Powerful-CB

SDRC 9.2.1:
Install and Commission Solution at an 11kV Substation

Contents

Glossary

Term	Description
ABB	Our technology partner for Method 1
AMAT	Applied Materials, our technology partner for Method 2 (this method has been de-scoped from project following Ofgem approval of change request)
BAU	Business As Usual
BEIS	The Department for Business, Energy and Industrial Strategy
BiGT	Bi-mode Insulated Gate Transistor
CB	Circuit Breaker – Protection device that interrupts the flow of current in an electric circuit in the event of a fault
CBA	Cost Benefit Analysis
COVID-19	Corona Virus Disease 2019
CHP	Combined Heat and Power – simultaneous generation of usable heat and power (usually electricity) in a single process; more efficient than generating heat and power separately
DG	Distributed Generation – generators that are connected to the distribution network
DNO	Distribution Network Operator
DSO	Distribution System Operator
EMC	Electromagnetic Compatibility
ENA	The Energy Networks Association
EPN	Eastern Power Networks plc (one of three UK Power Networks licence areas)
ENWL	Electricity North West Limited
FAT	Factory Acceptance Test
Fault Current	A surge of energy that flows through the network in the event of a fault. The energy comes from the momentum of rotating generators and motors connected to the network
Fault Level	The maximum fault current that could theoretically flow during a fault. “Make” fault level is the maximum fault current that could flow during the first current peak of the fault, and that a circuit breaker closing onto a fault would need to safely handle. “Break” fault level is the maximum fault current that could be flowing 100ms after the start of the fault, and that a circuit breaker clearing the fault would need to be able to interrupt.
Fault Level Headroom	The difference between fault level and fault rating at a particular substation or part of the network; corresponding to the amount of generation that can be connected to the network without exceeding its fault rating
FCL	Fault Current Limiter – a FLMT that attenuates fault current by increasing its impedance (only) during a fault.
FC-Protector	Commercial product offered by ABB which limits the short-circuit current during the first rise (https://new.abb.com/medium-voltage/apparatus/fault-current-limiters/fc-protector)
FCS	Fast Commutation Switch

FLCB	Fault Limiting Circuit Breaker – a FLMT that blocks fault level contributions from a transformer / bus coupler / generator by disconnecting it before the first current peak of the fault
FLMT	Fault Level Mitigation Technology – a technical solution that reduces fault levels on the network
FMEA	Failure Mode and Effects Analysis
FNC	Frazer-Nash Consultancy
FSP	The Powerful-CB Full Submission Proforma - http://bit.ly/Powerful CB-fsp
GB	Great Britain
GT	Grid Transformer
HAZID	Hazard Identification
HMI	Human Machine Interface
HSE	The Health and Safety Executive
HV	High Voltage
HVDC	High Voltage Direct Current
IGBT	Insulated Gate Bipolar Transistor
Imperial	Imperial Consultants (Imperial College London's consultancy company)
Inhibit Scheme	A hard-wired protection system that automatically disconnects generators from the network under pre-defined conditions, typically in the event of a transformer outage or other abnormal network configuration that causes elevated fault levels.
IPR	Intellectual Property Rights
I_s-limiter	Commercial product offered by ABB which limits the short-circuit current during the first rise (https://new.abb.com/medium-voltage/apparatus/fault-current-limiters/current-limiter)
KEMA Laboratories	Independent organisation for issuing Testing, Inspections & Certification certificates
LCNI	Low Carbon Networks & Innovation Conference
LPN	London Power Networks plc (one of three UK Power Networks licence areas)
M1	Method 1 – Installation of a FLCB at a substation
M2	Method 2 – Installation of a FLCB at a customer's premises (de-scoped from project following Ofgem approval of change request)
NIC	Network Innovation Competition
Ofgem	Office of Gas and Electricity Markets, the regulator for gas and electricity markets in Great Britain
PEHLA Testing Laboratory	Testing laboratories accredited for issuing Testing, Inspections & Certification certificates. ABB used the laboratory based in Ratingen, Germany
PPR	Project Progress Report
RIIO-ED1	The current electricity distribution regulatory period, running from 2015 to 2023
RMS	Voltage (Vrms) or Current (Arms) Root-Mean-Squared
Rotating DG	A generator that converts mechanical energy to electrical energy using a synchronous AC rotating alternator, e.g. CHP and diesel standby

	generators. These types of generators have a much larger impact on fault levels than inverter-connected generators e.g. solar PV.
Safety Case	A structured argument, supported by a body of evidence that provides a compelling, comprehensible and valid case that a system is safe for a given application in a given operating environment
SCADA	Supervisory Control and Data Acquisition
SDRC	Successful Delivery Reward Criteria
SECRC	ABB Corporate Research Centre in Västerås, Sweden
SLD	Single Line Diagram
SPN	South Eastern Power Networks plc (one of three UK Power Networks licence areas)
STC	Short Time Current
TRL	Technology Readiness Level
UKPN	UK Power Networks

