carried out to determine a standard connection to the network for the FPL and the considerations required before connection of a device. These findings were captured in the policy document "Standard Technique - Application and Connection of 33kV Flexible Power Link for Network Equilibrium".

9.3 FPL Operation and Control

Prior to the connection and energisation of the FPL it was imperative that policy documents were produced to ensure that all operators can safely control and operate the equipment. The "Standard Technique - Operation and Control of ABB 33kV Flexible Power Link installed at Exebridge Primary Substation for use on the Network Equilibrium project" policy was created and provided to relevant departments in WPD. This provides an overview of the FPL system, details on the basic operation of the device and control module, and an overview of the different alarm states.

9.4 Inspection and Maintenance

The inspection and maintenance policy "Standard Technique - Inspection and Maintenance of ABB 33kV Flexible Power Link installed at Exebridge primary substation for use on the Network Equilibrium project" was created in collaboration with the ABB. The document provides detailed guidance on the routine inspection and maintenance activities required for the FPL.

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Company Directive

STANDARD TECHNIQUE : OC1AC

Operation and Control of ABB 33kV Flexible Power Link installed at Exebridge Primary Substation for use on the Network Equilibrium project

Policy Summary

This document covers Western Power Distribution's requirements for the operation and control of the ABB 33kV Flexible Power Link (FPL) as part of the Low Carbon Networks Fund (LCNF) Tier-2 Project, Network Equilibrium.

Author: Jonathan Berry

Implementation Date: May 2018

Approved by: Network Services Manager (South Wales)

Date: May 2018

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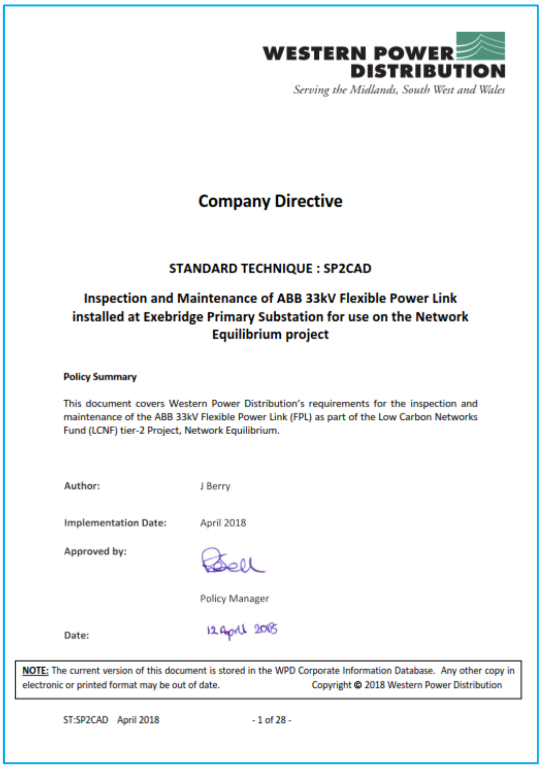
Figure 9-1: FPL Operation and Control Policy



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Company Directive

STANDARD TECHNIQUE : SP2CAD

Inspection and Maintenance of ABB 33kV Flexible Power Link installed at Exebridge Primary Substation for use on the Network Equilibrium project

Policy Summary

This document covers Western Power Distribution's requirements for the inspection and maintenance of the ABB 33kV Flexible Power Link (FPL) as part of the Low Carbon Networks Fund (LCNF) tier-2 Project, Network Equilibrium.

Author: J Berry

Implementation Date: April 2018

Approved by: Policy Manager

Date: 12 April 2018

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Figure 9-2: FPL Inspection and Maintenance Policy

9.5 Sharing of FPL Policies with other DNOs

All policies produced for the FPL and other technologies as part of the Network Equilibrium are made available to all DNOs and National Grid, through the data sharing portal, Huddle.

Innovation Managers from each organisation have access and should be contacted for these documents.

