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SDRC-8

Installation and Open-Loop Tests of Fault Level Mitigation Equipment

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Contents

Glossary

Abbreviation	Term
AC	Alternating Current
DC	Direct Current
DGA	Dissolved Gas Analysis
DNO	Distribution Network Operator
DPCR5	Distribution Price Control Review 5
EHV	Extra High Voltage (voltages above 22,000V)
EMF	Electro-Magnetic Field
FAT	Factory Acceptance Test
FLM	Fault Level Monitor
FCL	Fault Current Limiter
FL	Fault Level
GSP	Grid Supply Point
GT	Grid Transformer
HV	High Voltage (voltages above 1,000V but below 22,000V)
ITT	Invitation to Tender
LN_2	Liquid Nitrogen
MVA	Mega Volt Ampere
MW	Mega Watts
NOP	Normal Open Point
PEFCL	Power Electronic Fault Current Limiter
PSCFCL	Pre-Saturated Core Fault Current Limiter
PTN	Post Tender Negotiations
RMS	Root Mean Square
RSFCL	Resistive Superconducting Fault Current Limiter
SDRC	Successful Delivery Reward Criteria
Tc	Critical Temperature
WPD	Western Power Distribution
UPS	Uninterruptible Power Supply

1 Introduction

The LCNF Tier 2 project FlexDGrid offers an improved solution to the timely and cost effective integration of customers' generation and demand within Birmingham's urban High Voltage (HV) electricity network. Three separate methods have been identified within FlexDGrid to achieve these objectives:

- Method Alpha – An enhanced fault level assessment process;
- Method Beta – The real time management of fault level; and
- Method Gamma – Integration of fault level mitigation technologies.

This document fulfils the eighth Successful Delivery Reward Criterion of FlexDGrid "Installation and Open-Loop Tests of Fault Level Mitigation Equipment" (SDRC-8) by capturing the methodology and learning outcomes associated with the optioneering, design, testing, installation and operation of Fault Level Mitigation Technologies (FLMTs) as part of Method Gamma.

The term FLMT is used interchangeably with Fault Current Limiter (FCL) throughout this document.

At the outset of the project it was planned to install five FLMTs, to provide significant industry learning as to different technologies availability and the selected implementation methodology. As part of the project GE, who were contracted to deliver two FLMT devices, designed and developed a power electronic solution but due to project delivery time constraints could not deliver, and through the process of a Change Request delivered to Ofgem the number of FLMT installations was reduced to three. A separate document, by the end of the project, will be made available documenting the detailed learning generated through the design phase of the power electronic FLMT, however, significant learning is documented in this report as to the design, electrical and physical connection requirements of the GE device.

2 Overview

The document has been structured as follows:

- FCL Integration – This section provides an overview of different options that can be used to integrate FCLs at EHV substations. Four options were derived in the initial stages of FlexDGrid and three of these were used for FlexDGrid.
- FCL Technologies – Three different types of FCL technology were chosen to be implemented for FlexDGrid. This section provides a short description of each technology.
- Technical Design – This section provides details on how the FCLs were integrated at the selected substation sites in and around central Birmingham.
- Testing – The FCL technologies chosen for FlexDGrid underwent rigorous testing in HV laboratories, this section explains the testing procedures and the results that followed.
- Installation – The installation of the FCLs was a major milestone in FlexDGrid, this section covers the highlights of the installation phase.
- Policies – This section of the document provides a summary of the policy documents associated with the integration of the FCLs.
- Learning – The last section of the document summarises the learning of the FCL design, testing and installation phases.

3 FCL Integration

3.1 Connection Options

In the initial stages of FlexDGrid one of the main tasks was to identify a selection of high level connection options that could be used for the integration of FCLs. Investigation of the HV network in Birmingham resulted in four possible connection options being identified, these are summarised in Table 3-1 below.

Table 3-1: Description of FCL connection options

FCL Connection	Description
FCL In Series With Secondary Winding	Installation of FCL between the LV side of a 132/11kV transformer and the main substation 11kV switchboard
FCL Across Bus-Section	Installation of FCL across a bus-section of an 11kV switchboard at 132/11kV substation
FCL Within Interconnector	Installation of FCL within an 11kV interconnector connecting two existing 11kV switchboards
FCL Between Transformers	Installation of FCL between two separate transformer secondary windings

The option of installing an FCL within a generator 11kV feeder was considered, however for this option busbar fault levels would not be significantly reduced as the FCL would only mitigate the fault level contribution from that generator source. It also closely replicates the connection requirements in series with the secondary winding of a transformer, which is captured as part of the project. Due to the limited gains associated with this option it was not explored further for the FCLs to be connected as part of FlexDGrid.

For each connection option it was critical that the network could be returned to the original configuration should the FCL develop a fault, as part of the demonstration phase of the project. For most of the connection options a new switchboard would be required with a “by-pass” bus-section circuit breaker to allow the FCL to be disconnected safely and efficiently.

The following sections provide further detail on the four connection options identified above. Further details of the various FCL connection options can be found in SDRC-2.

3.2 Option 1 – Series Connection in Transformer LV Winding

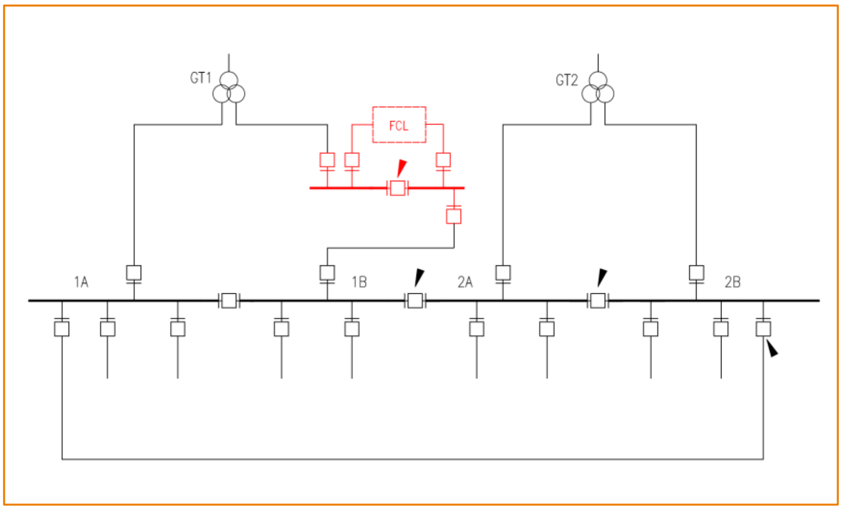


Figure 3-1: FCL connection in series with transformer

In this option the FCL is positioned in series with the secondary winding of the transformer as shown in Figure 3-1. To facilitate this connection the FCL is connected in to the 11kV cables from the transformer to the incoming circuit breaker 1B. The integration of the FCL in this scenario allows the secondary windings GT1A and GT1B to be paralleled by closing the normally open bus-section on the existing 11kV switchboard.

This option is generally considered when parallel operation of two separate transformers is not possible (i.e. fed from separate Grid Supply Points (GSPs)) and the only feasible parallel is between 1A and 1B secondary windings. In addition, as the FCL is connected in series with a transformer winding, it is imperative that the FCL technology for this option can “ride-through” faults without disconnecting.

3.3 Option 2 – Across Bus-Section

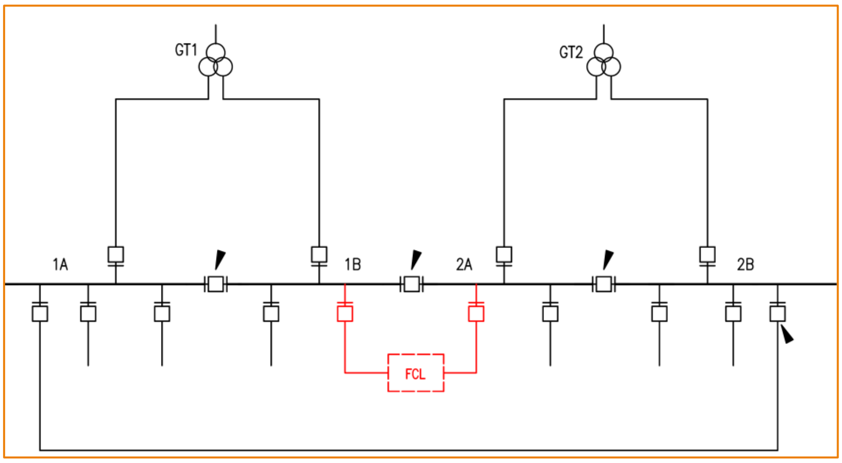


Figure 3-2: FCL connection across bus-section

Figure 3-2 shows the option of installing the FCL across a bus-section circuit breaker. Generally with existing switchgear it is not feasible to carry out this installation as it requires two busbar rated circuit breakers either side of a bus-section circuit breaker. Hence, this option is tailored towards primary substations where new switchgear is being installed.

3.4 Option 3 – Within Interconnector

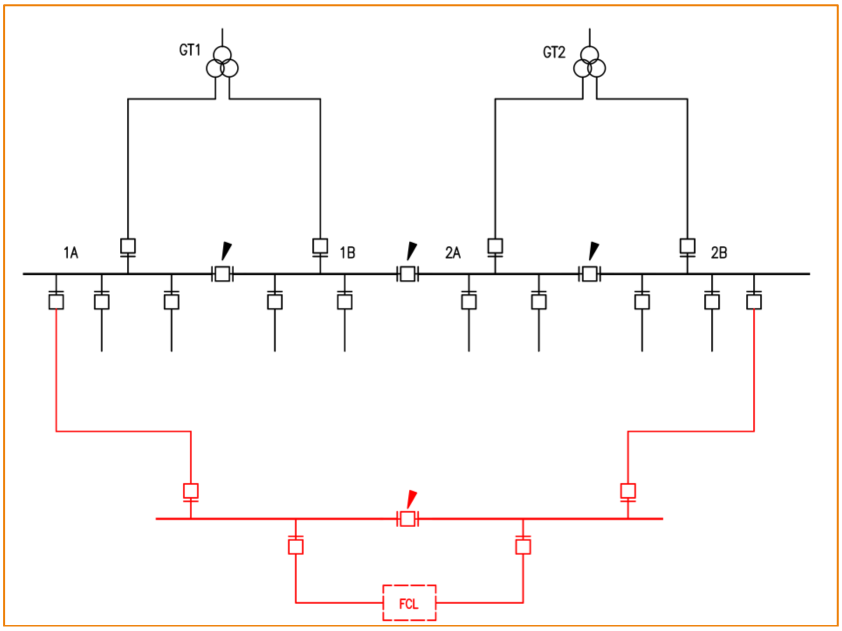


Figure 3-3: FCL connection across and 11kV interconnector

Many substations in WPD's Birmingham network are equipped with normally open interconnectors that provide alternative supplies between busbars. This option incorporates the FCL in to the interconnector between two sections of switchboard, sections 2B and 1A in this instance, as shown in Figure 3-3. A five circuit breaker switchboard is required to ensure that the interconnector circuits are protected and the FCL can be by-passed if necessary.

3.5 Option 4 – Across Two Transformers

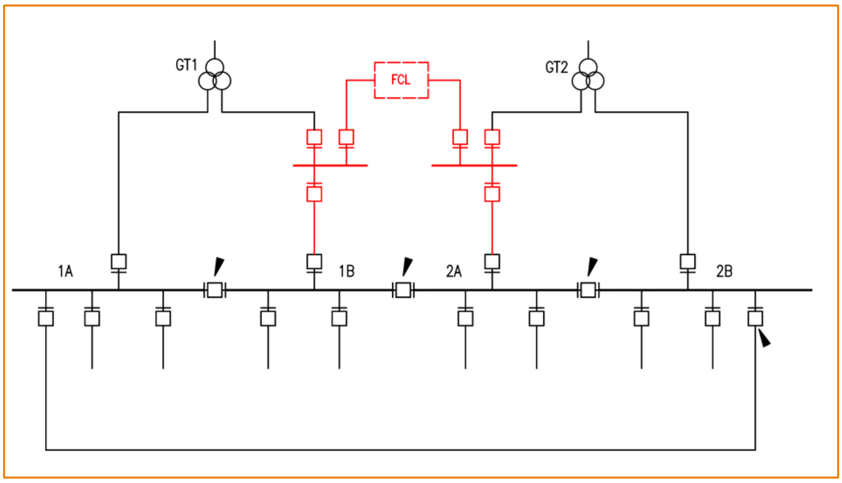


Figure 3-4: FCL connection across two transformers

As shown in Figure 3-4, this option connects the FCL between two separate transformer secondary windings. To facilitate this connection the FCL is connected in to the 11kV cables from GT1B and GT2A. When connecting an FCL in this position a significant amount of protection modifications would be required as the 11kV transformer protection needs to be transferred on to the new switchboard. In addition, this particular option can only be considered when both Grid Transformers are supplied from the same GSP.

4 FCL Technologies

4.1 Overview

There were three distinct technology types that were selected during the procurement phase of FlexDGrid namely; Resistive Superconducting Fault Current Limiter; Pre-Saturated Core Fault Current Limiter; and Power Electronic Fault Current Limiter. Each of the chosen technologies has different characteristics that have to be considered when deciding the suitability of connection into an existing substation.

The following sections provide a brief technical summary of the different fault current limiters. A more detailed description of the technologies can be found in SDRC-2.

4.2 Pre-Saturated Core Fault Current Limiter (PSCFCL)

The principle of PSCFCL technology is based on the properties of transformer design. Figure 4-1 shows a simplified single phase configuration of the PSCFCL. In this application, the primary AC winding of the device is placed in series with the network requiring fault level mitigation. The secondary winding is a DC coil which is used to saturate the core of the PSCFCL. Under normal operation, the flux generated by the DC coil is far greater than that produced by the primary winding and thus the core becomes saturated and the insertion impedance seen by the primary side is very low (see Figure 4-1 where the red arrow indicates the magnitude of flux generated by the DC coil and the blue arrow indicates the flux generated by the AC coil). As current increases on the primary winding (such as in a fault situation) the opposing flux generated AC coil increases resulting in the core coming out of saturation and the PSCFCL creating a high insertion impedance in series with the network (see Figure 4-2).

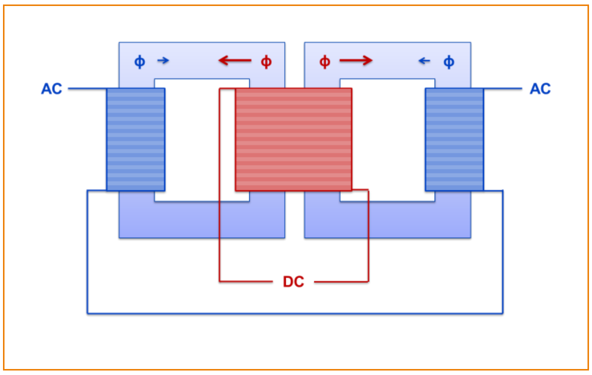


Figure 4-1: PSCFCL saturated under normal conditions

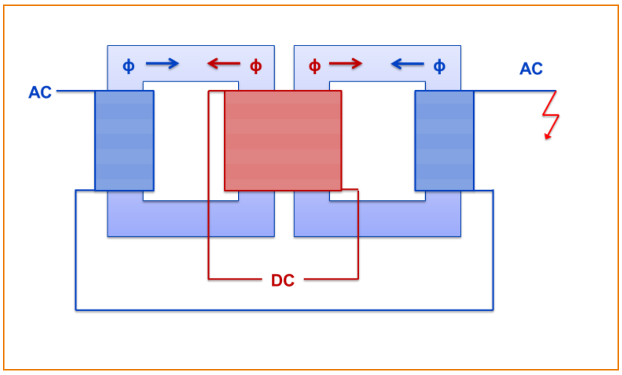


Figure 4-2: PSCFCL under fault conditions

The PSCFCL is a fail-safe device as the DC coil is required to keep the core in saturation in normal operation. Should the DC coil fail (or its controller fail), the core will automatically come out of saturation and the PSCFCL insertion impedance will be high.

The main components of the PSCFCL are as follows:

- Main tank containing AC and DC coils filled with insulating oil;
- Direct connected radiators with fan to provide cooling to the main tank;
- DC cubicle containing power supplies for the DC coils;

- AC cubicle containing the auxiliary systems for controlling and monitoring; and
- Uninterruptible Power Supply (UPS) to provide supplies in the event of power being lost.

Figure 4-3 shows a basic layout of the device and the main components (excluding the UPS).

The PSCFCL was provided by GridON.

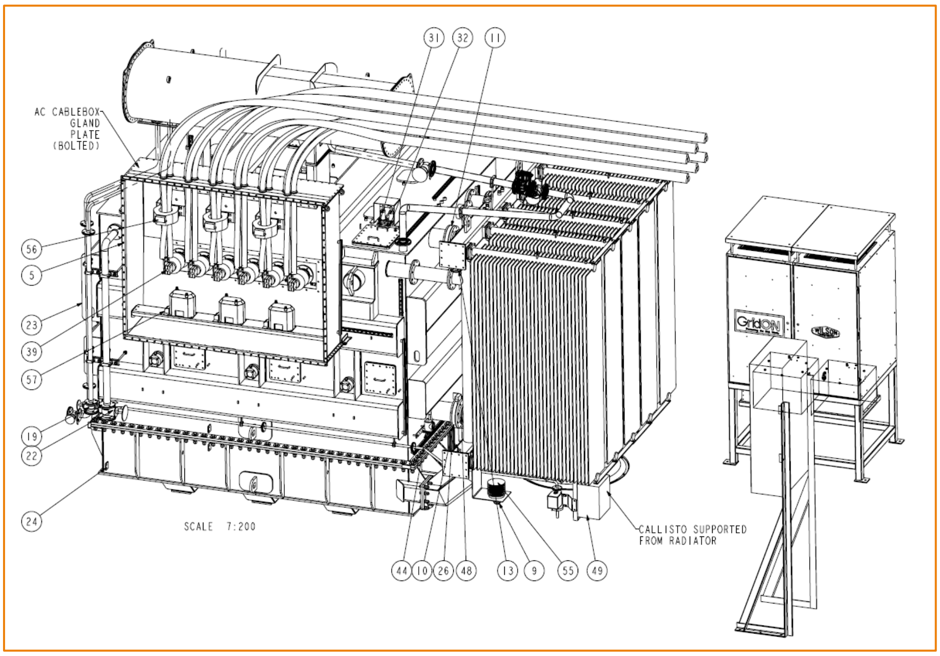


Figure 4-3: Outline drawing of PSCFCL

4.3 Resistive Superconducting Fault Current Limiter (RSFCL)

The RSFCL technology exploits the properties of High Temperature Superconducting (HTS) materials to limit fault current. HTS differs from standard conductors, in that the resistance of the conductor is extremely low when it is cooled below its critical temperature (Tc). Figure 4-4 below shows how HTS resistance changes with temperature.

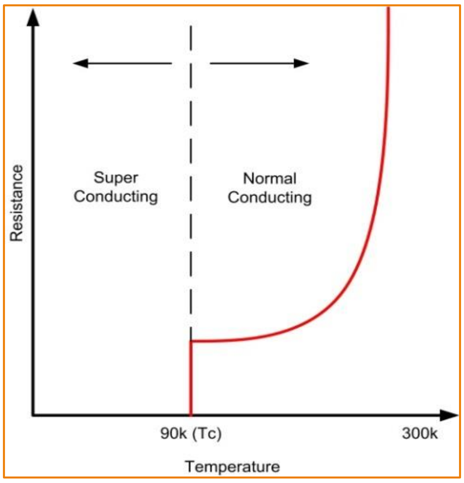


Figure 4-4: Resistance of a HTS

The RSFCL should be connected in series with the 11kV network and is designed so that the HTS behaves as a superconductor under normal operating conditions i.e. for the expected range of load current.

During a fault condition the current flowing through the device becomes greater than the critical current of the HTS. The critical current is the current at which the device transitions from its superconducting state into a resistive state due to the temperature rise of the conductor. This process is called “quenching”. When the device quenches it presents large impedance in series with the network that limits the prospective fault current.

The RSFCL requires disconnection from the network after the inception of a quench event to avoid damage to the HTS conductor due to the heating effects from the fault current.

The main components of the RSFCL are as follows:

- Three cryostats containing the cooling medium (liquid nitrogen) and HTS;
- Helium compressors for cooling the liquid nitrogen within the cryostats;
- Air recoolers for cooling the compressors; and
- Protection and control cubicles.

Figure 4-5 shows a layout of the RSFCL with the majority of equipment contained with a concrete enclosure.

The RSFCLs were provided by Nexans.