1. Executive summary

1.1 Background and Project Motivation

The Powerful-CB (Power Electronic Fault Limiting Circuit Breaker) project aims to demonstrate that fault-limiting circuit breakers (FLCBs) can enable us to connect more distributed generation (DG) to fault-constrained 11 kV distribution networks without the need for network reinforcement.

We are transforming our business into a Distribution System Operator[1] to respond to the needs of our customers, both now and in the future, and working with the wider industry to help deliver decarbonisation of the electricity system at the lowest cost. The Government's Carbon Plan and the Department of Energy & Climate Change (now known as BEIS) Community Energy Strategy report[2] highlight the importance of combined heat and power (CHP) in achieving the UK's carbon targets. In addition to this, the Mayor of London's target[3] is to generate 25% of London's heat and power requirements locally by 2025. We expect this to encourage CHP and district heating for new developments.

To date we have over 750MW of DG including 300MW of CHP connected to our London network but the ability to connect more may be limited as a result of fault level constraints. The traditional solutions to fault level constraints are: an inhibit agreement (therefore restricting output); connection at a higher voltage level; and network reinforcement with the latter two resulting in a connection cost which may make generation projects economically unviable.

A FLCB is a solid-state circuit breaker that operates 20 times faster than existing vacuum circuit breakers. This high-speed operation can mitigate fault level contributions from distributed generation, allowing us to connect more DG (including CHP) to fault-level constrained networks in dense urban areas. This will help facilitate the decarbonisation of heat, which is a key element of the Government's Carbon Plan Connecting more decentralised renewable generation also helps in achieving Net Zero and contributes to the transition to a Distribution System Operator (DSO) model.

We have been working with technology partner, ABB, who will develop a FLCB for use at a primary substation. This will be the world's first demonstration of a FLCB with a fast commutating switch.

Throughout the duration of the Powerful-CB project, the team has been and will continue to share key learnings with the industry. The project is delivering a number of Successful Delivery Reward Criteria (SDRCs) reports – which capture learnings from various stages of the project. The value of innovation is playing a major part in ensuring DNOs can support a low carbon future. UK Power Networks recognises the importance of sharing learning from its projects to ensure Distribution Network Operators (DNOs) in Great Britain (GB) can work collaboratively; such that successful solutions can be adopted faster by other networks for the benefit of customers and to facilitate Net Zero.

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1 http://futuresmart.ukpowernetworks.co.uk
2 https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/275163/20140126Community_Energy_Strategy.pdf
3 https://www.london.gov.uk/what-we-do/planning/london-plan/current-london-plan/london-plan-chapter-five-londons-response/poli-0

1.2 Purpose and Structure of This Report

The purpose of this report is to describe an overview of the installation, commissioning and energisation of the FLCB ready for network demonstration as well as information on operation to date of the FLCB. The structure of this document is shown in Table 1 below.

Table 1 Details of each section found within this document

Section 1: Executive Summary	Summarises the background, processes, and key findings described within the document
Section 2: Site Selection	Describes the selection criteria for choosing a trial site for the FLCB
Section 3: Site Preparation Works	Describes the work completed to ready the trial site for installation of the FLCB and other equipment
Section 4: Electrical Works	Describes the work carried out in order to connect the FLCB to the network. This includes the protection upgrades required
Section 5: Installation and Commissioning	Describes the installation of the FLCB and the commissioning experience of both the FLCB and integration into the network
Section 6: Trial Running Arrangements	Describes the various running arrangements that the FLCB will be trialled as part of the project
Section 7: Operation to Date	Summarises the data gathered from running the FLCB so far
Section 8: Challenges and Lessons Learned	Highlights the key challenges and lessons learned from the installation and commissioning process
Section 9: Summary and Next Steps	Summarises the installation and commissioning process and next steps for the project
Appendix A: ABB Commissioning Reports	The commissioning reports produced by ABB when commissioning the FLCB
Appendix B: UK Power Networks Commissioning Reports	The commissioning reports produced by UK Power Networks when commissioning newly installed equipment and integrating the FLCB into the network