10.0 Learning from the Installation and Commissioning of the 33kV FPL

Table 10-1: Learning Points from the Installation and Commissioning of the FPL

Item	Learning
FPL Site Selection	The critical parameters for consideration are the operational functionality of positioning an FPL at a specific location and the availability to include the device considering available space. The value of installing the device in to an existing substation is that there is no requirement for additional land purchase and wayleave requirements; however, a central location between two networks is the best electrical connection. Significant thought to optimised location and the cost versus technical benefit must be considered.
Network Protection	All existing main AC protection schemes at 33kV are unable to protect the FPL due to the DC conversion process. Only backup Overcurrent and Earth Fault protection is suitable for independent device protection. Main protection for the device is reliant on the FPL internal protection systems to trip for an FPL fault. The FPL is capable of operating when there is only a single source; however, an intertripping scheme for a remote fault was employed. This is suggested until the operational experience of these devices on the distribution network increases.
Technical Specification	A detailed and robust functional specification for a future 33kV and 11kV FPL has been generated, enabling other network operators to make informed decisions when procuring a technology of this type.
FPL CM Testing	During the FPL CM testing process, it was possible to send dynamic network data to the software to calculate a suitable FPL set point. However, it was not possible to see the effect of that set point on the network operation and then carry out a second logic run to determine another adjusted set point. Future testing would benefit from a full real time digital power system simulator (RTDS) test sequence.
FPL Device Testing	On the distribution network, equipment typically undergoes a full FAT process for the complete unit before installation. Due to the size and complexity this was not possible with the FPL system. A rigorous and robust process has been developed for the component testing of such systems.
Transformer Noise Enclosure	Previous projects, STATCOM installations, had provided prior knowledge regarding the noise emitted from transformers containing harmonics. Design, operation and testing of the transformer and noise enclosure have proven that these should be standard for an installation of this type.

Connection to Network	Installation and Operation of the FPL has shown that industry standard circuit breakers and connection methodologies are appropriate. It may be required that small amounts of additionality, such as circuit break fail protection to ensure that sensitive, power electronic, equipment is not affect during a system fault.
Bypass Circuit Breaker	Installing a bypass circuit breaker is essential to the operation of the wider FPL system. It both allows a simple arrangement to be created whereby the FPL isn't in service and enabled the full capacity of the FPL to be tested prior to full, closed-loop, operation.
LV Supply	Through the trialling of the device it was seem that a reliable LV supply was required. Due to the rural location of the FPL the LV was susceptible to faults, due to the overhead system. It is recommended that a dual redundant supply is provided for future implementations.

11.0 Conclusion

The information presented in this document demonstrates the successful design, testing and installation of the FPL device and control system. The document also captures the significant lessons learnt so far and the considerations for the use and installation of FPLs for future installations on both 33kV and 11kV networks.

The FPL will now be operated in conjunction with the other two methods being explored as part of the project to determine the combined benefits and capacity released. Details of this shall be described in SDRC-7.

Glossary

Term	Definition
AC	Alternating Current
AIS	Air-Insulated Switchgear
ANM	Active Network Management
AVC	Automatic Voltage Control
BIL	Basic Insulation Level
BSP	Bulk Supply Point
CB	Circuit Breaker
CSE	Cable Sealing End
CSM	Communication Server Module
DC	Direct Current
DG	Distributed Generation
DNO	Distribution Network Operator
EHV	Extra High Voltage
EMC	Electromagnetic Compatibility
EMF	Electromagnetic Field
ENA	Energy Networks Association
ER	Engineering Recommendation
EVA	Enhanced Voltage Assessment
FAT	Factory Acceptance Testing
FPL	Flexible Power Link
FPL CM	Flexible Power Link Control Module
GRP	Glass Reinforced Plastic
GSP	Grid Supply Point
HMI	Human Machine Interface
HP	High Pass
HV	High Voltage
ICCP	Inter-control Centre Communications Protocol
IEC	International Electrotechnical Commission
IGCT	Integrated Gate Commutated Thyristor
ITGT	Grid TransformerInformation Technology
kV	Kilo Volt
LCNF	Low Carbon Networks Fund
LCT	Low Carbon Technology
LV	Low Voltage
MVA	Mega Volt Ampere
MW	Mega Watt

NG	National Grid
NIC	Network Innovation Competition
NMS	Network Management System
NOP	Normal Open Point
P	Active Power
PSA	Power Systems Analysis
Q	Reactive Power
RMU	Ring Main Unit
RTDS	Real Time Digital Simulator
RTU	Remote Terminal Unit
SAT	Site Acceptance Test
SCADA	Supervisory Control and Data Acquisition
SDRC	Successful Delivery Reward Criteria
SFRA	Sweep Frequency Response Analysis
SIT	System Integration Test
SVO	System Voltage Optimisation
TRL	Technology Readiness Level
UI	User Interface
UPS	Uninterruptible Power Supply
VPN	Virtual Private Network
VT	Voltage Transformer
WPD	Western Power Distribution

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