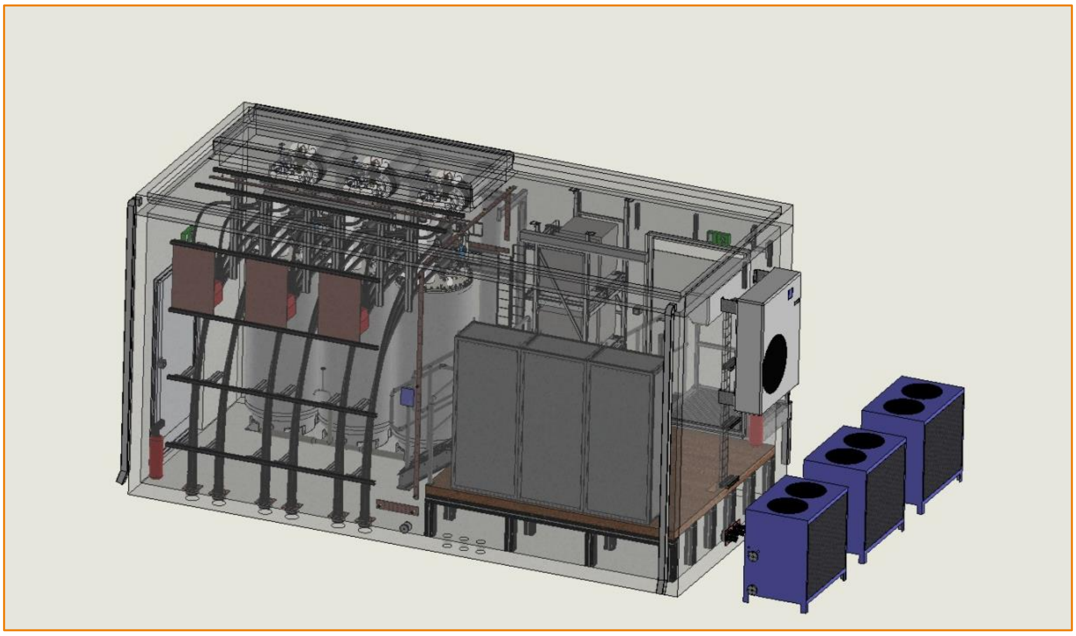


Figure 4-5: Outline drawing of RSFCL

4.4 Power Electronic Fault Current Limiter

The PEFCL technology exploits the properties of semiconducting power electronic devices to limit prospective fault current. The PEFCL is connected in series with the 11kV network and consists of a number of Insulated Gate Bipolar Transistors (IGBTs) configured as switches. Under normal operating conditions the IGBTs are closed to allow the flow of load current. If the PEFCL detects a fault on the network the IGBTs are opened very quickly (in the order of 20μs) thus reducing any fault level contributions through the device. Figure 4-6 below shows the proposed GE PEFCL housed within a container with 11kV switchgear at both ends and IGBT racks in the centre.

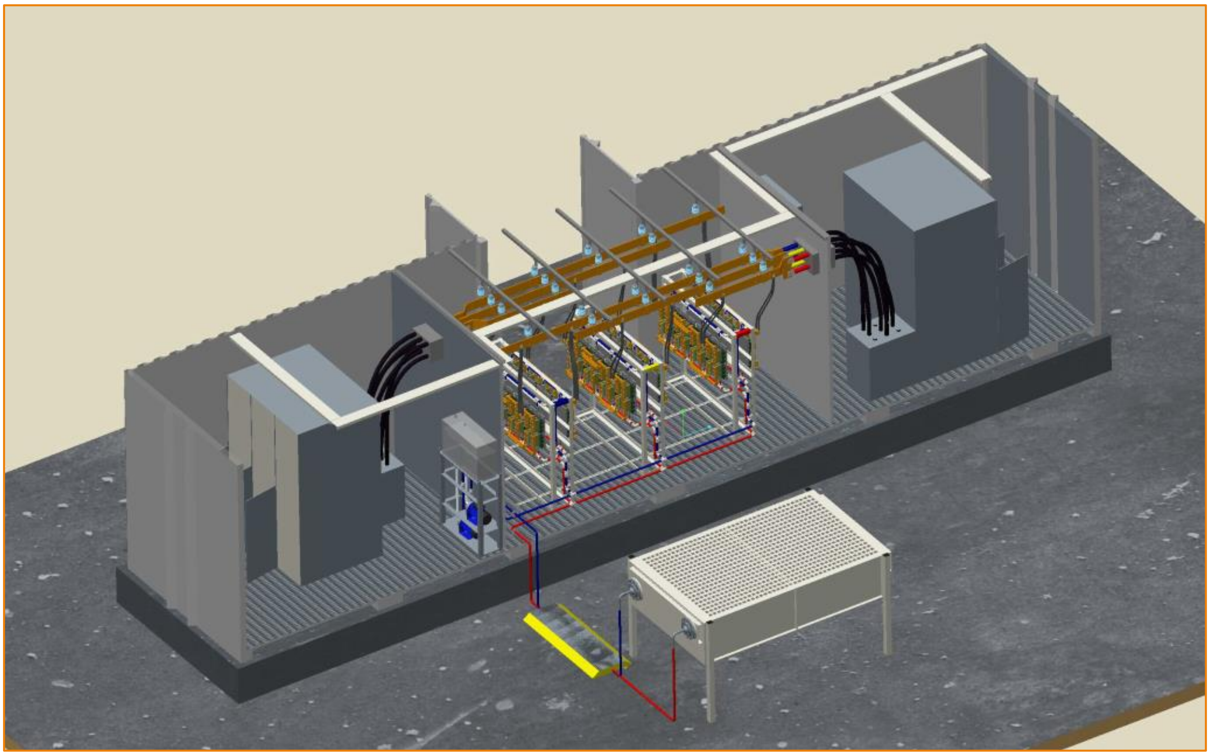


Figure 4-6: Outline view of GE PEFCL

The PEFCL does not insert impedance into the network like the PSCFCL and RSFCL. Instead the fault current path is interrupted allowing for much higher fault current reductions compared with the other FCL devices. In addition, being a switching device, the PEFCL can be controlled to reduce fault current at different magnitudes unlike the other devices which have a fixed level of reduction. The PEFCL is also a fail-safe device as any failure of the IGBTs or control system will automatically open the remaining IGBTs to stop all current flow through the device; further detailed in Section 5.6.

The PEFCL technology could not be assembled by the manufacturer, GE, to a state whereby it could be safely connected to the 11kV network within the timescales of FlexDGrid. At the time of writing, the PEFCL technology has not been developed beyond the design phase with no immediate signs of a device that would be in an adequate state ready for testing. GE is considering continuing the development, outside of the project, and is carrying out a market assessment for such a device. GE has requested that WPD offers further support in regards to the testing requirements if they chose to continue with the development.

4.5 Summary of Site Selection

The substations selected for the installation of FCLs were determined in SDRC-2. Substations were selected based on a selection process which was informed by scoring each primary substation against a set of criteria. A further selection process was used to determine which FCL technology was best suited for each of the substations.

Table 4-1 shows the final sites where FCL equipment was to be installed and the corresponding FCL technology that was chosen for each site.

Table 4-1: Sites with fault level mitigation equipment installed

Substation Name	PEFCL	RSFCL	PSCFCL
Castle Bromwich 132/11kV			✓
Chester Street 132/11kV		✓	
Bournville 132/11kV		✓	
Kitts Green 132/11kV	✓*		
Bartley Green 132/11kV	✓*		

*Technology was not installed due to incomplete design by manufacturer

5 Technical Design

5.1 Castle Bromwich

The following sections detail the design and installation of a PSCFCL at Castle Bromwich 132/11kV substation. The aim of this section is to disseminate the main learning outcomes obtained during the initial design stages through to project completion.

5.1.1 Substation Overview

Castle Bromwich 132/11kV substation is located on the edge of a residential area approximately six miles north east of Birmingham City Centre. The substation consists of 2 no. 132/11/11kV 60MVA transformers with GT1 supplied from Nechells East (via Dunlop) 400/132kV Grid Supply Point (GSP) and GT2 from Lea Marston 400/132kV GSP. The incoming 132kV underground circuits terminate on to 132kV indoor Gas Insulated Switchgear (GIS). Each transformer winding supplies a separate section of 11kV switchgear as shown in Figure 5-1 below.

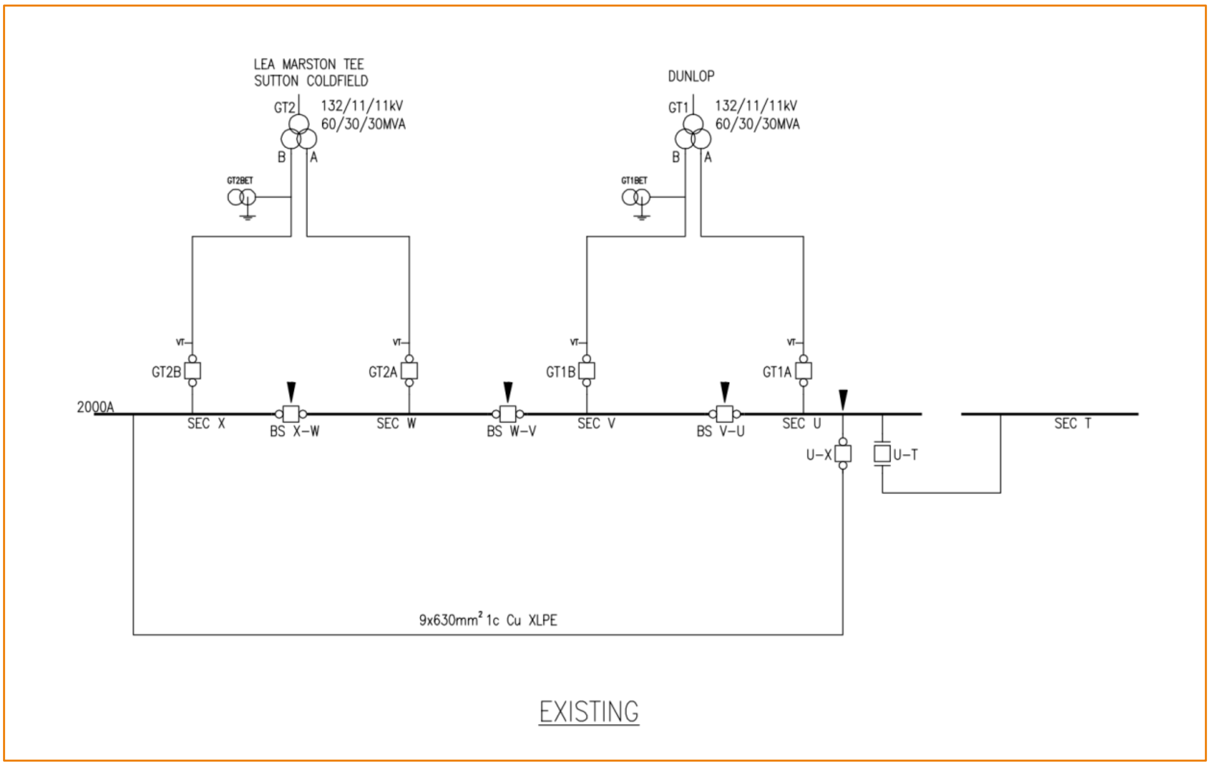


Figure 5-1: Single Line Diagram for Castle Bromwich prior to FCL installation

5.1.2 Network Connection

The FCL had to be integrated into one of the transformer secondary windings (see Figure 5-2 below) as the 132/11kV transformers at Castle Bromwich are fed from separate GSPs. The PSCFCL has instantaneous recovery and therefore does not interrupt supplies during fault inception. GT1A was chosen due to the practical considerations of extending switchgear and providing new cable connections.

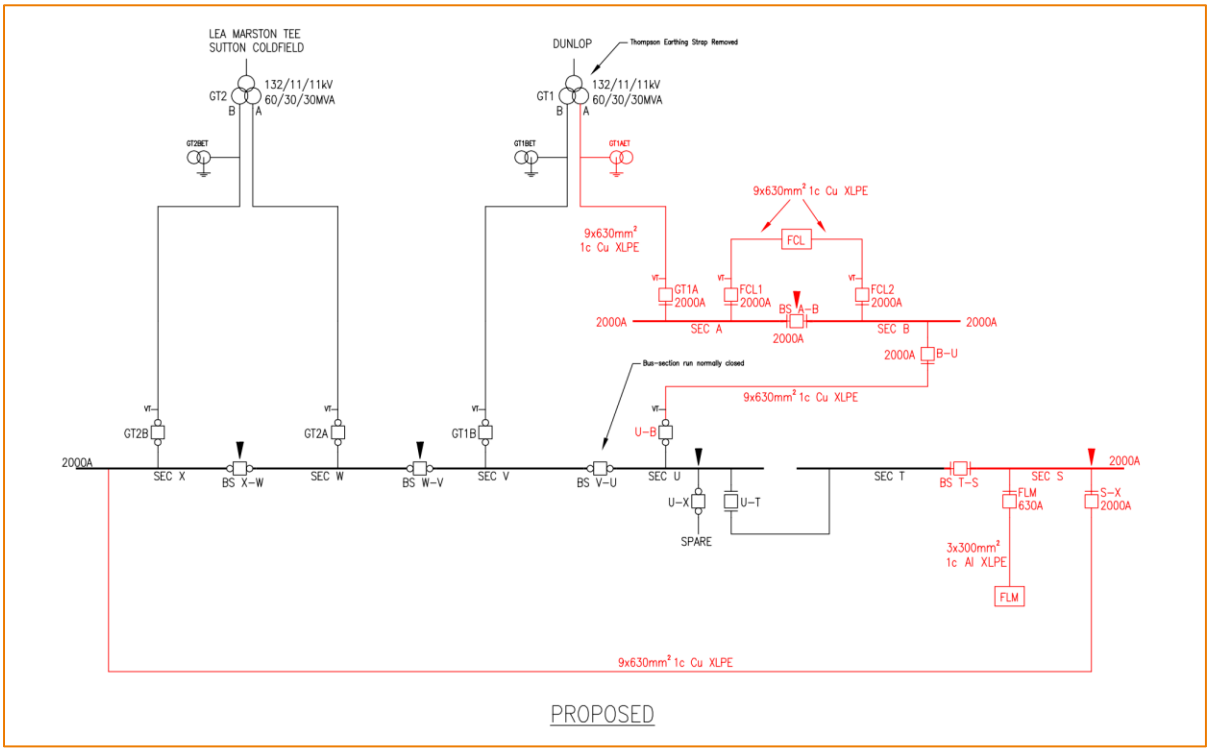


Figure 5-2: PSCFCL Connection at Castle Bromwich

To connect the PSCFCL to the 11kV network, a new 5 panel 11kV switchboard was installed. The switch room at Castle Bromwich had been designed to allow for future extension of the 11kV switchboard.

5.1.3 FCL Location

The substation building at Castle Bromwich was designed to accommodate a third transformer in the future with two spare indoor bays; one for the main tank and another for the cooler. From initial discussions with the FCL manufacturer, and allowing for at least a 20% margin, the PSCFCL would be able to be situated inside the third transformer indoor bay. An outline of the initial layout is shown in Figure 5-3 below.

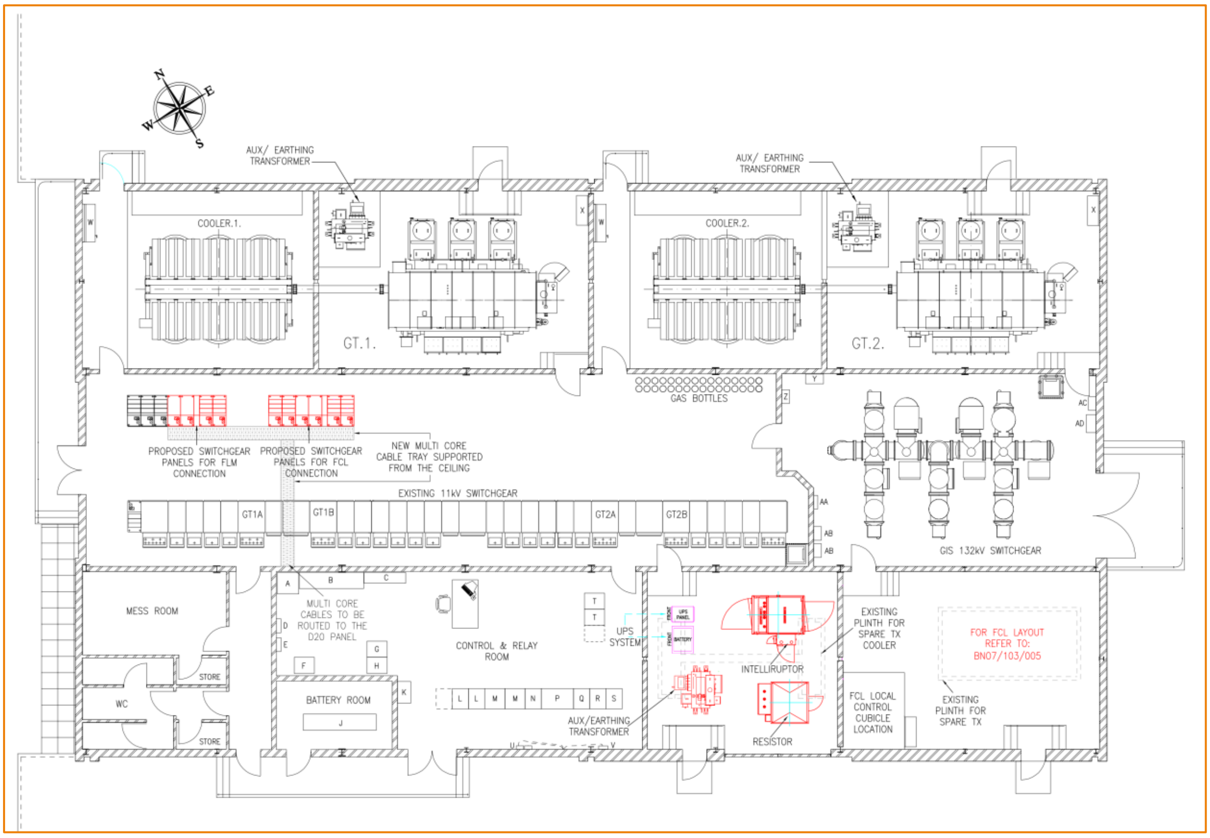


Figure 5-3: Initial layout of new equipment for Castle Bromwich

5.1.4 FCL Dimensions and Weight

During the initial tender negotiations details of the FCL dimensions and weight were requested to ensure the device could be accommodated within the indoor bay. A factor of 20% was added to these figures to allow for a margin of error during design.

Following detailed design by the manufacturer, the size and weight of the FCL increased significantly. However, as a 20% margin had been allowed, the FCL was still able to be installed within the indoor bay with only an extension of the existing transformer plinth necessary. The installation of a Magnetic Shield further impacted on the clearances around the FCL, however, careful positioning allowed for sufficient access and egress around the device for maintenance purposes. The final layout can be seen in Figure 5-4 below with a picture of the covered magnetic shield in Figure 5-5.

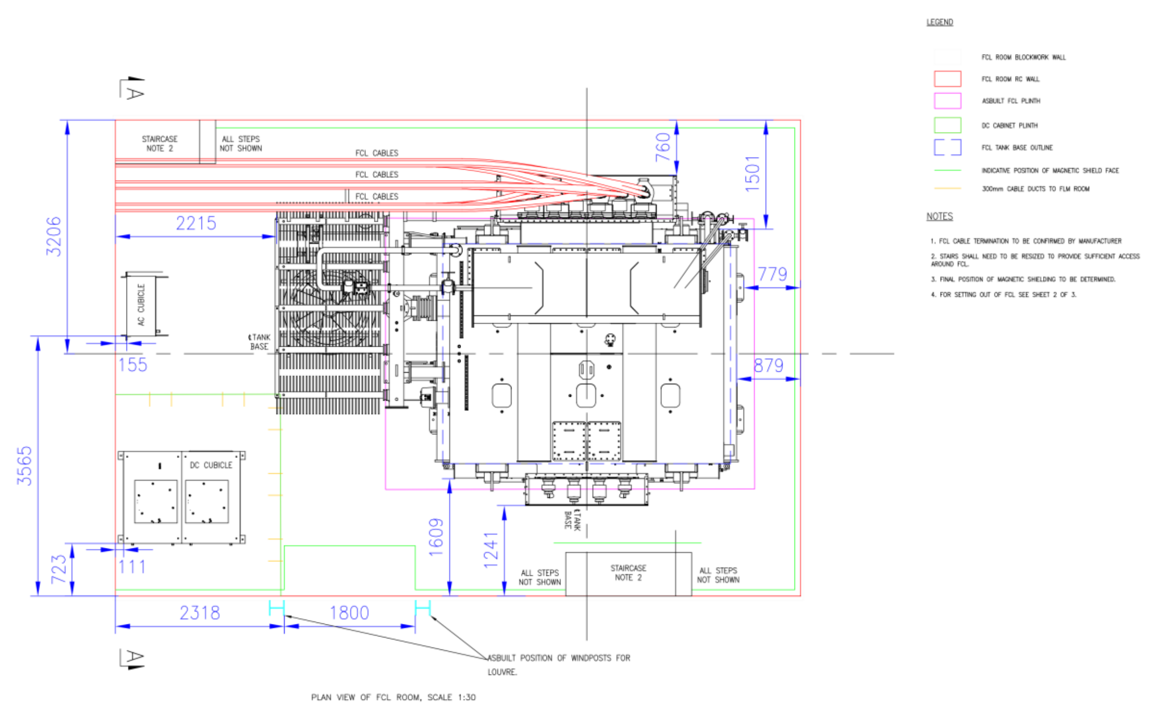


Figure 5-4: Final layout of FCL in spare transformer bay

Figure 5-5: Installed FCL with Magnetic Shield covered

5.1.5 Thompson Strap

The transformers at Castle Bromwich have a Thompson Strap installed, which negates the need for separate earthing transformers on each LV winding. The installation of a Thompson Strap on dual-wound 132/11kV transformers is believed to only be implemented in sites in and around the Birmingham area.

If the Thompson Strap was left in service and the FCL was installed in the transformer leg, this link between the two windings would bypass the FCL and the amount of fault level reduction would be reduced. As such it was chosen to remove the Thompson Strap and install a new earthing transformer on the other transformer leg (GT1B). This had the added benefit of providing the dedicated LV supplies for the FCL DC Power.

5.2 Chester Street

The following section details the design and installation of an RSFCL at Chester Street 132/11kV substation. This section aims to disseminate the main learning outcomes obtained during the design phase of the device.

5.2.1 Substation Overview

Chester Street 132/11kV Substation is located to the north east of Birmingham City Centre. It comprises three 132/11kV 30MVA transformers supplied via underground circuits from Nechells East 400/132kV GSP. GT1 is supplied via Summer Lane substation with GT2 and GT3 supplied by a single circuit directly from Nechells East. The two incoming 132kV underground circuits terminate on to 132kV outdoor Air insulated Switchgear (AIS). Each transformer winding supplies a separate section of 11kV switchgear as shown in Figure 5-6 below.