Specifically, this report forms SDRC 9.2.1: Install and Commission Solution at an 11kV Substation, which is the fourth Successful Delivery Reward Criteria (SDRC) for Powerful-CB that will be submitted over the course of the project, as described in the Project Direction. The Powerful-CB SDRCs have been designed to demonstrate clear progress towards the project objectives and disseminate valuable learning to interested stakeholders at key milestones of the project. Stakeholders include Ofgem, other DNOs, customers, industry groups and equipment manufacturers. Table 2 summarises the evidence supporting the stated objectives for SDRC 9.2.1.

Table 2 Summary of SDRC 9.2.1 supporting evidence in accordance with the Project Direction issued by Ofgem

Successful Delivery Reward Criterion	Evidence
Install and commission solution at an 11kV substation (Method 1)	**Publish Interim Learning Report – Demonstration of a FLCB for substations**, which will include results and learning from installation, commissioning, and operation to date of a FLCB at a substation.

1.3 Experience From Installation and Commissioning

The project trial site was selected to ensure the FLCB could be successfully trialled to maximise learnings. The first key principle for site selection was to ensure that the trial site was representative of sites where the solution could be deployed in the future to deliver the expected benefits once proven successful and approved for business as usual (BAU). The second principle was to choose a trial site that will allow the device functionality to be fully tested under a number of different running arrangements. Other key criteria for site selection is detailed in Table 3 below.

Table 3 Key selection criteria for trial site location

Criteria	Glaucus St Parameters and Explanation
Licence Area	Located within the LPN licence area in a dense urban environment and at a 11kV rated primary substation
Physical Space	Availability of space in the substation to accommodate the FLCB and auxiliary equipment
Significant Fault Level	Existing fault level at least 80% of fault rating of the substation equipment (indicating that fault level issues are likely to arise in the future, either in RIIO-ED1 or RIIO-ED2)
Secure Under N-1 Operating	Existing fault level does not exceed fault rating under normal conditions or N-1 conditions (this is essential as fault levels cannot be allowed to exceed fault ratings of the existing equipment until the FLCB has been proven safe and reliable)
Network Reliability	History of faults on outgoing circuits. This was consideration was made to maximise the opportunity for the FLCB to operate under real network faults

Following site selection, the next step was preparing the substation for installation and integration into the network. This included preparing the specific substation room prior to FLCB delivery, extension of the existing busbar, protection upgrades and installation of other equipment.

In preparation for the FLCB installation, equipment historically stored in the room, was relocated and an existing wall had to be moved to allow space to extend the existing busbar. As the existing wall contained asbestos it could not be reused as directed by HSE's "Control of Asbestos Regulations 2012" and so a new durasteel wall was installed. A second durasteel wall was also installed near the entrance of the building as the existing wall was not suitably fire rated to house switchgear. The floor had to be levelled, holes drilled for cable access, supporting steelwork installed in the basement, the entrance door replaced to allow access for equipment of larger height and small power & lighting replaced.

Following the preparation of the room, the FLCB was delivered to site and installed in parallel with the busbar extension works necessary to connect the FLCB to the network. The switchgear at the trial substation was manufactured in 1968 which meant that spare panels were not readily available for extending the existing busbar; however, panels from another substation that was undergoing an upgrade were redeployed to this site. Similarly, due to the age of the equipment on the site, there were limited resources who possessed the necessary skills to complete the busbar extension of this specific type. As such, the two-fold issue of spare part availability and equipment specific expertise due to the age of substation equipment must be considered for the future application of FLCBs in existing substations.

Figure 1 FLCB installation in progress

During the commissioning phase of the FLCB and other equipment including, protection systems and SCADA, the project team experienced and resolved a number of challenges. Some key learnings gained through the resolution of these issues are detailed below in Table 4.

Table 4 Key insights and learnings made from the installation and commissioning process

Insights from key challenges in the commissioning phase	Detailed Description
Installation of Uninterrupted Power Supplies (UPSs) into the FLCB to act as back-up for the substation 110V DC supply to improve	The original power supplies provided with the FLCB for the control system were suitable for use as the substation site has an 110V DC battery backup supply. However, it was identified during commissioning, in December 2019, that in case of a loss of supply to the FLCB control system, the FLCB would be connected in the network but unable to react to a fault. Although the probability of this occurring was observed to be low, the impact could be significant on the wider connected network. As such, the project team decided to mitigate this by complementing the existing power supplies with UPSs in order to make the FLCB as robust, reliable and safe as

robustness and reliability of the FLCB	possible. With the UPS, the control system remains powered up and can perform a safe shut down and disconnect the FLCB from the network by opening the adjacent CBs as well as triggering the FLCB faulty/ out of service alarm. When the 110V DC power is restored, the FLCB and its control system need to be switched off and then switched back on again to return to normal operation.
Added protection logic to automatically isolate the FLCB as a safety precaution when a "FLCB Out of Service/Faulty" alarm is raised by the FLCB	The FLCB has an alarm labelled "FLCB Out of Service/Faulty", which shall be raised when any internal problems associated with the FLCB and its control system are detected. On a conventional circuit breaker if a faulty alarm is raised, the typical response from control engineer is to switch the circuit breaker off, reset the alarm and raise a maintenance job. However for FLCB trial period, the alarm should not be reset until ABB maintenance teams have completed an investigation. Although UK Power Networks' control engineers could respond to this alarm by operating the two adjacent circuit breakers manually to isolate the FLCB, the project team had added additional features to ensure safety of the network; a protection logic has been incorporated in the scheme, which will initiate a trip of the two adjacent circuit breakers to automatically isolate the FLCB as a precaution upon the receipt of this alarm.
Latched trip alarm from FLCB so that the Supervisory Control and Data Acquisition (SCADA) system could register the alarm and software patched SCADA equipment	When testing the tripping of the FLCB, UK Power Networks' Supervisory Control and Data Acquisition (SCADA) system was unable to register the FLCB trip alarm due to its super-fast speed. To overcome this, ABB latched the alarm to a spare relay contact and we subsequently liaised with our SCADA provider, GE, to apply a new software patch.
Repaired FLCB HV door interlock so that energisation could take place	While retesting all alarms and functions during commissioning, we identified a fault with the HV door interlock of the FLCB requiring modification. As the interlock is a critical safety mechanism, energisation was postponed until this was fixed; however the works were delayed due to COVID-19 related restrictions and eventually resolved in August 2020.

Following the resolution of all aforementioned issues and relaxation of COVID-19 related restrictions, the FLCB was successfully energised – commencing the network demonstration phase of the project on 12 August 2020.

1.4 Operation to Date of the FLCB

For the network demonstration three running arrangements have been chosen to trial the FLCB.

Running Arrangement 1 as shown in Figure 2, was designed as a soak test for the FLCB, where the device was idly connected and energised on the network while bus coupler, BC2, remains closed. In this running arrangement when the device is energised and connected in parallel with the existing bus coupler, it is unlikely to put a great strain on the device. This approach is typical when introducing a new equipment on the network, and by following this approach some minor problems can be identified during this "soak" phase. During this trial phase, the FLCB continued to report healthy with no issues including when confidence switching took place or when outages of transformers and circuit breakers were taken to complete wiring of the auto-close scheme and external fault recorders.