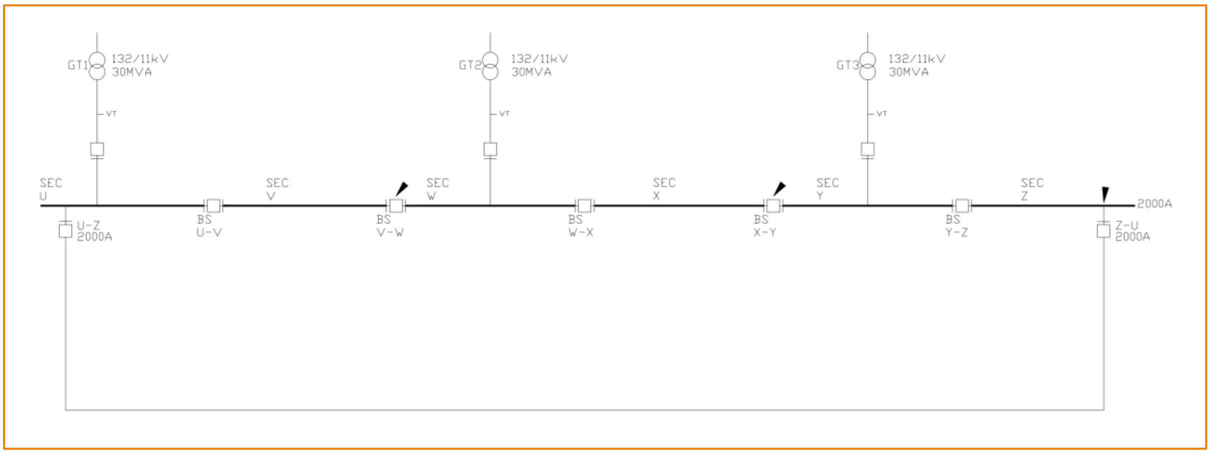


Figure 5-6: Single Line Diagram for Chester Street prior to FCL installation

The substation was commissioned in 1961 with all the 11kV equipment located within a three storey brick building. As part of WPD's DPCR5 asset replacement programme the old GEC KN series switchgear has now been fully replaced by new Hawker Siddeley Eclipse switchgear.

5.2.2 Network Connection

At Chester Street the 132/11kV transformers are fed from the same GSP, however, there is a Normal Open Point (NOP) on the 132kV network between GT1 and GT2/GT3. This ruled out the connection of the RSFCL in the existing interconnector or across bus-section V-W. Therefore the RSFCL was installed across bus section X-Y (see Figure 5-7 below).

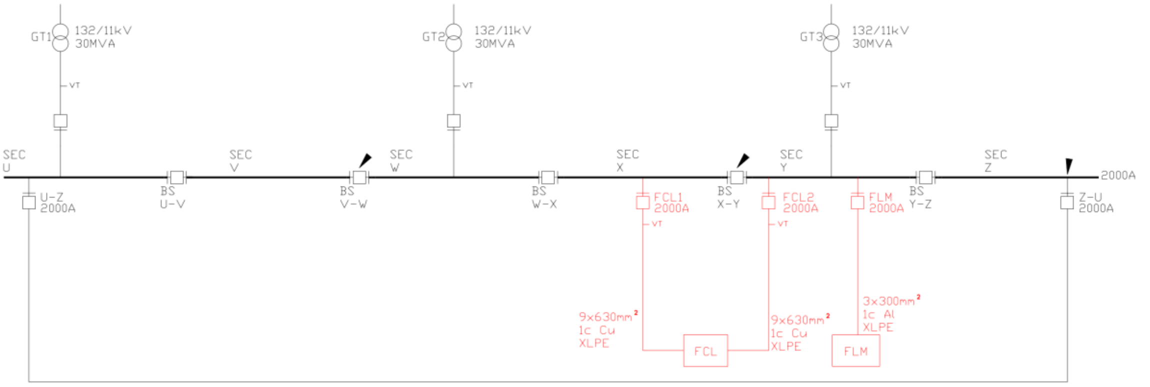


Figure 5-7: FCL Connection at Chester Street

Two new 11kV circuit breakers were installed to connect the FCL to the 11kV network. The DPCR5 project to replace the 11kV switchboards at Chester Street was being implemented concurrently allowing for specification of the additional circuit breakers as part of these asset replacement works.

5.2.3 FCL Location

The Chester Street RSFCL was installed in the north western perimeter of the 132kV compound. This area was chosen due to the available space and ease of access from Chester Street. The 132kV compound perimeter fencing was extended to create a new FCL compound. The initial layout is shown in Figure 5-8.

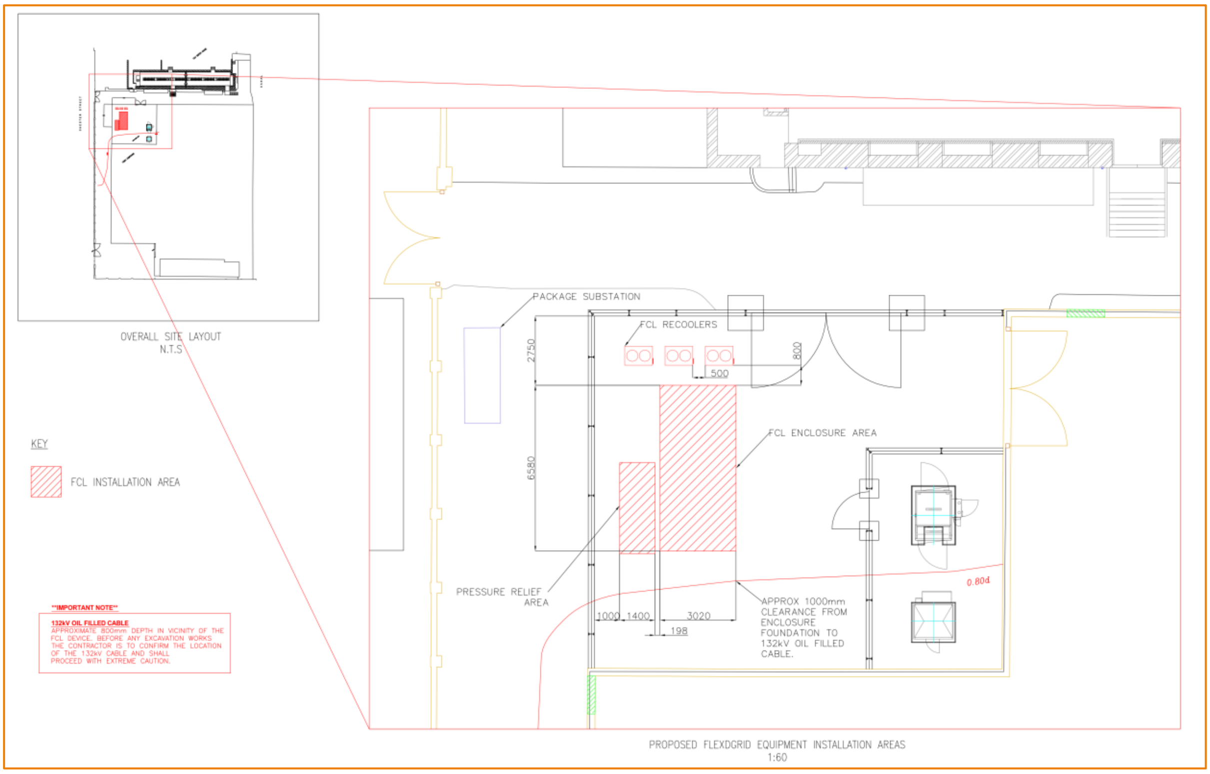


Figure 5-8: Initial layout of new equipment at Chester Street

5.2.4 132kV Oil Filled Cable

During the design phase of the project a ground radar survey of the area proposed for the installation of the RSFCL was performed. The survey identified an underground 132kV oil filled cable passing through the designated area. The safety of WPD and contractor staff was of the utmost concern during the design, installation and commissioning stages of the project. As such, significant design work was undertaken to ensure that the layout of the FCL and auxiliary equipment was positioned as far away from the cable as possible and that all staff working at the site were briefed of the hazard.

5.2.5 LN_2 Containment

The RSFCL contains a significant volume of Liquid Nitrogen (LN_2) in its cryostat vessels. This substance has a temperature of approximately 77k which represents a hazard to site operatives that are working in proximity to the device. The RSFCL design incorporated a containment bund that was capable of containing the maximum volume of LN_2 in the device. The bund was positioned adjacent to the exhaust pipes of the RSFCL. If in the event of a catastrophic failure within the cryostat vessels the design of the RSFCL ensures liquid and gaseous Nitrogen is exhausted through the exhaust pipes and safely into the containment bund. The bund will hold the liquid until evaporates naturally into the atmosphere.

5.2.6 Protection

The protection scheme for the RSFCL was much simpler than that employed for the PSCFCL at Castle Bromwich as the device was installed across a bus-section. The feeder circuit breakers were specified with CTs to provide unit protection across the RSFCL and a back-up overcurrent scheme. The system was designed so that both feeder circuit breakers to the RSFCL were tripped for any protection trip generated by the WPD protection scheme or the Nexans RSFCL control system.

In addition to the main and back-up protection schemes the design allowed for a circuit breaker fail function. In the event that the feeder circuit breakers fail to operate for a trip the overcurrent relay trips the upstream bus-section W-X and GT3 circuit breakers after a 250ms delay.

5.3 Bournville

The following section disseminates the main learning outcomes obtained during the design of the RSFCL at Bournville 132/11kV substation. This is the second RSFCL to be successfully installed on WPD’s distribution network, the first being at Chester Street 132/11kV substation.

5.3.1 Substation Overview

Bournville 132/11kV substation is located five miles south of Birmingham City Centre. The site is bordered to the west by a canal and commuter rail line. The substation is supplied by Kitwell 400/132kV GSP and consists of four 132/11kV 30MVA transformers supplying four double busbar sections of 11kV switchgear. The incoming 132kV overhead line terminates on 132kV tower cable sealing end platforms. Short cable sections from the terminal towers connect onto outdoor Air Insulated Switchgear (AIS) switchgear before carrying on towards Selly Oak and Shirley substations. Each transformer supplies a separate busbar section of 11kV switchgear as shown in Figure 5-9 below.

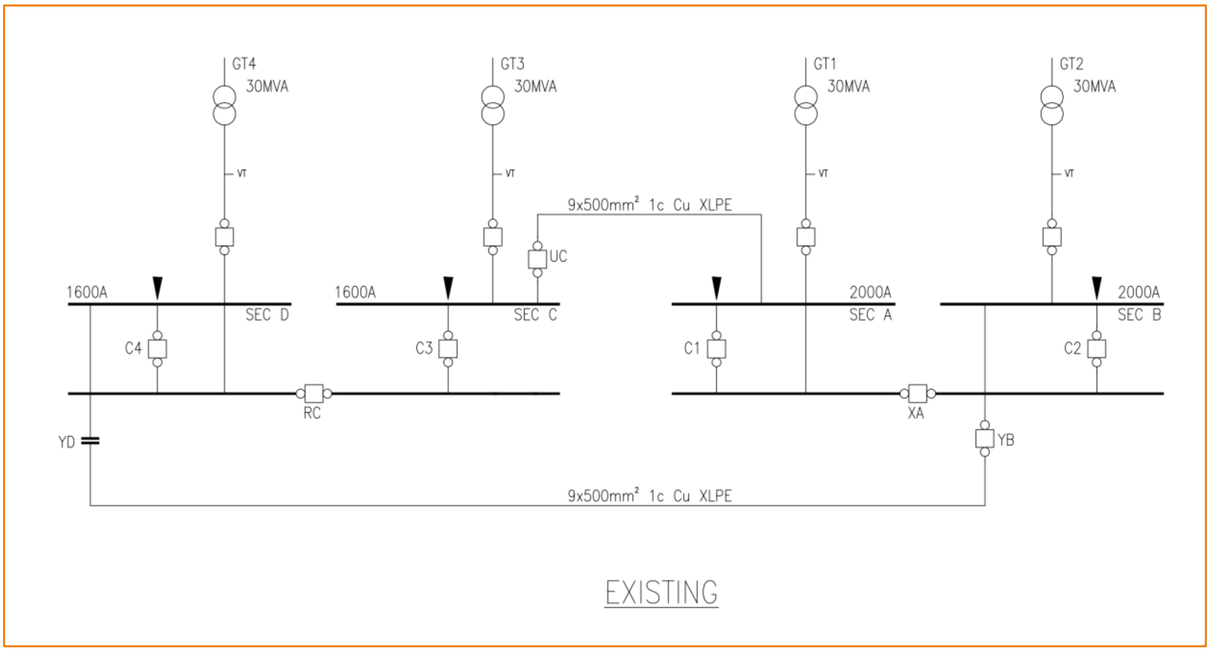


Figure 5-9: 11kV Single Line Diagram for Bournville prior to FCL installation

The substation building which houses the 11kV switchgear was constructed in circa 1920; however, the majority of the existing equipment was commissioned in the 1960s. The building and the substation equipment have been modified and developed over its lifetime. There are significant works planned at Bournville under a RIIO ED1 asset replacement project. This includes replacement of the four 30MVA 132/11kV transformers, KN 11kV switchgear and 132kV switchgear.

5.3.2 Network Connection

At Bournville the 132/11kV transformers are fed from the same GSP. It was chosen to install the RSFCL in the existing interconnector between busbar sections A and C. (see Figure 5-10 below).

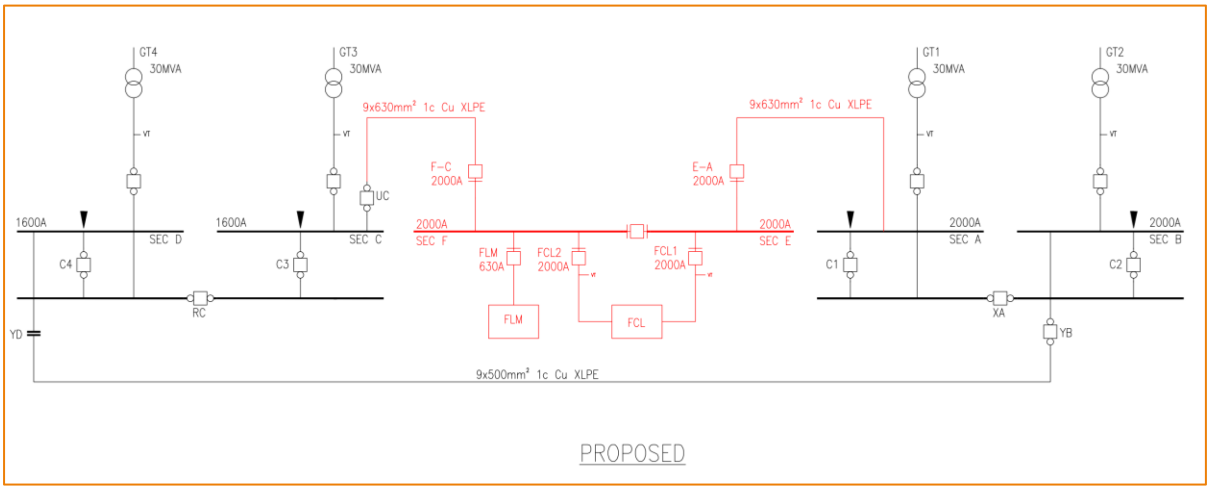


Figure 5-10: SLD of FCL Connection at Bournville

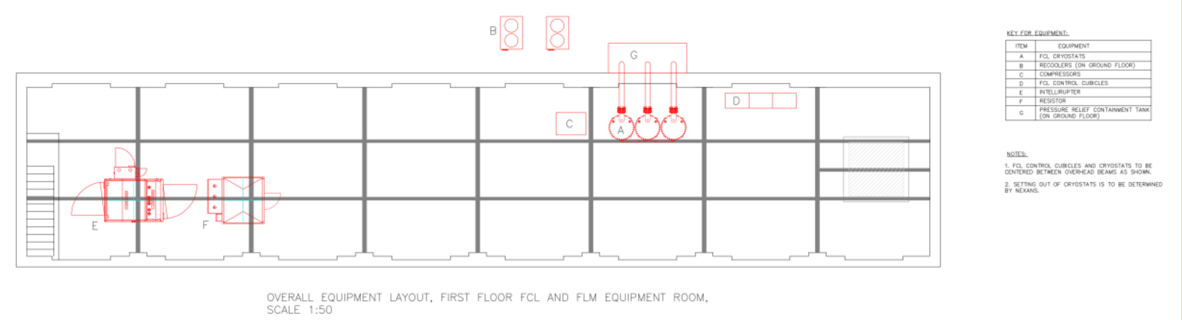
A new six panel switchboard was installed to connect the RSFCL to the 11kV network. The switchboard also includes a switchgear panel for connection of the Fault Level Monitor (FLM) equipment.

5.3.3 FCL Location

The Bournville RSFCL was installed in a disused switchroom on the first floor of the substation building, directly above switch house no. 2 containing busbar sections A and B. The location of the switchroom is indicated in Figure 5-11. This area was chosen to avoid locating the RSFCL in the disused transformer yard adjacent to the substation building which is shown in Figure 5-12. It was anticipated that this area would be required for the asset replacement works described in Section 5.3.1. The first floor also had sufficient space available for the installation. The initial layout of the equipment is shown in Figure 5-12 below. A comparison of the first floor switchroom before and after the installation works is shown in Figure 5-14 and Figure 5-15 respectively.

Figure 5-11: Substation building as seen from the disused transformer yard (first floor switchroom indicated by red arrow)

Figure 5-12: Disused transformer yard



KEY FOR EQUIPMENT:

ITEM	EQUIPMENT
A	FCL CRYOSTATS
B	RECOOLERS (ON GROUND FLOOR)
C	COMPRESSORS
D	FCL CONTROL CUBICLES
E	INTELLIRUPTER
F	RESISTOR
G	PRESSURE RELIEF CONTAINMENT TANK (ON GROUND FLOOR)

NOTES:

1. FCL CONTROL CUBICLES AND CRYOSTATS TO BE CENTERED BETWEEN OVERHEAD BEAMS AS SHOWN.

2. SETTING OUT OF CRYOSTATS IS TO BE DETERMINED BY NEXANS.

Figure 5-13: Initial layout of new equipment for Bournville (FCL equipment A – D)

Figure 5-14: View from inside the first floor switchroom prior to FCL installation

Figure 5-15: View from inside the first floor switchroom after FCL installation

5.3.4 Protection

The protection scheme at Bournville was similar to that installed at Chester Street. The feeder circuit breakers were specified with Current Transformers (CT) to provide a unit protection across the RSFCL and a back-up overcurrent scheme. The system was designed so that both feeder circuit breakers to the RSFCL were tripped for any protection trip generated by the WPD protection scheme or the RSFCL control system.

In addition to the main and back-up protection schemes the design allowed for a circuit breaker fail function. In the event that the feeder circuit breakers fail to operate for a trip the overcurrent relay trips the upstream interconnector E-A and F-C circuit breakers after a 250ms delay.

5.3.5 Earthing in Substation Basement

The Bournville substation has a vast cable basement for routing 11kV and multicore cables. The earthing connections from the substation equipment are routed and connected to the main earth grid located in the cable basement. It was discovered that certain sections of the main earth grid was depleted and this was taken as an opportunity, by our maintenance team, to carry out some improvement works. This work was not funded by the project.

5.3.6 Lead Paint

The first floor area where the RSFCL was proposed to be installed was previously used as a switchroom but had been left redundant for a number of years after the switchgear was removed. During the design phase it was identified that the paint on the walls could be lead based. It was also found to be peeling off the walls due its age (refer to Figure 7-9).

Analysis into the properties of the paint was commissioned. The results showed that the paint contained high levels of lead which would pose a health risk to the installation contractor and WPD personnel. The decision was taken to completely remove the paint from the first floor switchroom prior to the installation works. This was performed by a specialist contractor and delayed the start of the Bournville FCL installation works by approximately five weeks.

5.4 Kitts Green

The PEFCL was not installed at Kitts Green as the manufacturer (GE) could not provide WPD with a functional and safe device for connection to the 11kV distribution network within the required project timescales. However, the following sections detail the design and preparatory works that were implemented by WPD to allow the integration of the PEFCL at Kitts Green. The aim of this section is to disseminate the main learning outcomes obtained during the design stages of the project.

5.4.1 Substation Overview

Kitts Green substation was commissioned in circa 2008 and is equipped with three 60MVA, 132/11/11kV transformers feeding six sections of 11kV single busbar switchgear. A single line diagram of the existing network arrangement is shown in Figure 5-16.