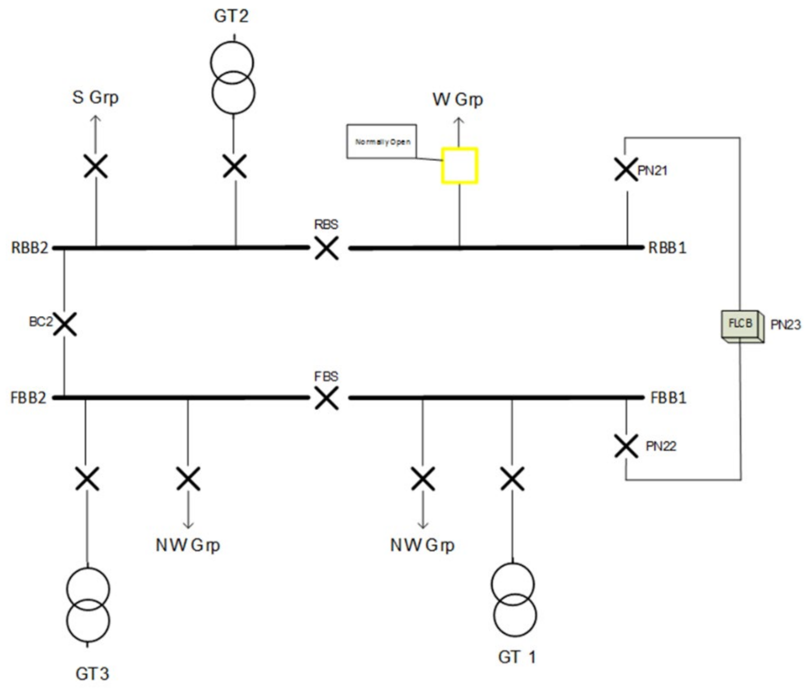

Figure 2 Running Arrangement 1. Note yellow indicates 'normally open'

Running Arrangement 2 as shown in Figure 3, will see the FLCB operated as a transformer incomer circuit breaker for Grid Transformer 1 (GT1) by opening circuit breaker RBS and switching GT1 to the busbar RBB1.

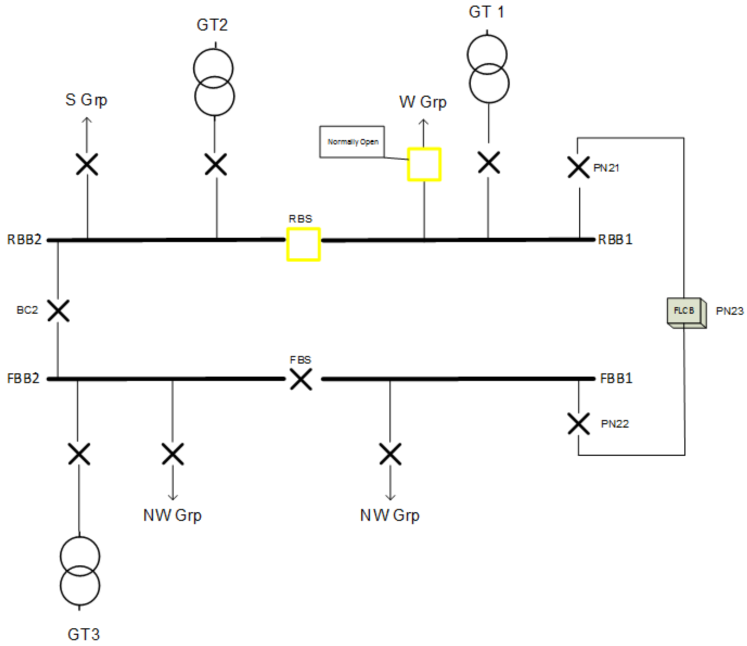

Figure 3 Running Arrangement 2. Note yellow indicates 'normally open'

Running Arrangement 3 as shown in Figure 4, will see the FLCB operated as a bus coupler by opening the existing bus coupler BC2. Under this arrangement there is a scenario where there may be a loss of supply if the Grid Transformer 2 (GT2) circuit breaker is tripped along with the FLCB. To mitigate this an auto-close scheme has been installed on BC2 which automatically closes this breaker if the GT2 circuit breaker is tripped.

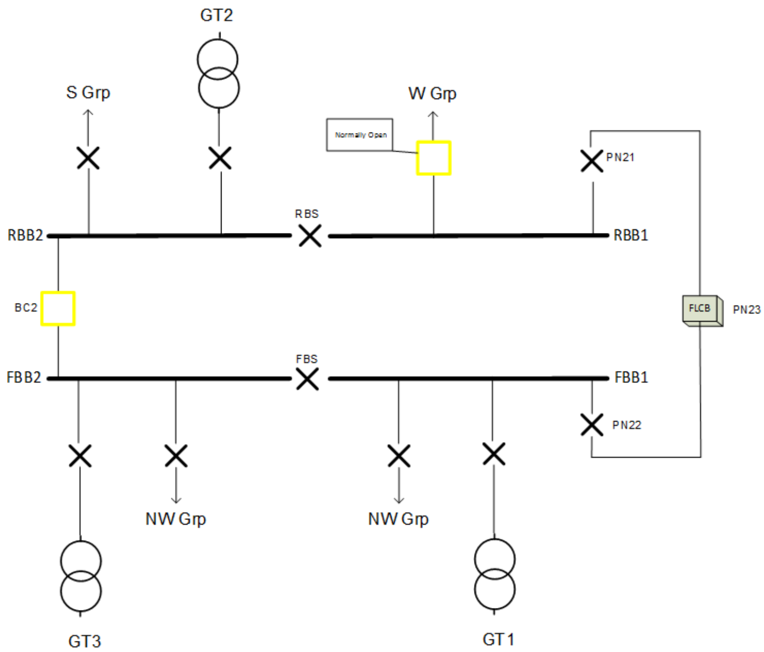

Figure 4 Running Arrangement 3. Note yellow indicates 'normally open'