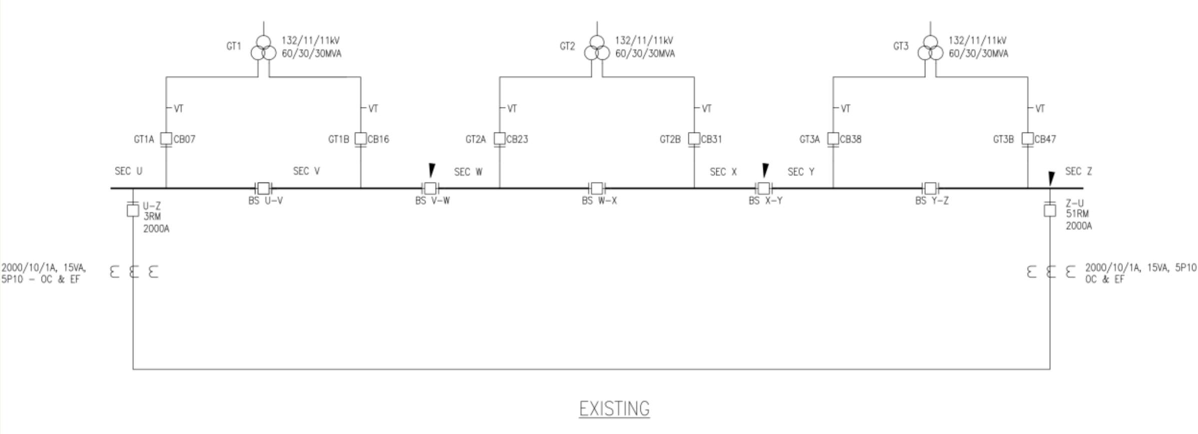


Figure 5-16: Single Line Diagram for Kitts Green prior to FCL installation

5.4.2 Network Connection

SDRC-2 explored the options for connection of a FCL at Kitts Green. The design analysis identified that the optimal solution for FCL connection was integration into the 11kV interconnector between switchgear sections U and Z using a new switchboard comprising of five circuit breakers, allowing GT1 and GT3 to be paralleled. The initial proposal for the connection of the PEFCL at Kitts Green is shown in Figure 5-17.

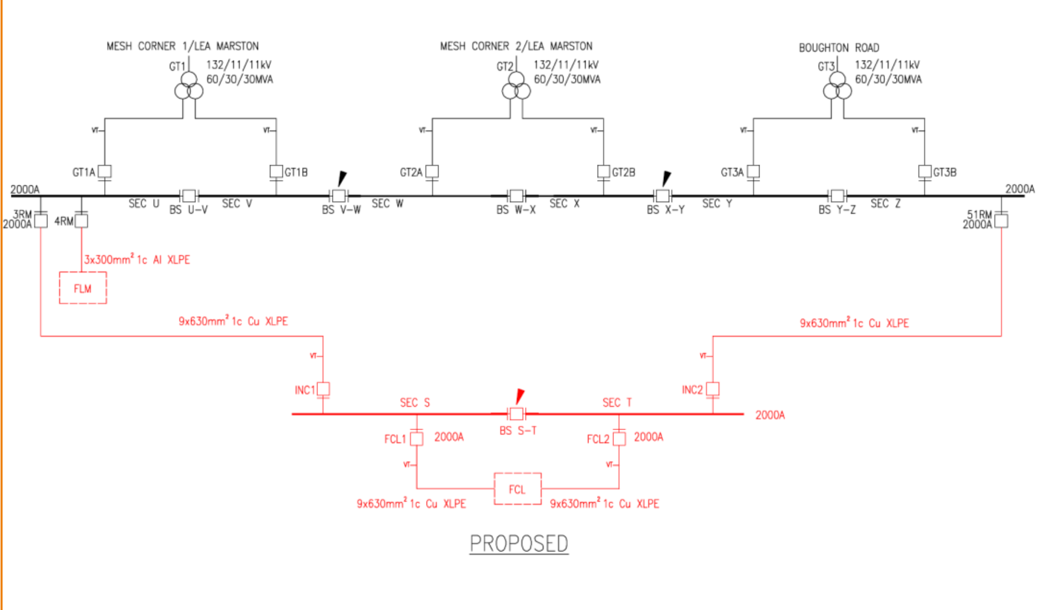


Figure 5-17: Initial PEFCL connection at Kitts Green

During the detailed design phase of the GE PEFCL a number of design changes were implemented to the device. One of these changes was to incorporate the FCL1 and FCL2 circuit breakers into the PEFCL enclosure. In addition, WPD decided to include an additional Bypass circuit breaker inside the PEFCL enclosure. The Bypass circuit breaker was required to bypass current flow from the PEFCL and restore the interconnector to its previous running arrangement, for the instance the FCL is off or a transformer is out of service so limitation is not required. With the incorporation of these circuit breakers inside the enclosure there was now no requirement for the new five panel switchboard. The rationalised design reduced the number of new circuit breakers by two units. The final single line diagram is presented in Figure 5-18.

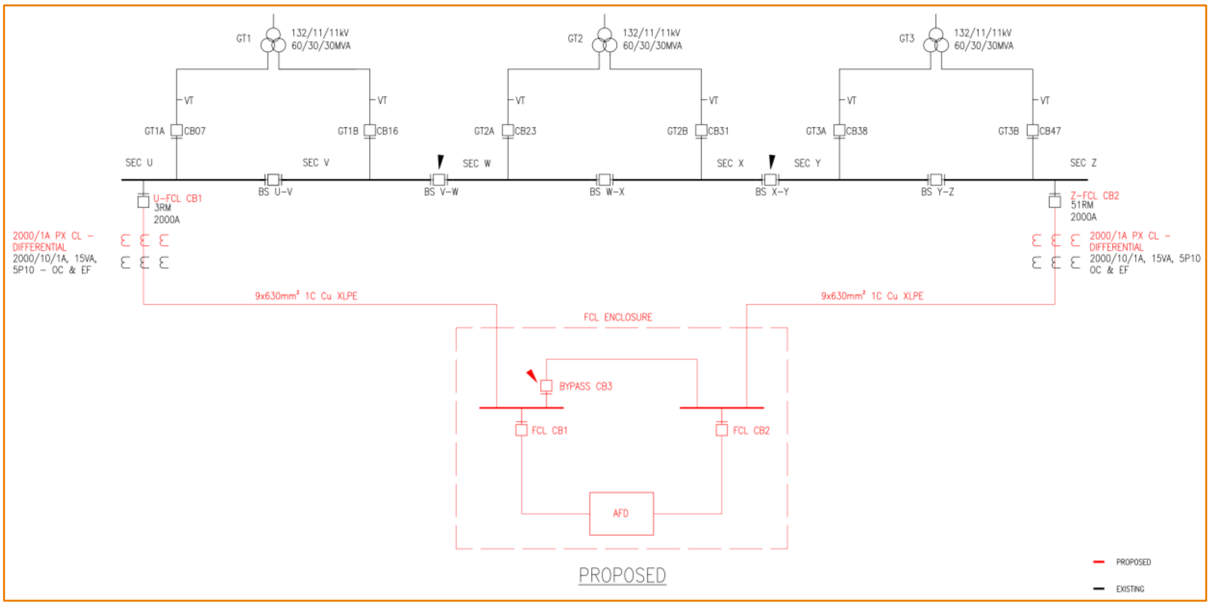


Figure 5-18: Final PEFCL connection at Kitts Green

5.4.3 FCL Location

The Kitts Green PEFCL was planned to be installed adjacent to the Fault Level Monitoring (FLM) compound on the large area of empty land in the South East corner of the substation compound and opposite the existing substation building. There are a number of 11kV feeder cables traversing the spare land adjacent to the substation building. The final setting out point of the PEFCL was chosen to avoid these cables so as to reduce the risk of cable damage during the device installation. The layout of the PEFCL is shown in Figure 5-19. The PEFCL container is shown in the bottom left corner of the figure.

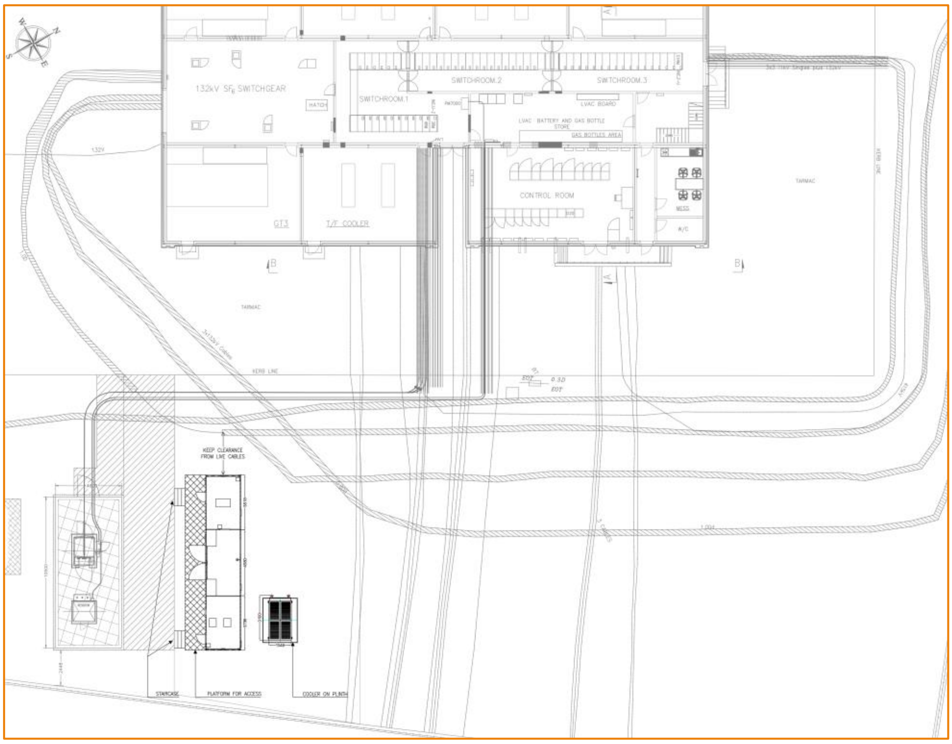


Figure 5-19: Layout of the PEFCL at Kitts Green

5.4.4 Protection

The design of the PEFCL protection scheme was simple as the device had negligible impedance and could therefore be treated as if it were a cable. A basic current differential scheme was to be employed across the two interconnector circuit breakers supplying the PEFCL with back-up overcurrent protection. Additional CTs were to be installed in the two interconnector circuit breakers as there was no current differential scheme on the 11kV interconnector at Kitts Green.

A new protection panel was ordered to receive the hardwired alarm and trip signals from the PEFCL. This panel would be used as the interface between the PEFCL and WPD circuit breakers and Network Control. The protection panel was equipped with a mimic panel which would allow operators to see the position PEFCL and associated circuit breakers. Figure 5-20 shows the configuration of the mimic on the panel.

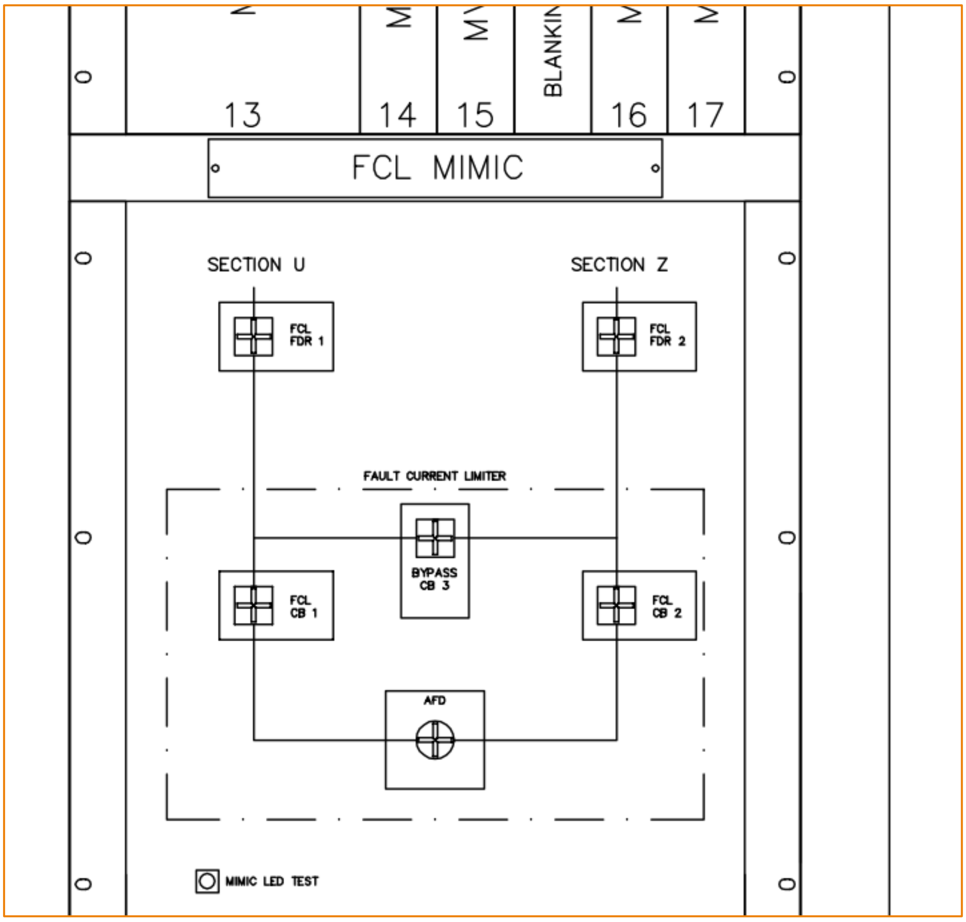


Figure 5-20: PEFCL mimic on protection panel

5.5 Bartley Green

The PEFCL was not installed at Bartley Green as the manufacturer (GE) could not provide WPD with a functional and safe device for connection to the 11kV distribution network within the required project timescales. However, the following sections detail the design and preparatory works that were implemented by WPD to allow the integration of the PEFCL at Bartley Green. The aim of this section is to disseminate the main learning outcomes obtained during the design stages of the project.

5.5.1 Substation Overview

Bartley Green 132/11kV substation was commissioned circa 1960. The 132kV equipment is open busbar and located in a dedicated compound. There are two incoming 132kV underground cable circuits from Kitwell and Chad Valley. Each circuit supplies a 132/11kV, 30MVA transformer, with each transformer supplying a single section of 11kV single busbar. A single line diagram of the substation is shown in Figure 5-21 below. The original GEC 11kV switchgear was replaced by modern Hawker Siddeley Eclipse switchgear in 2014.

5.5.2 Network Connection

Bartley Green has two grid transformers each supplying a single section of 11kV busbar with an 11kV interconnector between the bus section U and X as shown in Figure 5-21. It was therefore decided to integrate the PEFCL in the existing interconnector as this was the solution with the minimum requirement for new circuit breakers. The final single line diagram is presented in Figure 5-22.

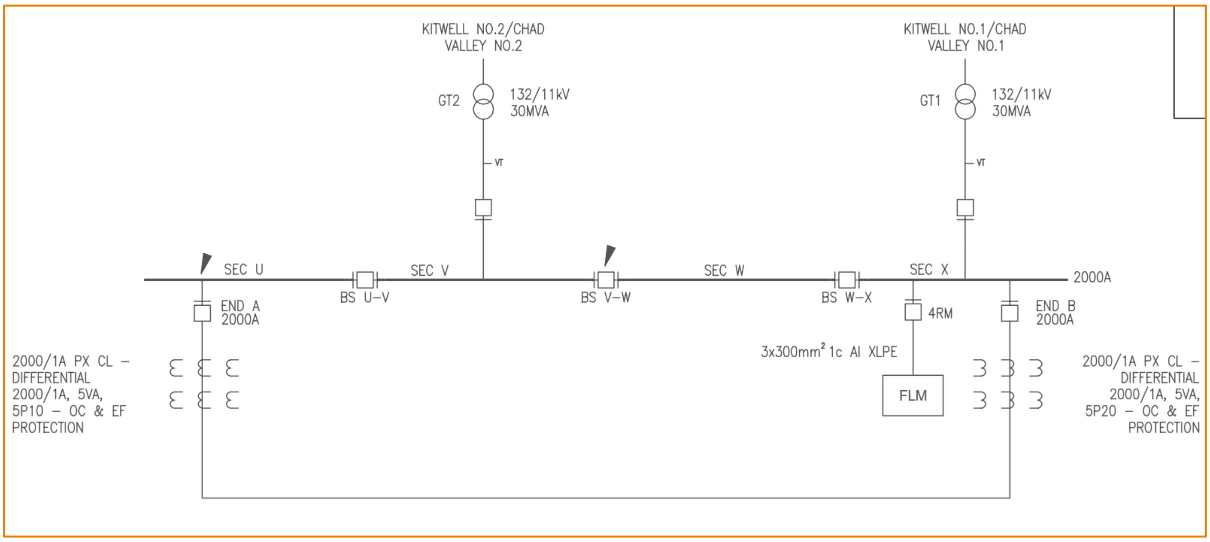


Figure 5-21: Single Line Diagram for Bartley Green prior to FCL installation

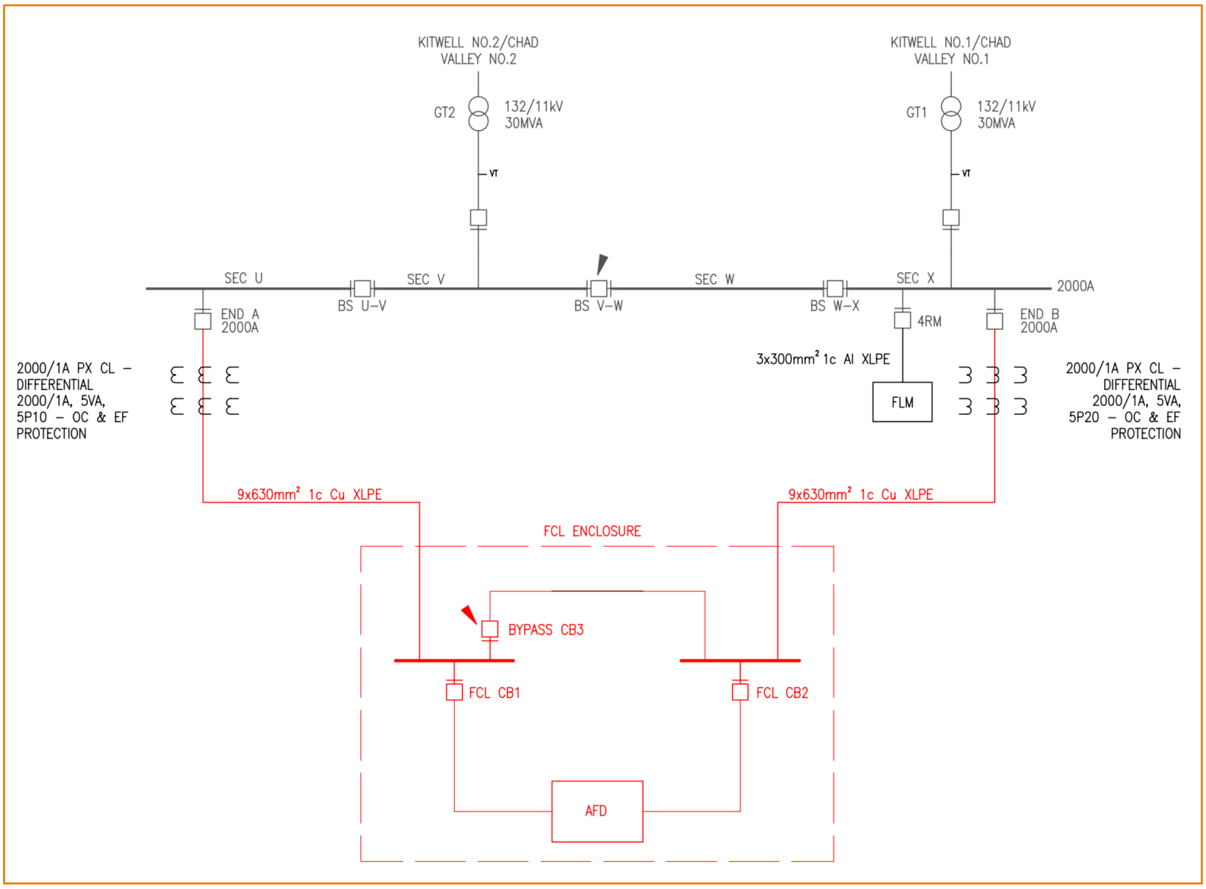


Figure 5-22: Final PEFCL connection at Kitts Green

5.5.3 FCL Location

The Bartley Green PEFCL was planned to be installed on a spare plot of land opposite the 132kV compound and adjacent to the FLM equipment. This location was chosen because of the available space and the road access for the 132kV compound which could have been used for delivery and offloading of the PEFCL. This area of land also had the benefit of having very few buried utility services in the vicinity. The layout of the PEFCL is shown in Figure 5-23. The PEFCL container is shown in red. The positioning of the equipment was carefully considered to ensure sufficient access around the FCL and FLM equipment, whilst ensuring no clearance infringements were created with existing buildings.