Following the successful 'soak' test of the FLCB, we worked with our Outage Planning teams to transition to Running Arrangement 2 on 30 September 2020. By shifting to this running arrangement, the current flowing through the FLCB has increased when compared to Running Arrangement 1 as there is no parallel path. Figure 5 shows the data captured to date from operation of the FLCB.

The project team are awaiting a network fault to see how the FLCB will perform and will continue to monitoring the performance of the FLCB and carryout any necessary analysis following a network fault and/or trip of the FLCB.

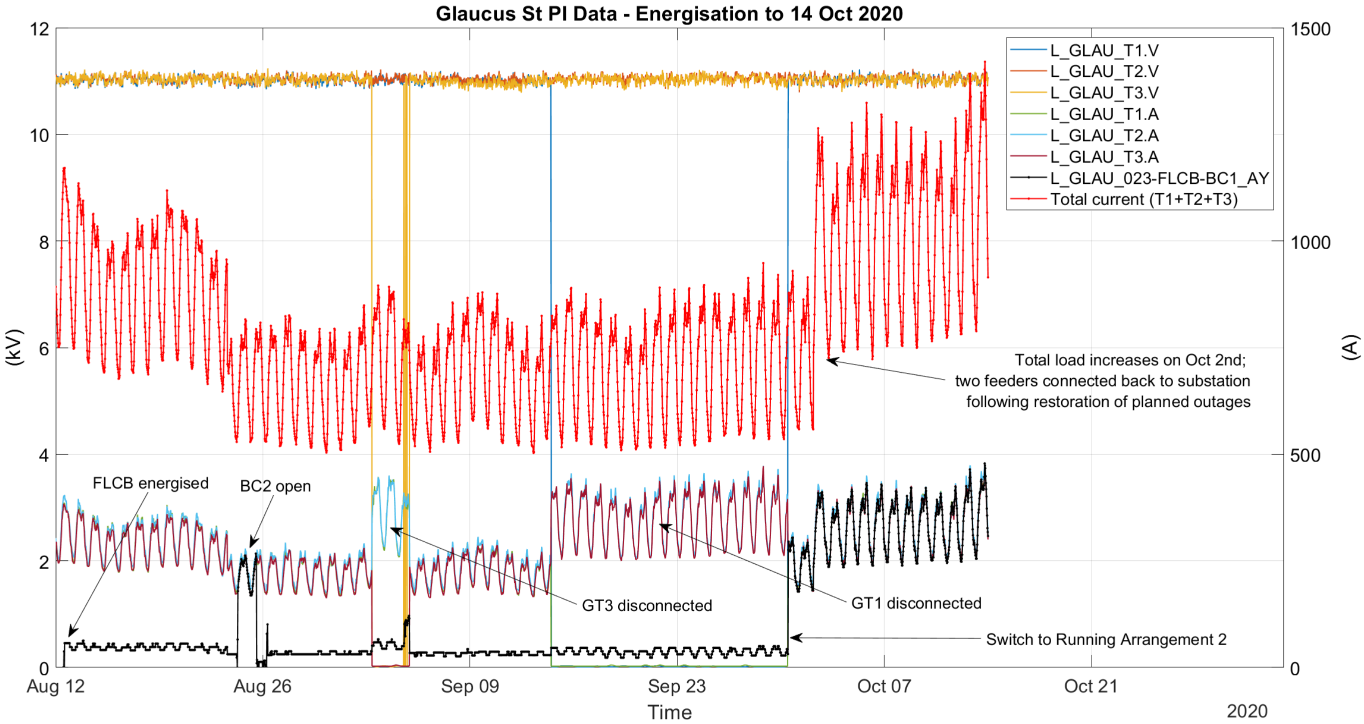

Figure 5 Operation to date of the FLCB through Running Arrangement 1 and Running Arrangement 2

2. Site Selection

The fault limiting circuit breaker (FLCB) is being trialled at Glaucus Street substation within our London Power Networks (LPN) licence area in east London. The site selection was based on thorough criteria prepared to ensure that the device could be successfully demonstrated to maximise learnings for business as usual (BAU) installation, commissioning and operation.