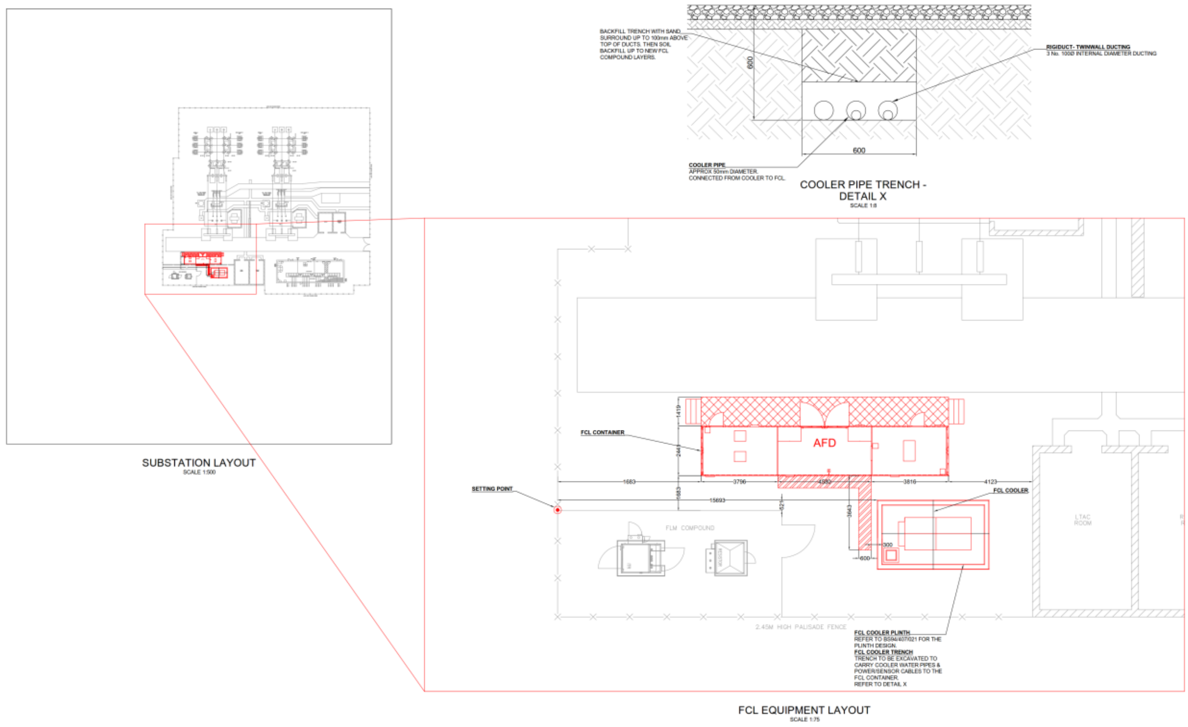


Figure 5-23: Layout of the PEFCL at Bartley Green

5.5.4 Protection

The protection design for Bartley Green PEFCL was very similar to Kitts Green as the device interface was identical. However, the Automatic Voltage Control (AVC) scheme at Bartley Green would have required modification as the existing scheme was not capable of determining when the network was operating in parallel through the PEFCL, as without an FCL this would be managed manually. Figure 5-24 shows a picture of the existing relays at Bartley Green.

Figure 5-24: Existing AVC relay panels at Bartley Green

A new AVC design was produced to replace the 1950 AVE3 relays with more modern SuperTAPP RVM/4M relays capable of determining when to run in split and parallel configuration.

5.6 PEFCL Design

5.6.1 FCL Dimensions and Weight

The initial GE proposal for the PEFCL container can be seen in Figure 5-25. It was proposed to install the equipment in a modified 20ft shipping container. A number of significant issues with this initial design were communicated to GE. The main comments were as follows:

- Insufficient safety clearances around the switchgear;
- Insufficient clearances for cabling;
- Switchgear inside the same room as the exposed 11kV conductors for the power electronic components; and
- Insufficient space for ancillary equipment.

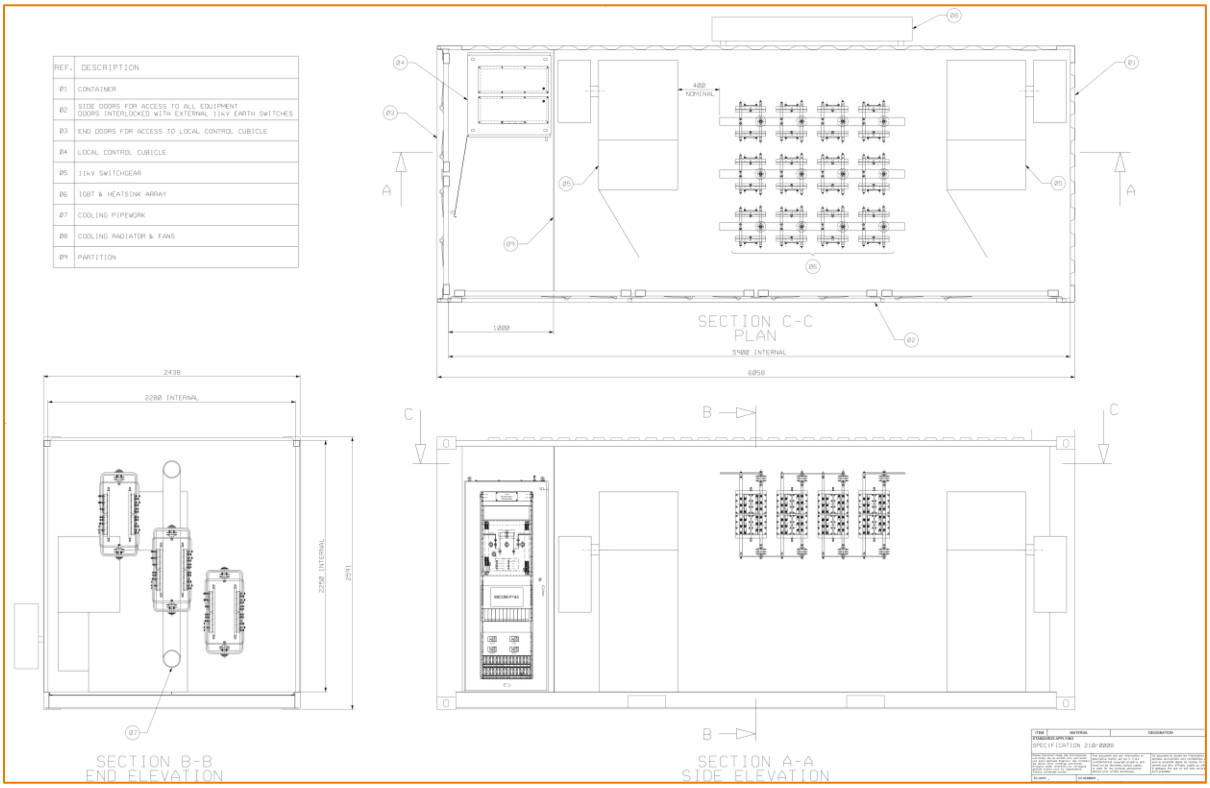


Figure 5-25: Initial PEFCL container layout

A number of iterations of the draft general arrangement were reviewed and commented on by WPD during the detailed design. The final draft general arrangement is shown in Figure 5-26 below. It is important to note that a final detailed general arrangement was not received from GE during the design phase of the project. This is discussed further in the Learning and Conclusions in Section 9.

It can be seen from a comparison of the two figures that a significant increase in the size of the enclosure was required to allow the proper setting out of the switchgear, power electronic equipment and ancillary equipment. The enclosure was changed from a standard 20ft shipping container to a larger 40ft unit. In addition, the exposed 11kV conductors were contained in a central room away from all operational equipment and with appropriate interlocking arrangements.

The final 40ft enclosure had an approximate weight of 14 tonnes, marking a significant increase from the initial 20ft container design which had a weight of approximately 4 tonnes with all equipment installed. The increase in both dimensions and weight as the project progressed was correctly managed at the design stage and did not have an impact on the works to integrate the device into the 11kV distribution network.

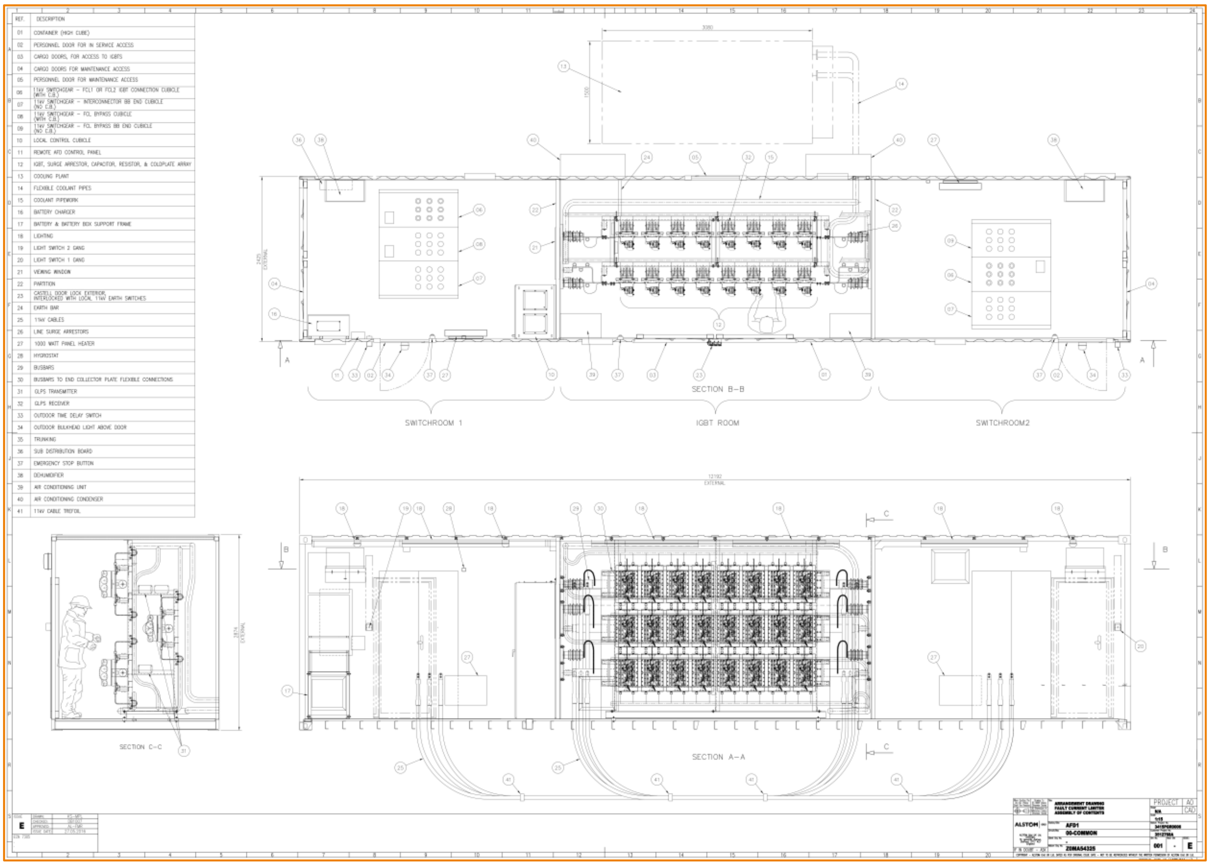


Figure 5-26: Final PEFCL container layout

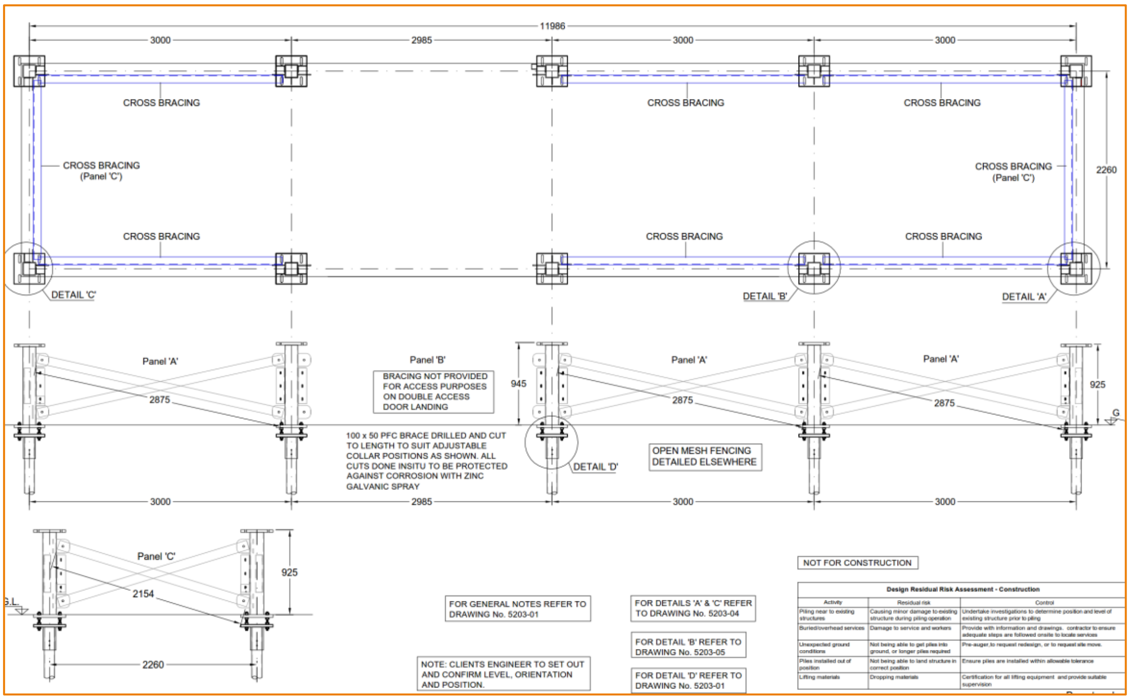
5.6.2 Civil works

The PEFCL is housed in a standard 40ft shipping container which was modified to allow integration of the various PEFCL components. WPD investigated a range of options for providing the foundation supports for the PEFCL. It was decided to utilise a helical pile support structure for the PEFCLs. An example of a helical pile structure from another project is shown in Figure 5-27.

Figure 5-27: An example of a helical pile support solution

The piling solution was chosen because it allowed for quicker erection and installation times over a traditional concrete foundation. In addition, the piles allowed the PEFCL container to be raised approximately 1m above ground level which would have allowed sufficient space underneath for the installation and termination of the HV cabling to the device.

The size and number of the helical piles are designed according to the structural loading of the PEFCL and the soil bearing capacity of the site. We gathered the required information and submitted this to the helical pile subcontractor to design the required structure. The helical pile structure for the Kitts Green device was designed and constructed. An extract from the approved piling design drawings is given in Figure 5-28 below. WPD stopped the design for the Bartley Green helical pile structure prior to approval after it was learnt that the PEFCLs would not be ready for testing and installation as per the project timescales.



Design Residual Risk Assessment - Construction

Activity	Residual risk	Control
Piling near to existing structures	Causing minor damage to existing structure during piling operation	Undertake investigations to determine position and level of existing structure prior to piling
Buried/overhead services	Damage to service and workers	Provide with information and drawings. contractor to ensure adequate steps are followed onsite to locate services
Unexpected ground conditions	Not being able to get piles into ground, or longer piles required	Pre-auger,to request redesign, or to request site move.
Piles installed out of position	Not being able to land structure in correct position	Ensure piles are installed within allowable tolerance
Lifting materials	Dropping materials	Certification for all lifting equipment and provide suitable supervision

Figure 5-28: Kitts Green helical pile design drawing

5.6.3 Tenders

The main contractor for the installation and commissioning works at Kitts Green was successfully appointed and preparatory civil works had been implemented prior to the redesign of the PEFCL. The redesign was triggered after a number of fundamental design issues were discovered with the device. These issues are described in detail in Section 6.4. After this discovery the main contractor was informed to cease all site activity until the redesign was complete. When the redesign of the PEFCL was nearing completion the Kitts Green main contractor was instructed to mobilise for a second time. Concurrently, the Bartley Green tender was produced and released. We had received the responses to the tender prior to further design and build issues were discovered with the PEFCLs. At this point we decided to cease works at both Kitts Green and Bartley Green as the PEFCLs were unable to be built and tested to the required project timescales.

6 Testing

6.1 Castle Bromwich - PSCFCL

6.1.1 Factory Acceptance Testing

The Castle Bromwich PSCFCL underwent Factory Acceptance Testing (FAT) at the Wilson facilities in Melbourne, Australia on 6th September 2014. The standard procedure for type testing new equipment usually involves performing the short-circuit tests last in the sequence. However, due to constraints in the availability of accredited short circuit test stations, the short circuit test was witnessed before the FAT.

The design of the PSCFCL is similar to a standard power transformer and hence many of the tests in IEC 60076 are applicable. The tests performed were as follows:

- Measurement of Winding Resistance;
- Zero Sequence Impedance with Coupling Measurement;
- Measurement of Harmonic Voltage Drops;
- Measurement of Coupling Factor;
- Separate Source AC Withstand Test;
- Temperature Rise Test at Rated Continuous Current and Overload Current;
- Measurement of Acoustic Sound Power Level at Rated and Overload Currents;
- Lightning Impulse Test;
- Vacuum Withstand Test;
- Hydrostatic Oil Pressure Withstand Test on Tank;
- Immunity to Electromagnetic Disturbances;
- Magnetic Field Levels;
- Partial Discharge Measurement; and
- Sweep Frequency Response Analysis.

The device successfully passed all functional and HV tests. Figure 6-1 shows the device undergoing factory testing in Melbourne, Australia.

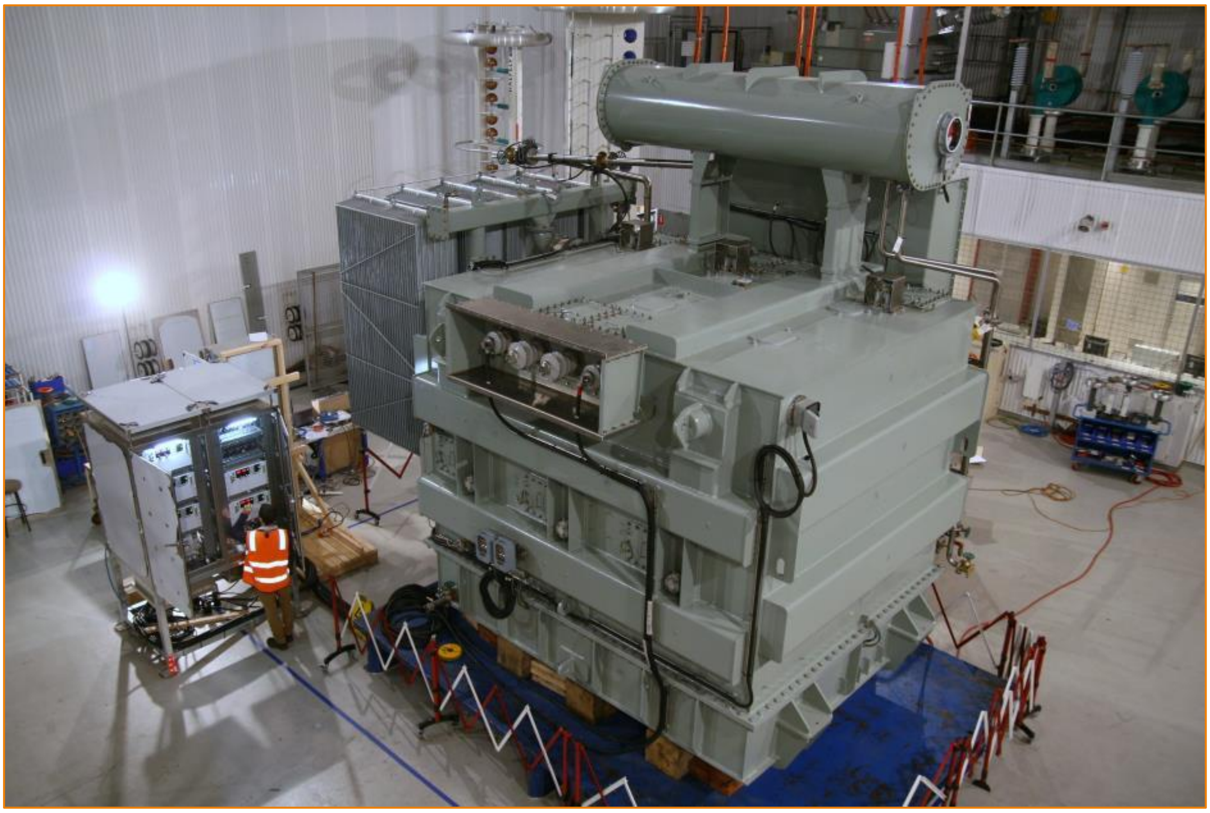


Figure 6-1: Castle Bromwich PSCFCL undergoing factory testing in Melbourne, Australia

6.1.2 Short Circuit Testing at Ausgrid Laboratory

The Castle Bromwich PSCFCL underwent type testing at Ausgrid's Testing & Certification Lab in Sydney, Australia on the 15th August 2014. The following tests were performed:

- Winding Resistance Test (before short circuit tests);
- Insulation Test (before short circuit tests);
- AC Withstand Test (before short circuit tests);
- Rated Impedance and Losses Test (before short circuit tests);
- Short Circuit Tests;
- Rated Impedance and Losses Test (after short circuit tests);
- Winding Resistance Test (after short circuit tests);
- Insulation test (after short circuit tests); and
- AC Withstand Test (after short circuit tests).

The testing station has a direct feed from Ausgrid's 132kV network. The test set-up for the short circuit testing is shown below in Figure 6-2.

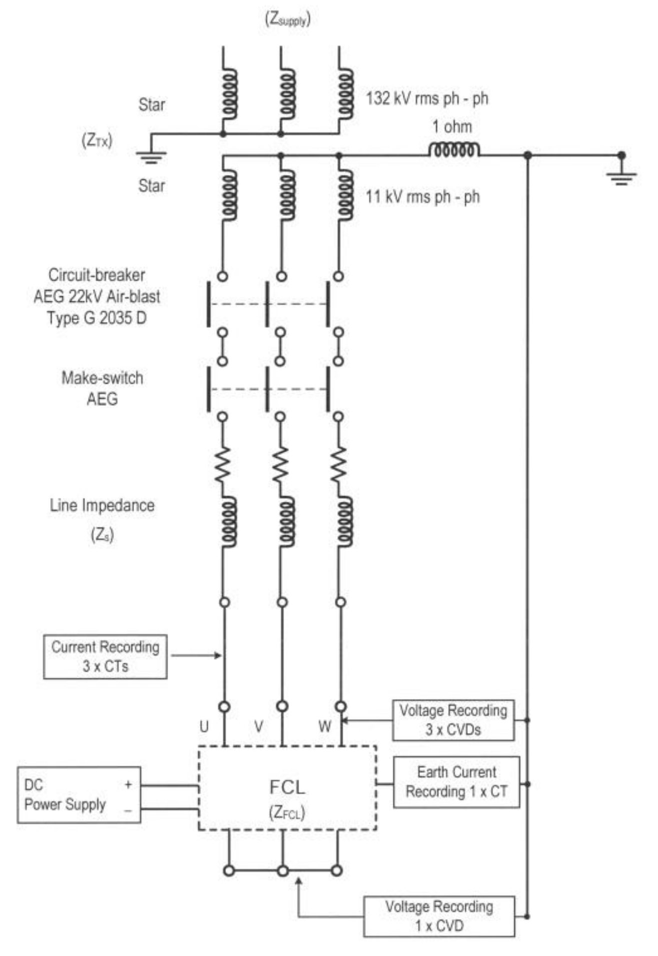


Figure 6-2: Connection diagram showing the short circuit test set-up for Castle Bromwich PSCFCL

The short circuit tests were performed with the DC bias set at its nominal value (365A) which relates to the bias required for saturation of the PSCFCL at its 30MVA rating. This level of bias was chosen because it provides the most onerous condition on fault limiting performance for the device. Additional tests were also performed on lower DC bias levels so that a comparison could be made between modelled and actual fault level reduction.

6.1.3 Short Circuit Current Limitation Results

Whilst performing the HV short circuit tests all the auxiliary equipment on the PSCFCL were monitored to ensure that any potential issues were highlighted immediately and can be investigated. During the first short circuit test, the laboratory detected that the buchholz trip relay had operated. Normally this would indicate a potential catastrophic failure inside the main tank. However, after investigation it was found the buchholz relay had operated due to the high magnetic fields generated during the short circuit. Several other tests were simulated and it was discovered that the Dissolved Gas Analysis (DGA) monitor and electronic dehydrating breather were also malfunctioning due to the high magnetic fields.

To overcome these issues the respective devices were relocated further from the main tank where the magnetic field was at the highest levels. The manufacturer was able to fabricate additional pipework which was immediately shipped from Melbourne to Sydney so that the tests could continue. Figure 6-3 shows a picture of the repositioned buchholz relay.

Figure 6-3: Repositioned buchholz relay for the PSCFCL

Following these modifications the PSCFCL successfully passed all the short circuit tests as shown in Table 6-1.

Table 6-1: Short circuit test results for PSCFCL

Scenario	Prospective Current	Required Limitation	Actual Limitation	Difference
RMS Break (nom. DC Bias)	6.85kA	4.06kA	3.71kA	**0.35kA**
RMS Break (min. DC Bias)	6.85kA	4.06kA	3.75kA	**0.31kA**
Peak Make (nom. DC Bias)	20.2kA	10.16kA	10.13kA	**0.03kA**

As part of the short circuit tests the PSCFCL also successfully underwent a 13.1kA RMS short time withstand test for three seconds under minimum DC bias (130A).

It can be seen from the test results that the PSCFCL has a greater impact on RMS break fault levels compared with peak make fault levels. The main influencing factor of this is the reaction time of the PSCFCL to sudden increase of current experienced during a fault.

6.2 Chester Street - RESFCL

6.2.1 Factory Acceptance Testing Part 1

The Chester Street FCL failed its initial Factory Acceptance Tests (18th May – 20th May 2015). When operating at its rated current of 1600A the cooling system was unable to regulate the temperature of the LN_2 to the required set-point. The temperature was seen to rise slowly and would have eventually led to a quench event. The device was unable to run continuously at its rated current of 1600A.

Nexans carried out a series of investigations to understand the behaviour of the FCL. They discovered that the device had higher electrical power losses than expected. Further investigation led to the conclusion that the additional losses were attributed to eddy currents present in the various electrical contacts in the device. In addition, it was found that air was able to leak into the cryostat vessels via a pressure relief safety valve when the pressure inside the vessel was reduced to below atmospheric pressure (1000mbar). The water vapour present in the air condensed and froze on the cold heads causing reduced heat transfer from the LN_2.

The air leakage issue was remedied by replacing the 3 no. pressure relief safety valves with a single electronic valve rated for sub-atmospheric pressures. The valve assembly on top of the vessel was redesigned with flexible pipework to accommodate the new valve and ensure a tight seal to the valve.

A solution to resolve the eddy current losses could not be found without a fundamental redesign of the internal components of the FCL. Another option could have been to replace the cryocoolers (cold head and compressors) with more powerful units capable of delivering more cooling power to the LN_2. Both solutions would have incurred significant costs and delays to the programme. A decision was made to accept the device in its de-rated condition. The Chester Street device is now rated for 1300A continuous operation with an overload capability of 1600A for a maximum of 5 hours.

In summary, the RSFCL design did not provide an adequate margin of cooling power to cover the unexpected additional electrical losses above the total calculated losses in the system.

Figure 6-4: RSFCL undergoing current testing at the Nexans factory in Hanover

6.2.2 Factory Acceptance Testing Part 2

The Chester Street device went through a second round of Factory Acceptance Tests on 21st-23rd September 2015. The device successfully passed all functional and HV tests. See Figure 6-4 showing the device undergoing current testing during the second round of testing. The tests performed were as follows:

- Insulation Resistance Measurement (before and after each test sequence);
- Temperature Rise Test;
- Acoustic Sound Level Test;
- Withstand Voltage Test;
- Lightning Impulse Voltage Test; and
- Partial Discharge Measurement Test.

Following the successful completion of the FAT the FCL went through a ‘warm-up’ process which consisted of gradually draining the LN_2 from the cryostat vessels. When the device was brought up to ambient temperature it was transported to the KEMA test laboratory in Arnhem, Netherlands for the short circuit testing.

6.2.3 Short Circuit Testing at KEMA Laboratory

The FCL was tested on 5th October 2015 in Test Bay 5 in the high current laboratory. The test set-up is shown below in Figure 6-5.

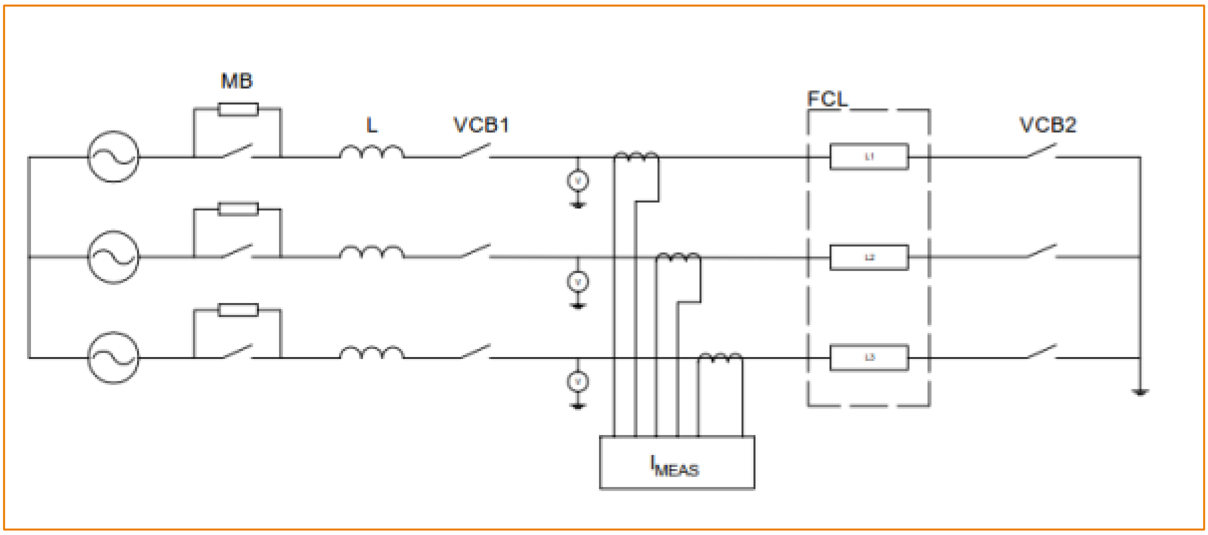


Figure 6-5: Connection diagram showing the KEMA short circuit test set-up for Chester Street FCL

The test circuit was adjusted from the original test specification to more closely follow the actual site layout. The circuit breaker VCB2 was moved downstream of the FCL prior to the start of the tests so ensure that the device was energised at 11kV prior to the initiation of the short circuit current. This was required to ensure the correct operation of the quench detection system.

The KEMA laboratory uses a generator set as the source for the short circuit tests. The excitation level and circuit X/R ratio is set prior to the testing to provide the correct prospective currents as stated in the testing specification. The master circuit breaker MB and vacuum breaker VCB1 was closed to energise the device to 11kV. The circuit breaker VCB2 was closed to initiate the short circuit current. Upon initiation of the short circuit a timer was started by the KEMA control system. An open command was sent to VCB2 after 100ms to ensure that the FCL was disconnected from the source to avoid damage to the FCL.

The Chester Street FCL is shown undergoing the short circuit testing in Figure 6-6.


Figure 6-6: Chester Street FCL during short circuit testing at the KEMA laboratory

6.2.4 Short Circuit Current Limitation Results

The testing began with two short circuit tests without the FCL connected in the test circuit. This was to measure the prospective currents and modify the circuit parameters to ensure the prospective current values were as close to those specified in the test specification as possible. The prospective current values for Chester Street were specified as 19.76kA (make) and 7.17kA (break).

Three short circuit tests were carried out with the FCL connected into the circuit. The results of these tests are summarised in Table 6-2. The tests were carried out so that the prospective peak current was applied initially to phase L3 and then lastly phase L1. This was to ensure that each phase had a similar number of tests to avoid unduly stressing any particular phase. The table shows that all tests were passed successfully.

One of the parameters for a successful test pass was that the ‘trip signal’ from the quench detection system was under 20ms. It is to be noted that in the first test the trip signal exceeded this value. After an investigation it was found that the quench detection system had an unnecessary auxiliary relay in the trip circuit which was slowing the transmission of the trip signal to the KEMA measurement equipment. This was removed as it was unnecessary. For the remaining tests the trip signal was successfully received in less than 20ms.

Table 6-2: Chester Street short circuit testing summary

Prospective Current (@10ms) (kA)	Prospective Current (@90ms) (kA)	Phase	Required Limitation (@10ms) (kA)	Required Limitation (@90ms) (kA)	Limited Current (@10ms) (kA)	Limited Current (@90ms) (kA)	Trip Signal (ms)
20.0	7.17	L3	9.90	3.68	9.07	2.86	24.0
20.0	7.17	L3	9.90	3.68	9.11	2.83	15.0
20.0	7.17	L1	9.90	3.68	9.14	2.87	15.0

6.2.5 Short Circuit Withstand Results

The final test to be performed on the FCL was the short circuit withstand test. The test utilised the same test circuit for the short circuit limitation tests (refer to Figure 6-5).

The testing began with two short circuit tests without the FCL connected in the test circuit. This was to measure the prospective current and modify the circuit parameters to ensure the prospective current value were as close to that specified in the test specification. This test required the device to withstand a short circuit current of 33.4kA.

A single short circuit test was then carried out with the FCL connected into the circuit. The test was carried out so that the prospective peak current was applied to phase L2 which previously hadn’t experienced a short circuit test. The device successfully withstood a peak prospective current of 34.2kA and limited this current to 9.59kA. The limitation of the short circuit current is shown graphically in Figure 6-7.

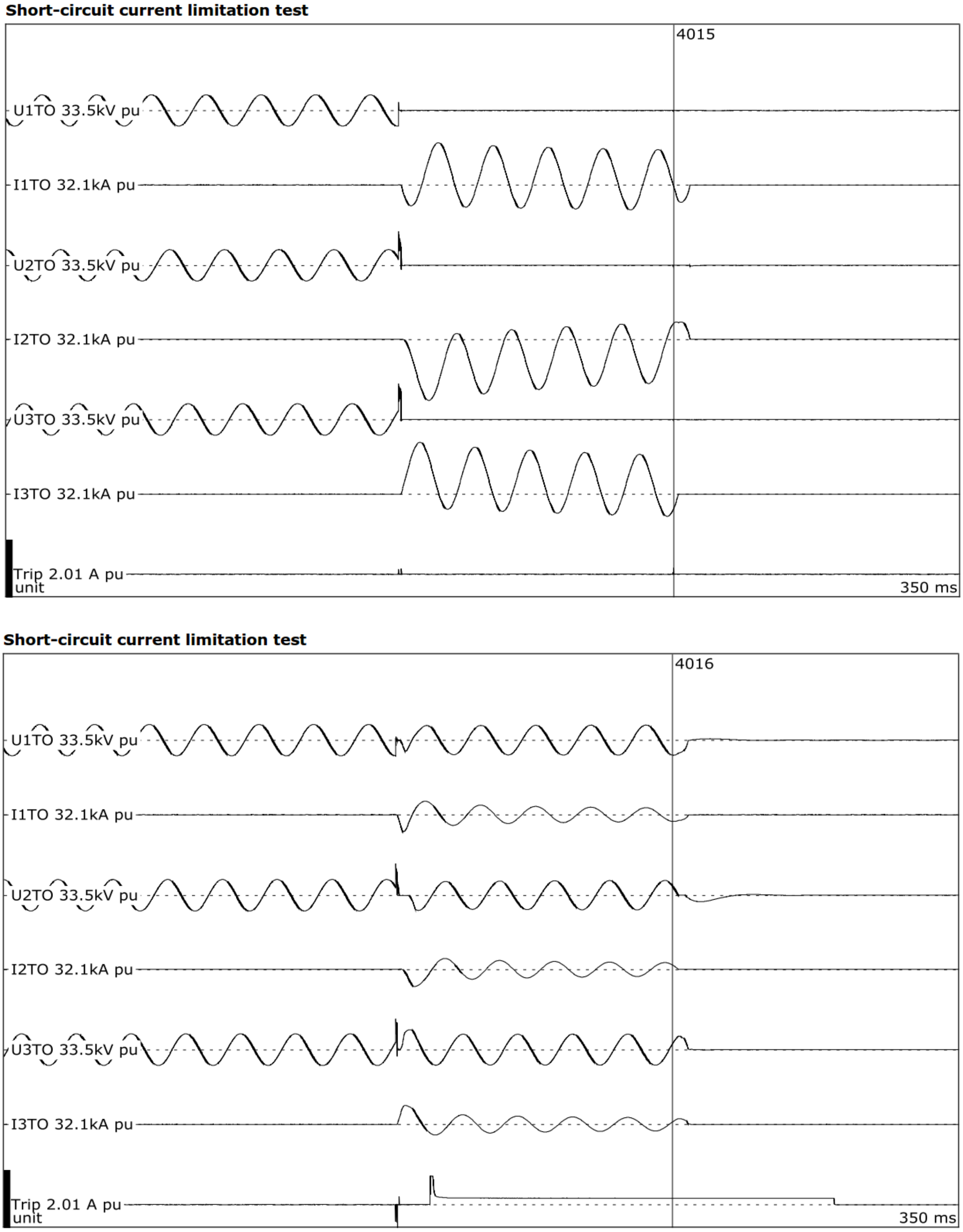


Figure 6-7: Graph showing the short circuit withstand prospective peak current applied to phase L2 (top) and the limited current through the Chester Street FCL (Bottom)

6.3 Bournville - RSFCL

6.3.1 Factory Acceptance Testing

During the FAT of the first RSFCL device it was discovered that the cooling system did not provide an adequate margin of cooling power to cover the total electrical losses in the device. Nexans confirmed that this was due to a design flaw in the internal connections of the RSFCL which was common to both Chester Street and Bournville devices.

It was proposed to install an additional two cryocoolers (cold head and compressor) on the device to increase the cooling power and ensure that the Bournville device could operate at its continuous rated current. Additional modifications to the safety valve assembly were also implemented. The changes to the cooling system subsequently introduced delays into the site construction programme.

The modified Bournville device was subjected to Factory Acceptance Tests between 30th November and 2nd December 2015 in Hanover, Germany. The device successfully passed all functional and high voltage testing. The tests performed were as follows:

- Insulation resistance measurement (before and after each test sequence);
- Temperature rise test;
- Acoustic sound level test;
- Withstand voltage test;
- Lightning impulse voltage test; and
- Partial discharge measurement test.

Figure 6-8 below shows the Bournville FCL undergoing testing during the FAT in Nexans facility in Hanover, Germany.

Figure 6-8: Bournville FCL undergoing testing during FAT

Following the successful completion of the FAT the FCL went through a ‘warm-up’ process which consisted of gradually draining the LN_2 from the cryostat vessels. When the device was brought up to ambient temperature it was transported to the KEMA test laboratory in Arnhem, Netherlands for the short circuit testing.

6.3.2 Short Circuit Testing at KEMA Laboratory

The FCL was tested on 7th December 2015 in Test Bay 5 in the high current laboratory. The test set-up is shown below in Figure 6-9.

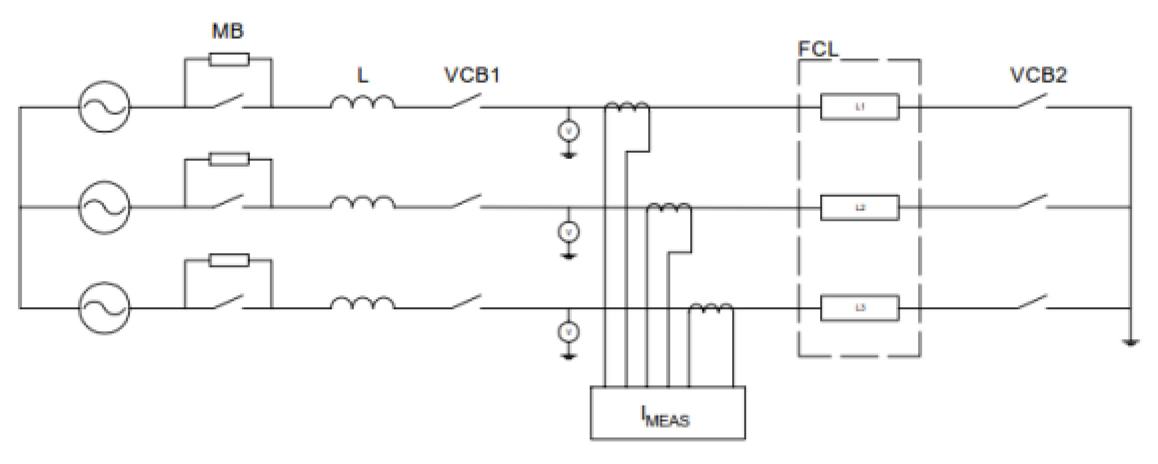


Figure 6-9: Connection diagram showing the KEMA short circuit test set-up for Bournville FCL

The KEMA laboratory uses a generator set as the source for the short circuit tests. The excitation level and circuit X/R ratio is set prior to the testing to provide the correct prospective currents as stated in the testing specification. The master circuit breaker MB and vacuum breaker VCB1 was closed to energise the device to 11kV. The circuit breaker VCB2 was closed to initiate the short circuit current. Upon initiation of the short circuit a timer was started by the KEMA control system. An open command was sent to VCB2 after 100ms to ensure that the FCL was disconnected from the source to avoid damage to the FCL.

The Bournville FCL is shown undergoing the short circuit testing in Figure 6-10 below.

Figure 6-10: Bournville FCL during short circuit testing at the KEMA laboratory

6.3.3 Short Circuit Current Limitation Results

The testing began with three short circuit tests without the FCL connected in the test circuit. This was to measure the prospective currents and modify the circuit parameters to ensure the prospective current values were as close to those specified in the test specification as possible. The prospective current values for Bournville were specified as 21.97kA (make) and 7.66kA (break).

Three short circuit tests were carried out with the FCL connected into the circuit. The results of these tests are summarised in Table 6-3. The tests were carried out so that the prospective peak current was applied initially to phase L1 and then lastly phase L3. This was to ensure that each phase had a similar number of tests to avoid unduly stressing any particular phase.

One of the parameters for a successful test pass was that the 'trip signal' from the quench detection system was under 20ms. All tests were successfully passed as shown in Table 6-3.

Table 6-3: Bournville short circuit testing summary

Prospective Current (@10ms) (kA)	Prospective Current (@90ms) (kA)	Phase	Required Limitation (@10ms) (kA)	Required Limitation (@90ms) (kA)	Limited Current (@10ms) (kA)	Limited Current (@90ms) (kA)	Trip Signal (ms)
22.5	8.0	L1	7.70	3.05	6.64	2.05	13.3
22.5	8.0	L2	7.70	3.05	6.56	2.03	13.6
22.5	8.0	L3	7.70	3.05	6.43	1.98	13.6

6.3.4 Short Circuit Withstand Results

The final test to be performed on the FCL was the short circuit withstand test. The test utilised the same test circuit for the short circuit limitation tests (refer to Figure 6-9).

The testing began with one short circuit test without the FCL connected in the test circuit. This was to measure the prospective current and modify the circuit parameters to ensure the prospective current value were as close to that specified in the test specification. This test required the device to withstand a short circuit current of 33.4kA. The prospective peak current was set at 33.8kA.

A single short circuit test was then carried out with the FCL connected into the circuit. The test was carried out so that the prospective peak current was applied to phase L3. The device successfully withstood the peak prospective current of 33.8kA and limited this current to 6.45kA. The limitation of the short circuit current is shown graphically in Figure 6-11.

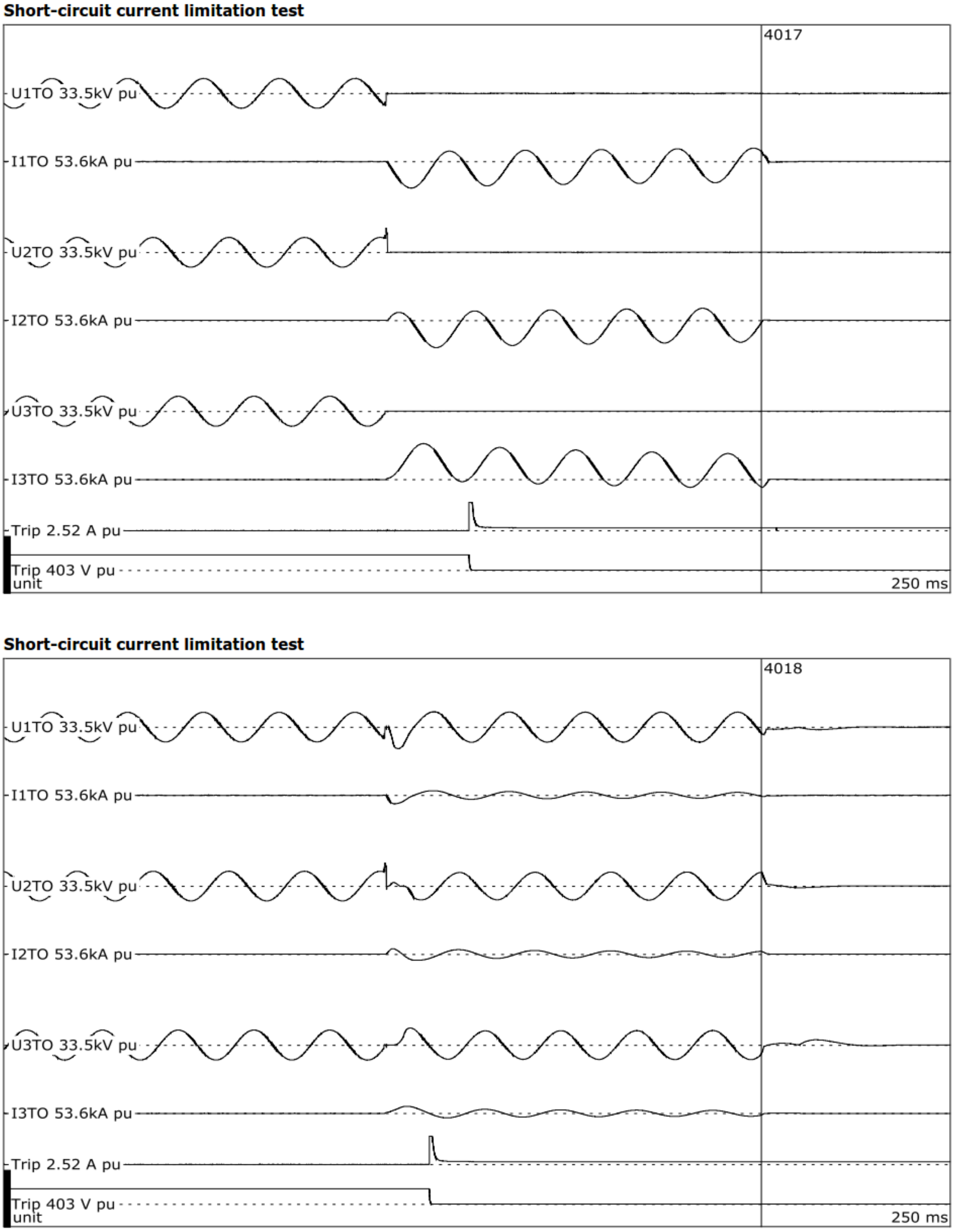


Figure 6-11: Graph showing the short circuit withstand prospective peak current applied to phase L2 (top) and the limited current through the Bournville FCL (Bottom)

6.4 Preparatory Work for PEFCL

6.4.1 Overview

As explained previously, the electrical and mechanical build for the GE PEFCL was delayed beyond the acceptable delivery timescales of the project. Through the design process testing procedures were being written in preparation for Factory Acceptance and Short Circuit Testing of the PEFCL. However during the initial review of the testing specification a number of issues arose that resulted in the re-design of the PEFCL. The level of re-design of the PEFCL was significant along with the requirement to change the GE delivery meant that the re-designed device was never able to be tested. This section describes the review of the GE Testing Specification and the subsequent design alterations that had to be implemented to ensure that the PEFCL would meet the requirements in the contract.

6.4.2 Testing Specification

There were several revisions of the GE Testing Specification that were produced. The initial review found that the testing specifications were not suitably detailed to allow the reader to understand the procedure and methodology for each test. After further review of the testing specification it was decided that the PEFCL would not be able to successfully pass the tests required by the contract. The short circuit limitation test and voltage withstand test were two main areas of concern. A description of these issues and the subsequent design alterations are listed in the following sections.

6.4.3 Current Chopping

The PEFCL is designed to “switch-off” high levels of current in around 20µs to limit the fault current before it reaches the first peak. When the current is suddenly interrupted, the energy generated is transferred into a significant transient over voltage. The design of the PEFCL did not allow for this energy to be fully absorbed and hence the PEFCL and adjacent equipment would be subject to unacceptable levels of over voltage.

The proposal to overcome this issue was to increase the rating of the surge arrestors located inside the 11kV switchgear panels from 6kJ to 11kJ.

6.4.4 IGBT Voltage Sharing

The PEFCL comprises of a number of “banked” IGBTs to allow for the passage of current up to 2000A and operation at 11kV. The PEFCL had the risk that the IGBTs may not share voltage equally and therefore some IGBTs may be subject to more stress than others. In addition, we requested that GE consider the potential over voltages that could occur due to out of synchronisation switching of IGBTs during normal operation.

GE proposed to install a resistor and capacitor in series across the collector and emitter of each IGBT to ensure that any stresses are constrained across each IGBT and resolve this potential issue.

6.4.5 Insulation Level

The functional and contractual requirements of the PEFCL require a dielectric design to withstand 28kV (rms) and 95kV lightning impulse (peak). Having reviewed the design of the PEFCL it was identified that it would not be able to undergo the insulation tests and withstand the figures quoted previously.

A number of changes had to take place to rectify this design issue:

- Re-design the 11kV busbar connections;
- Use insulators to isolate the IGBTs from the metal frame;
- Relocate the pump temperature sensors to the plastic pipework;
- Replace cooling fluid with de-ionised water; and
- Isolation of the IGBT power drives.

7 Installation

The following sections describe the installation of the three FCLs as part of the FlexDGrid project. For each site, a description of how the FCL was transported, delivered and positioned in its final location is given. In addition, the main aspects of the installation and commissioning of the FCLs is presented.

7.1 Castle Bromwich

The Castle Bromwich FCL was delivered to site on 10th December 2014 after the successful type tests in Melbourne, Australia on 6th September 2014. This large time difference between testing and delivery was due to the time required to ship the device to the UK from Australia.

7.1.1 Logistics

The initial logistics plan was to ship the device to Southampton where it would be offloaded and transported to Castle Bromwich by road. Government regulations stipulated that the device had to be shipped to the nearest port to the final installation location due to the size and weight of the device. Therefore, the plan was modified so that the device was initially shipped to Southampton, transferred onto another ship that proceeded to Ellesmere Port and then offloaded for road transit. Figure 7-1 shows the device being offloaded at Ellesmere Port.

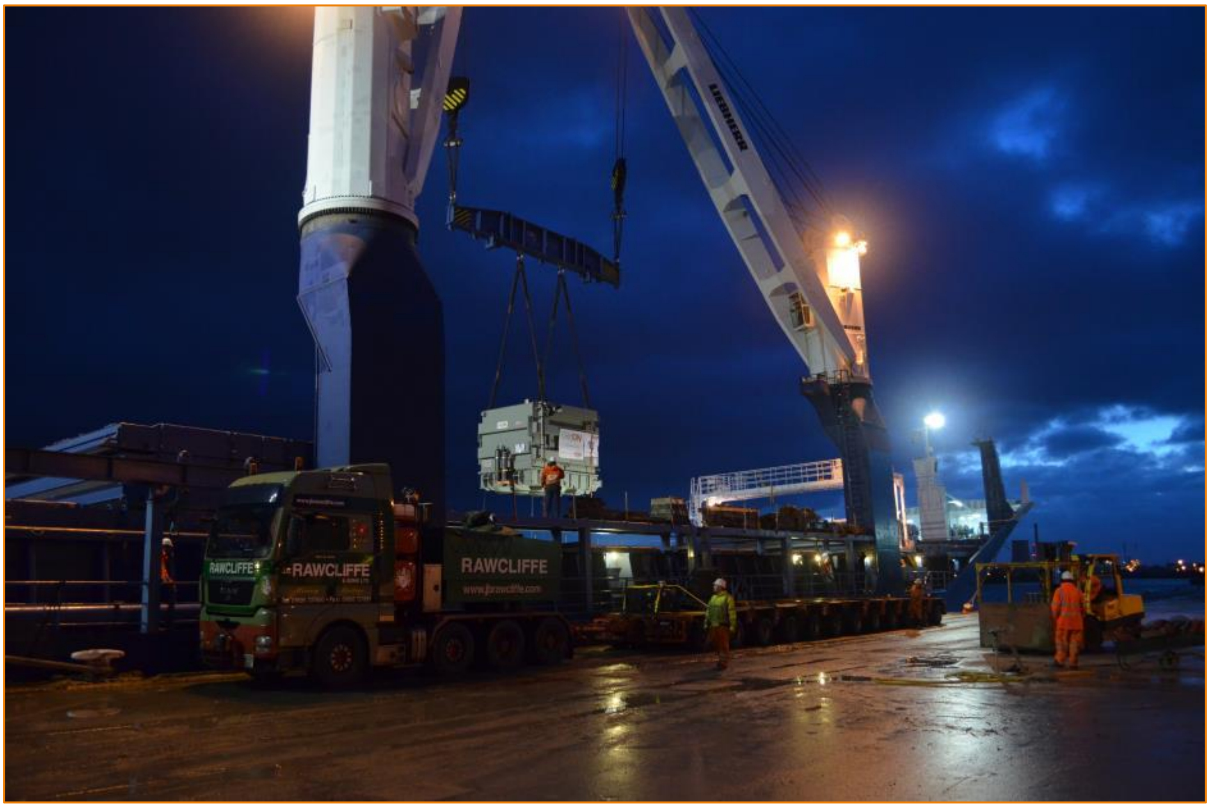


Figure 7-1: Castle Bromwich FCL being offloaded at Ellesmere Port

7.1.2 Final Positioning

The FCL was installed in the spare indoor transformer bay at Castle Bromwich substation. An external wall of the transformer bay was removed to allow the FCL to be skidded into its final position on the plinth inside the transformer bay. It was ensured that adequate clearances were available to enable the installation of the device during the detailed design. Figure 7-2 shows the device being prepared for skidding into its final position at site.

Figure 7-2: Castle Bromwich FCL being prepared for skidding into the spare transformer bay

Once the device was positioned correctly the external wall was reinstated and the remaining installation and commissioning works were completed.

7.1.3 Magnetic Shielding

As part of the contractual requirements a maximum strength of magnetic field that the device should produce at a pre-determined distance was identified. For the Castle Bromwich FCL it was determined that the maximum value of 500µT (the maximum safe exposure level for the public) should not be apparent outside of the FCL bay. The FCL manufacturer produced simulations to show the strength of the magnetic field and how this could be controlled to be within the limits of the contract. Due to the DC power supplies producing a high strength field around the core of the device, a substantial steel shield had to be installed inside the FCL bay.

The steel shield required structural calculations to be undertaken to ensure the strength of the substation building was sufficient to accommodate the additional load.

Following installation, the shield was tested and found to need some minor modifications. The second magnetic field test was successful and passed the requirements in the contract.

The appearance of the bare steel shield was not found to be acceptable due to poor installation by the sub-contractor employed by the FCL manufacturer. Therefore the decision was made to provide a covering over the shield to ensure staff could not be injured by protruding parts of the shield (see Figure 5-5).

7.1.4 Impact on Protection Settings

Before commissioning there were a number of studies undertaken to establish the effect that the FCL would have on the fault level at Castle Bromwich under different scenarios. These studies formed the basis for the calculation of protection settings on the new 11kV switchboard and surrounding equipment.

It was discovered during these studies that the fault level contribution from the FCL for busbar faults in Castle Bromwich was quite low. This was not an issue for the primary protection on the new 11kV switchboard as busbar protection had been provided. However, back-up protection settings had to be carefully calculated to ensure that correct grading was achieved. Working closely with the Primary System Design (PSD) team a solution was identified to incorporate additional intertripping between circuit breakers to ensure the protection system was not compromised. Figure 7-3 shows the modifications that were made to the existing protection system to overcome the shortfalls.

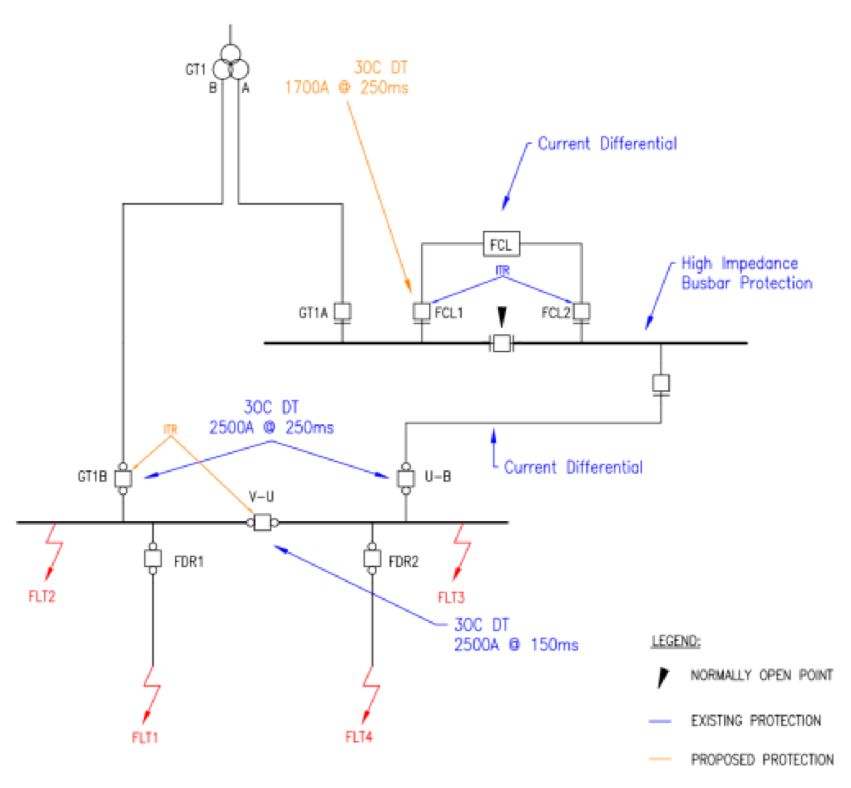


Figure 7-3: Existing and proposed protection modifications

7.2 Chester Street

The Chester Street FCL was delivered to site on 11th October 2015 after successful short circuit testing at the KEMA test facilities in Arnhem, Netherlands.

7.2.1 Logistics

The Chester Street device was pre-installed in a concrete enclosure weighing approximately 30 tonnes. The device was transported via road from the testing facility in Arnhem to Chester Street. The device was then craned into its final position over the substation boundary fence from the adjacent public road. For this to take place a temporary road closure was organised. Figure 7-4 shows the device being delivered at Chester Street.

Figure 7-4: Chester Street FCL being delivered to site

7.2.2 HV Cabling

The bushings to allow connection of the 11kV cables to the FCL are positioned on the top of the cryostat vessels. There are two bushings per phase; an incoming and outgoing connection point. The cables are connected to the bushings via Euromold standardised encapsulated coupling connectors that are stackable to allow for the required cross-sectional area. The FCL required six 630mm^2 cables per phase (3 incoming, 3 outgoing). The connectors required for a single bushing are shown in Figure 7-5. The top connector is for the Voltage Transformer (VT) cable.

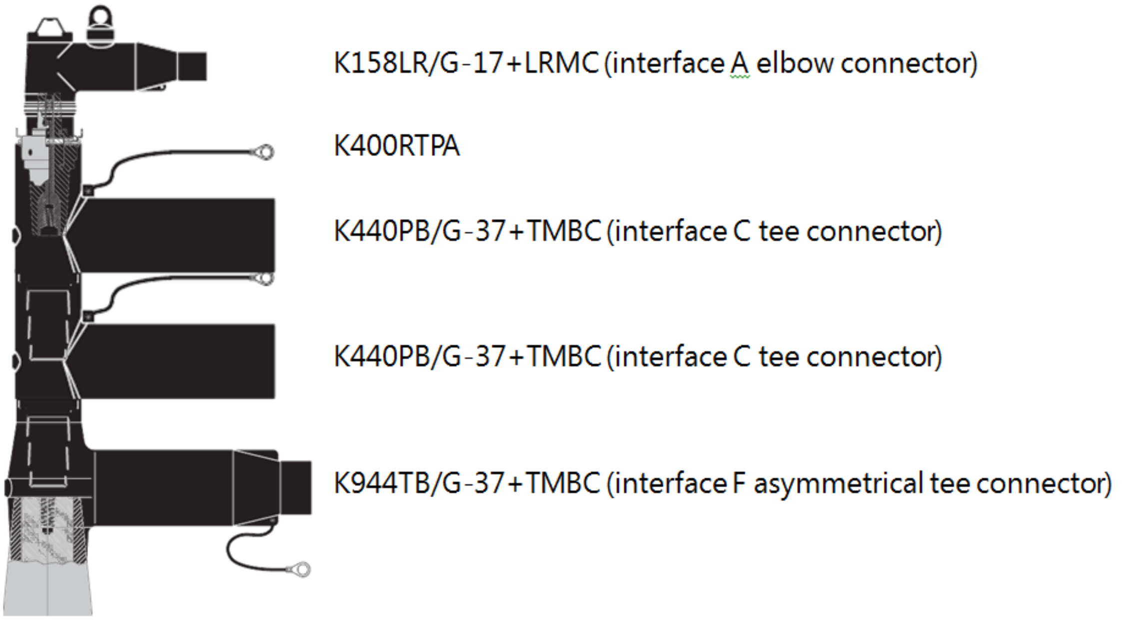


Figure 7-5: HV cable interface connection

The 11kV cabling was the first installation activity after the offloading and positioning of the concrete enclosure onto the foundation. The cables were pulled into the enclosure through ducts at the base of the enclosure at the opposite side to the cryostats and bent by 90 degrees to enable termination to the device. The installation team experienced difficulty with terminating the cables to the stacked connectors using the cable support frame provided. If the cables were not interfacing with the connectors at exactly right angles to the bushing there was considerable pushing or pulling forces exerted on the bushing. Substantial modification of the frame was required to allow the cables to be successfully terminated.

7.2.3 LV Supply

In order to begin commissioning the device it was necessary to cool down the RSFCL so that it could be filled with LN_2. To ensure that the LN_2 is kept at the appropriate temperature the cooling system must be operational. The first step to commission the cooling system was to fill the water circuit connected between the recoolers and compressors and to test that the recooler pumps and fans would start when connected to the LV supply.

During the commissioning it was found that the recooler units did not start and furthermore a number of recooler error messages were present on the Human Machine Interface (HMI) alarm and trip log. After investigation, it was determined that the LV supply voltage was above the maximum voltage rating of the recooler motors.

The recoolers operate at a nominal voltage of 400V (3 phase) with a maximum rating of 420V; however, the measured voltage at site was recorded at 437V. This was because the LV supply was taken directly from an 11/0.433kV distribution transformer where the off-circuit tap changer was set to compensate for voltage drop down the line.

To resolve the issue a 440/400V, 100kVA autotransformer was ordered. It was found that the existing Glass Reinforced Plastic (GRP) housing and associated concrete plinth for the LV cut-out and CT metering unit was inadequately sized to house the additional transformer. Therefore, the existing plinth was extended and a larger GRP housing was sourced and installed. The transformer was then installed in the LV circuit after the metering unit. This successfully reduced the voltage to 395V.

7.2.4 Damage to Recooler Pipework

It was found that the water circuit could not be pressurised during the commissioning of the recoolers. This pointed towards a crack present in the recooler pipework. After some investigations, it was found that each recooler had a crack in a 90 degree bend section of pipework caused by poor build quality (see Figure 7-6). This was replaced with a pipe that was more flexible to avoid a repeat of the issue. Once the replacement part was delivered a technician from the manufacturer successfully carried out the required repairs.

Figure 7-6: Damage to copper pipework in recooler

This issue along with the works to rectify the LV supply voltage delayed the energisation of the RSFCL. The original date for energisation was 29th October 2015 and the device was energised on 25th November 2015.

7.2.5 Alarm and Trip Contacts

During the cold commissioning of the FCL it was required to test the point-to-point alarm and trip signals from the FCL control panel to the remote FCL protection panel. During the testing it was identified that the RSFCL alarm and trip signal contacts were of a ‘normally closed’ configuration which was not reflected in the associated control panel wiring schematics where they were shown as ‘normally open’. The normally closed configuration is a European standard. The outcome was that the alarm and trip logic was reversed at the FCL protection panel i.e. under normal operation all alarm and trip signals were present. To rectify this problem the panel was required to reflect the UK standard of normally open configuration.

7.2.6 AVC Scheme

During the design phase it was identified that the transformers GT2 and GT3 would be connected in parallel when the FCL is switched into the network. The existing automatic voltage control (AVC) scheme was investigated to identify whether there was the possibility of adapting it for parallel transformer operation through the use of a circulating current scheme. The GT3 AVC relay panel housed a MVGC Type relay with this functionality embedded in the relay. However, the GT2 relay panel housed an electromechanical AVE3 relay unsuitable for this application. Modifications were made to replace the GT2 AVC relay with the MVGC type.

The FCL was successfully energised on the 25th November 2015 with the AVC modifications in place. However, after energisation it was found that the existing settings had not been changed to accommodate the new parallel operation. As such, the RSFCL was removed from the system until new parallel settings were applied. Whilst reviewing the AVC settings an improvement was made to the AVC wiring scheme. An additional logic scheme was implemented to allow automatic detection of split transformer operation and blocking of the parallel AVC operation. The FCL switched into the network successfully on 5th January 2016.

7.3 Bournville

The Bournville FCL was delivered to site on 12th December 2015 after successful short circuit testing at the KEMA test facilities in Arnhem, Netherlands.

7.3.1 Logistics

The Bournville FCL was installed on the first floor of an existing substation building. In this instance the main subsystems of the device were disconnected after the end of the short circuit testing. The three cryostat vessels were left assembled on their frame and transported together via road from the Netherlands to the UK. The recooler and compressor components were transported with the cryostat units and everything offloaded at Bournville using a forklift truck.

7.3.2 Final Positioning

The Bournville FCL consists of three cryostat vessels. Each vessel had to be lifted from the ground floor to the first floor of the substation via an existing equipment lifting hatch at the gable end of the first floor switchroom, shown in Figure 7-7.

It was originally planned that the existing lifting beam above the hatch was to be used to lift the vessels (refer to Figure 7-9). This was tested to a safe working load of 2 tonnes which was acceptable for the maximum weight of a single cryostat. However, it was decided to use a portable steel frame above the hatch instead (see Figure 7-8). This had the advantage of allowing the cryostat vessels to be lifted and moved to their final position in one action making the lifting process both more efficient and safer.

Each cryostat vessel has four lifting eyes equally spaced on the circumference of the vessel (refer to Figure 7-10). The lifting team attached two slings to the vessel, each sling threaded through two adjacent lifting eyes. Each sling was then attached to a crane hoist on the lifting frame above the first floor hatch.

The first attempt to lift the cryostat had to be aborted as the manufacturer observed the slings were applying pressure to sensitive pipework on the vessel lid assembly when they were brought under tension. A site meeting was held to discuss alternative lifting methods to avoid damage to the device. Two alternatives existed:

1. To design/procure a frame that would fit around the circumference of the vessel. The slings would attach to the frame and allow a gap to the sensitive pipework when under tension.
2. To lift the vessels via two lifting eyes only. This was the preferred method as it was the lowest cost solution and had minimal impact to the project programme. However, the loading capability of the lifting eyes was unknown and the potential tipping of the device during lifting was a concern.

The manufacturer of the cryostat vessels confirmed that utilising two lifting eyes was acceptable. Once this was known the slings were attached and a test lift was performed to determine the tipping angle of the device by lifting one of the vessels a few inches off the ground. The tipping angle was deemed acceptable and the vessels were successfully lifted and positioned on the first floor. A photograph of the vessels being lifted is shown in Figure 7-11.

Figure 7-7 – Area underneath first floor equipment lifting hatch

Figure 7-8 – Portable lifting frame used to lift the cryostat vessels to the first floor

Figure 7-9 – Area above first floor lifting hatch showing lifting beam (top) and sealed emergency exit (left)

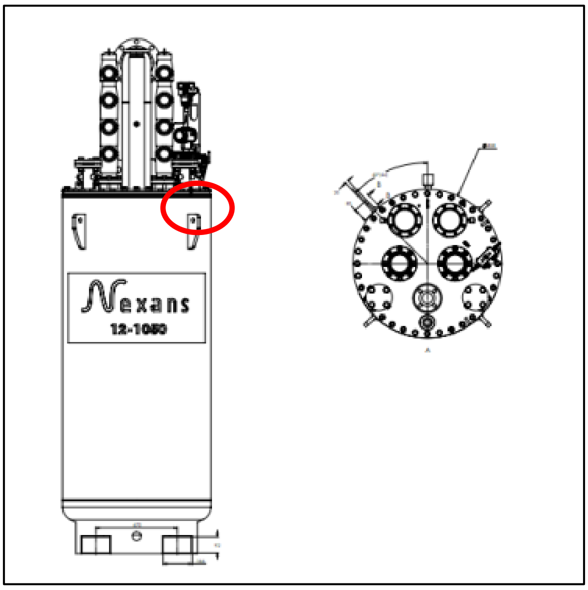


Figure 7-10 – General arrangement showing lifting eye locations

Figure 7-11 – Placement of L2 cryostat vessel in its final position on the first floor

7.3.3 LV Supply

In order to begin commissioning the device it was necessary to cool down the FCL so that it could be filled with LN_2. To ensure that the LN_2 is kept at the appropriate temperature the cooling system must be operational. The first step to commission the cooling system was to fill the water circuit connected between the recoolers and compressors and to test that the recooler pumps and fans would start when connected to the LV supply.

The recooler pumps and fans would not start during the installation of the RSFCL at Chester Street because the LV supply voltage was above the maximum rating of the recooler motors (420V). To resolve the issue a 440/400V, 100kVA autotransformer was ordered and installed in the LV circuit to reduce the voltage at the motors (refer to the Chester Street installation report for further detail).

Measurements of the LV voltage at the metering panel cut-out were taken during the Bournville installation to determine whether the same transformer would be required. The recoolers operate at a nominal voltage of 400V (3 phase) with a maximum rating of 420V. All voltage measurements were within the specified range. Therefore the decision was taken that there was no requirement for the transformer.

However, prior to the commissioning of the FCL a further measurement was taken and the measured voltage at site was recorded at 426V, above the maximum allowed. The manufacturer would not start the recoolers with the voltage above the maximum rating in order to avoid damage to the recooler motors.

To resolve the issue a 415/400V, 100kVA autotransformer was ordered. The transformer was then installed in the LV circuit after the metering unit. The unit was housed in the existing GRP housing containing the metering equipment. The transformer successfully reduced the voltage to allow the operation of the recooler equipment.

This issue along with the works to rectify the LV supply voltage delayed the energisation of the RSFCL by approximately one week.

7.3.4 AVC Scheme

During the design phase it was identified that the transformers GT1 and GT3 would be connected in parallel when the FCL is switched into the network. The existing AVC scheme was investigated to identify whether there was the possibility of adapting it for parallel transformer operation. Both GT1 and GT3 AVC relay panels housed a MVGC type AVC relay. This relay allows both circulating current and negative reactance schemes to achieve voltage regulation.

A circulating current scheme was chosen because it has greater accuracy over the negative reactance scheme. In addition, the scheme had been successfully implemented at Chester Street substation as part of the works to install the first RSFCL. The disadvantage of the circulating current scheme is that it requires bus wiring between the two relays and additional multicore wiring from circuit breaker auxiliary contacts in the switchgear to detect parallel operation.

Approximately one week prior to the scheduled Bournville energisation date a decision was taken to change the AVC scheme at Chester Street to a negative reactance scheme. The motivation for this change was to:

a. Bring the scheme in line with the majority of the existing AVC schemes on the WPD network, which are negative reactance controlled; and
b. To avoid the use of the ‘maintenance link’. This link was required to be manually inserted at site to short out the circulating current wiring should the transformers need to be manually taken out of parallel.

The bus wiring was shorted and the new negative reactance settings were implemented at Chester Street. The Chester Street FCL was successfully reconnected on 12th February 2016 and the negative reactance scheme was found to work satisfactorily. WPD Engineering Design requested the scheme to be replicated at Bournville following successful implementation at Chester Street.

The Bournville FCL was successfully energised with the new negative reactance settings on Wednesday 17th February 2016. However, over the proceeding days GT1 and GT3 tap positions began to diverge until they were five taps apart. It was decided to remove the RSFCL from service on 23rd February 2016 to avoid excessive circulating currents in the transformers. Subsequent investigations found that the CT and VT connections to the AVC panels did not provide the correct phasing to ensure correct operation of the negative reactance scheme. To solve the problem the correct voltage and current signals were taken from the substation metering panel. This required the installation of two additional multicores from the metering panel to the AVC panels. The Bournville FCL was successfully reconnected on Wednesday 16th March 2016.

7.3.5 Fire Escapes

The new six panel switchboard for the RSFCL was installed in a redundant room on the ground floor of the switchroom adjacent to switch house no. 2 containing busbar sections A and B. The new switchroom is located directly underneath the first floor where the RSFCL has been installed. The new switchroom had two emergency egress points. The first was via the adjacent switchroom at one end of the room and the other, on the opposite side of the room, was a passage leading to the substation cable basement. It was deemed unacceptable to have an emergency egress point leading into a cable basement which is designated as a confined space. As part of the civil works contract a new emergency staircase and fire escape exit were installed.

The redundant first floor switchroom utilised to house the RSFCL was only accessible from one location, via a staircase from the ground floor control gallery. There had been an emergency exit located adjacent to the lifting hatch at the opposite end of the room which led to the disused transformer yard on the ground floor. This, however, had been removed and the door opening sealed when the previous switchgear installation was removed. This emergency escape route was reinstated as part of the civil works associated with the RSFCL installation. This involved the design and installation of a new fire escape door and staircase leading to the external compound on the ground floor.

8 Policies

8.1 Overview

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

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

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

8.2 Application and Connection of FCLs – Standard Technique SD4S

During the initial stages of FlexDGrid a significant period of time was allocated to defining a standard process of when and how FCLs should be connected to the system. This process was applied for the FCLs for FlexDGrid and captured in a separate WPD policy document "Standard Technique : SD4S – Application and Connection of 11kV Fault Current Limiters (FCLs) for FlexDGrid" (see Figure 8-1). This policy is a live document on WPD's intranet and has been circulated to other DNOs at various dissemination events as described in SDRC-10.

WESTERN POWER DISTRIBUTION
Serving the Midlands, South West and Wales

Company Directive

STANDARD TECHNIQUE : SD4S

Application and Connection of 11kV Fault Current Limiters (FCLs) for FlexDGrid

Policy Summary

This policy sets out requirements for the application and connection of Fault Current Limiter Devices on WPD's 11kV network. This policy is intended for the Low Carbon Networks Fund (LCNF) project, FlexDGrid and will be reviewed following the successful completion of this project.

Author: J Berry
Innovation and Low Carbon Networks Engineer

Implementation Date: October 2014

Approved by
Policy Manager

Date: 10 October 2014

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ST:SD4S October 2014 - 1 of 14 -

Figure 8-1: Standard Technique - SD4S

8.3 FCL Specification – Engineering Equipment Specification 202

The process of producing the technical contract documentation for FlexDGrid and the subsequent review of the FCL manufacturer proposals meant that the project team gained a lot of experience with all different technologies. The key elements of the rating, design, construction and testing of different FCL technologies were captured in a new WPD policy document "Engineering Equipment Specification : EE202 – Fault Current Limiter (FCL) Devices for use on the 11kV Network (FlexDGrid)" (see Figure 8-2).

WESTERN POWER DISTRIBUTION
Serving the Midlands, South West and Wales

Company Directive

ENGINEERING SPECIFICATION

EE SPEC: 202/1

Fault Current Limiter (FCL) Devices for use on the 11kV Network (FlexDGrid)

Policy Summary

This specification covers Western Power Distribution's engineering specifications for fault current limiter (FCL) devices on the 11kV network.

Implementation Date: **April 2015**

Approved by

Policy Manager

Date: 16 April 2015

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EE SPEC : 202/1 April 2015 - 1 of 45 -

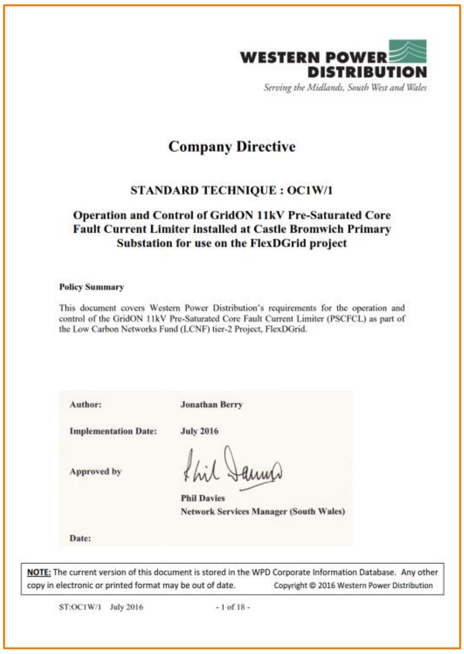
Figure 8-2: Engineering Equipment Specification - EE202

The document amalgamated the relevant clauses from other WPD engineering policies along with specific requirements for FCL technologies. This document can now be used by WPD when tendering for further FCLs on the 11kV network. The document was shared with other DNOs during the workshop held on 14th May 2014.

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

Prior to connecting any new device to the network it is imperative that policy documents are produced to ensure that all operators are able to safely control and operate the equipment. A Standard Technique was developed for the operation and control of each FCL technology. Before the technology was connected to the system the document was circulated to the relevant departments in WPD for comment before final approval.

Each Standard Technique explained how the technology operated and what processes must be followed for safe energisation and de-energisation. In addition, each of the main device functions are described along with reference documentation so that operators can easily identify any alarms or faults should they occur. Figure 8-3 and Figure 8-4 show the two policy documents for the PSCFCL and RSFCL.



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Company Directive

STANDARD TECHNIQUE : OC1W/1

Operation and Control of GridON 11kV Pre-Saturated Core Fault Current Limiter installed at Castle Bromwich Primary Substation for use on the FlexDGrid project

Policy Summary

This document covers Western Power Distribution's requirements for the operation and control of the GridON 11kV Pre-Saturated Core Fault Current Limiter (PSCFCL) as part of the Low Carbon Networks Fund (LCNF) tier-2 Project, FlexDGrid.

Author:	**Jonathan Berry**
Implementation Date:	**July 2016**
Approved by	**Phil Davies** **Network Services Manager (South Wales)**
Date:	

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ST:OC1W/1 July 2016 - 1 of 18 -

Figure 8-3: Standard Technique - OC1W

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STANDARD TECHNIQUE : OC1Y/1

Operation and Control of Nexans 11kV Resistive Superconducting Fault Current Limiter (FlexDGrid)

Policy Summary

This document covers Western Power Distribution's requirements for the operation and control of the Nexans 11kV Superconducting Fault Current Limiter (RSFCL) as part of the Low Carbon Networks Fund (LCNF) Tier-2 Project, FlexDGrid

Author:	**Jonathan Berry**
Implementation Date:	**July 2016**
Approved by	**Phil Davies** **Network Services Manager (South Wales)**
Date:	

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ST:OC1Y/1 July 2016 - 1 of 27 -

Figure 8-4: Standard Technique - OC1Y

8.5 Inspection and Maintenance of FCLs – Standard Technique SP2CAA & SP2CAC

Two separate Standard Techniques were produced for the inspection and maintenance of the FCLs. Similar to the operation and control Standard Techniques, these two documents were produced and approved before the FCLs were connected to the network.

The documents were produced in collaboration with the FCL manufacturers to determine the routine inspection and maintenance procedures for each technology. Safety is at the forefront of these documents as they describe the processes that should be followed when carrying out both visual inspections and intrusive maintenance.

The maintenance intervals associated with these Standard Techniques are included in WPD's maintenance logging system, CROWN. After the FCLs were connected to the system, the details were logged and the system automatically generates work items based on the maintenance intervals. The operators undertaking the maintenance can then refer to the relevant Standard Technique as shown in Figure 8-5 and Figure 8-6.

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STANDARD TECHNIQUE : SP2CAA

Inspection and Maintenance of GridON 11kV Pre-Saturated Core Fault Current Limiter installed at Castle Bromwich Primary Substation for use on the FlexDGrid project

Policy Summary

This document covers Western Power Distribution's requirements for the inspection and maintenance of the GridON 11kV Pre-Saturated Core Fault Current Limiter (PSCFCL) as part of the Low Carbon Networks Fund (LCNF) tier-2 Project, FlexDGrid.

Author: **J Berry**

Implementation Date **March 2015**

Approved by:

Paul Jewell
Policy Manager

Date: 6 March 2015

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ST:SP2CAA March 2015 - 1 of 20 -

Figure 8-5: Standard Technique – SP2CAA

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STANDARD TECHNIQUE : SP2CAC

Inspection and Maintenance of Nexans 11kV Resistive Superconducting Fault Current Limiter (FlexDGrid)

Policy Summary
This document covers Western Power Distribution's requirements for the inspection and maintenance of the Nexans Resistive Superconducting Fault Current Limiter (RSFCL) as part of the Low Carbon Networks Fund (LCNF) Tier-2 Project, FlexDGrid.

Author: **Jonathan Berry**

Implementation Date: **December 2015**

Approved by

Policy Manager

Date: 8 December 2015

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ST:SP2CAC December 2015 - 1 of 15 -

Figure 8-6: Standard Technique – SP2CAC

All policies created as part of FlexDGrid are available to other DNOs upon request.

9 Learning and conclusion

Table 9-1: Learning points from design and installation of FCLs summarises the main learning points that have been captured within this report that could be used for future innovation projects.

Table 9-1: Learning points from design and installation of FCLs

Item	Learning
Increased footprint and weight	All the dimensions and weights of the FCLs that were provided in the original ITT documentation increased during the design phase. WPD provided an additional 20% margin on top of these original figures when designing the integration of the FCLs. This meant that the increases during the design phase could be accommodated with only minor changes to the original integration designs. Allowing an appropriate margin for changes in design is recommended for projects where new technology is being installed in existing substation sites.
Substation Surveys	The installation of FCLs required significant works at the selected substation sites. To mitigate the risk of encountering issues that could affect the installation, surveys should be carried out to ascertain as much information about the existing site as possible as the design stage. For FlexDGrid sites a number of different surveys were carried out and influenced the design from a technical and health and safety perspective: i) Underground service radar survey ii) Hazardous materials survey (asbestos, lead paint) iii) Earthing survey iv) Structural survey v) Geotechnical survey vi) Topographical survey
PSCFCL Magnetic Field	The high magnetic field emitted from the presented a number of challenges during the design and installation. For any future PSCFCL installation the following points shall be considered: i) The magnetic field should be controlled as

	much as possible to ensure that only a small controlled exclusion zone is required. ii) Sensitive auxiliary equipment should be located away from the main source of the magnetic field. iii) Detailed designs for magnetic field mitigation should be submitted at an early stage so that it can be included in the initial design phase.
RSFCL Enclosure	Having installed two RSFCLs as part of FlexDGrid, WPD would recommend that future installations should be provided in an enclosure due to the following points: i) Although access is restricted within the enclosure for testing, a significant amount of time is saved as the individual components are pre-installed and connected. ii) The transportation of the RSFCL in the enclosure resulted in lower risk due to reduced time off-loading and handling equipment. iii) The time for installation and commissioning on site was significantly lower for the enclosure. In addition, the risk of errors due to incorrect wiring / component interconnection is greatly reduced. WPD would recommend that future RSFCL enclosures are slightly larger in width to allow for easier termination of HV cables.
RSFCL Cooling	During the project a number of issues were discovered with RSFCL cooling system. If a cooling system is to be used for any future innovation devices, it is imperative that the cooling system is designed such that: i) Sufficient margin is provided in the cooling power required to keep the device at its set point temperature. ii) Ensure that the cooling system is fully tested and also run for an extended period of time to confirm that the cooling system can dissipate the required energy and is reliable prior to installation on site. iii) If possible avoid having cooling systems with a significant number of moving parts and connections. This reduces the on-going

	maintain requirements and energy consumption of the device.
Programming of build	Two RSFCLs were installed as part of FlexDGrid. Both of the units were being designed and built simultaneously. When a problem was discovered with the first unit during testing, the second unit was also adversely affected by the same issue. For this reason if more than one of the same device is to be installed as part of an innovation project , consideration should be made into the benefits of designing, building and testing the first unit in its entirety prior to the construction of subsequent units should the project programme allow.
Schedule of responsibility	During the installation of the FCLs there were a number of instances where the manufacturer and contractor disagreed on the responsibilities for carrying out certain tasks. This was partly due to the manufacturers being less experienced in the installation of equipment in high voltage substations. It is recommended that both manufacturer and contractor attend regular site visits before and during the construction phase to agree the safe working methods and responsibilities.
PEFCL Enclosure	A fundamental design principle for enclosures is that they are designed around the equipment to be housed rather than vice versa. The use of a shipping container for the GE PEFCL was not the correct solution as it significantly constrained the layout of equipment which had a detrimental impact on clearances and future design changes. It is recommended that bespoke enclosures are designed for new technology rather than using heavily modified shipping containers.
Design Review	The design of new technology requires input from the DNO to ensure that the operation of the technology is understood and it is designed in accordance with the industry standards and specifications. GE did not adequately plan or schedule the submission of design stage submissions which led to delays in the overall project build. In addition, GE did not expect that WPD

	would review the detailed schematics or control diagrams. However, errors were found during the review by WPD which had to be corrected by GE. For future tenders it is recommended that the supplier is made aware of the design review stages at the start of the project. The supplier shall ensure that sufficient time is allowed for design review and subsequent changes to meet the requirements of the DNO.
General Arrangement	There were several iterations of the PEFCL General Arrangement (GA) during the design stage. The initial layouts had to be modified to ensure that safe operational access could be provided for personnel. This resulted in the container having to increase from 20ft in length to 40ft. Detailed GAs were never provided by GE despite requests from WPD. GE progressed with the build of the PEFCL without a detailed GA at their own risk. This led to equipment being installed incorrectly and with live HV conductors infringing basic electrical safety clearances. The build programme for any new device should have stage gate review, whereby the approval of a detailed GA shall be necessary before proceeding with the build.
Testing Specification	Testing specifications are critical documents that define the procedures to be followed to ensure that the test object meets the required standards. The testing specification produced by GE for the PEFCL was not sufficiently detailed and did not have test diagrams. The lack of information was a concern to WPD and this was further highlighted by KEMA's own review in October 2015. It is recommended that outline test specifications are submitted for review at least 6 months before commencing testing of any new technology.

The information presented in this document demonstrates the successful design, testing and installation of three FCLs. In addition, the document captures the processes that have been followed and the main learning points that have arisen through the implementation of the project. With the FCLs now successfully connected to the network, the final phase of the project will focus on the closed loop testing and performance of the devices. The details of this will be described in SDRC-9.