The first key principle for our site selection was to ensure that the trial site was representative of sites where the solution could be rolled out to achieve customer savings once proven successful and approved for BAU. The second principle was to choose a trial site that will allow the device functionality to be fully tested under a number of different running arrangements.

The following site selection criteria was used:

- **Location –** Located within LPN licence area in a dense urban environment and at 11kV rated primary substation;
- **Physical and operational constraints –** Is there adequate space to install new equipment, is there adequate site access, could the installation be done while minimising outages, etc.;
- **Significant fault level –** Existing fault level at least 80% of fault rating of the substation equipment (indicating that fault level issues are likely to arise in the future, either in RIIO-ED1 or RIIO-ED2);
- **Secure under N-1 operating conditions –** Existing fault level does not exceed fault rating under normal conditions or N-1 conditions (this is essential as fault levels cannot be allowed to exceed fault ratings of the existing equipment until the FLCB has been proven safe and reliable);
- **Asset replacement programme –** No asset replacement planned or likely before the end of the trial;
- **Network reliability –** History of faults on outgoing circuits. This was a consideration, where we looked for substations with higher number of faults to increase the likelihood for the FLCB to operate under real network faults;
- **Generator connections –** Ideally, has existing non-firm generator connections (i.e. they must disconnect in N-1 conditions), so that the FLCB, once proven safe and reliable, could enable these customers to benefit immediately by obtaining firm connections for their existing generators; and
- **Forecast connections –** Evidence of a high demand for future DG connections was also considered for site selection

When describing substation configurations, sometimes we refer to them based on the number of transformers installed and the rating of these transformers. For example a 1x15MVA transformer means there is one 15MVA transformer installed. Both 4x15MVA and 3x60MVA substation configurations were considered equally when selecting a trial site for the project. Based on the above criteria, Glaucus St was found to have the results found in Table 5 and hence selected on this basis. A full list of evaluated trial sites is not provided for commercially sensitive reasons.

Table 5 Site selection results and notes for choosing Glaucus St

Criteria	Glaucus St Parameters and Explanation
Licence Area	Glaucus St is located within LPN licence area and located in a dense urban environment as shown in Figure 7
Physical space	Empty switch room adjacent to existing switchgear that the FLCB could be installed
Site Access	Good street access for delivery of FLCB and large double doors to substation building for moving equipment in and out of as shown in Figure 6
Max Fault Level of Substation Rating (%)	94% – Existing site fault levels to be greater than 80% of substation rating. Existing fault level does not exceed fault rating under normal conditions or N-1 conditions
Number of HV Faults (since 2011)	25 – the higher the occurrence of faults in the area increases the likelihood of the FLCB operating under fault conditions
Planned Asset Replacement	No planned asset replacement at Glaucus St prior to conclusion of project
Other Issues/Risk	Presence of asbestos identified so will require safe handling and disposal

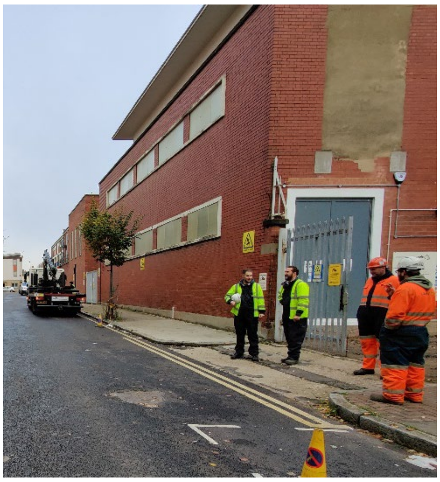

Figure 6 Street view of Glaucus St showing site access

Figure 7 Location of Glaucus Street (highlighted within red circle) depicting surrounding dense urban environment

The physical layout of the trial substation can be seen in Figure 8 below. The FLCB is situated in a separate room to the existing switchgear. To enable this, the existing busbar has been extended and two additional circuit breakers installed, however more details are provided in Section 3.

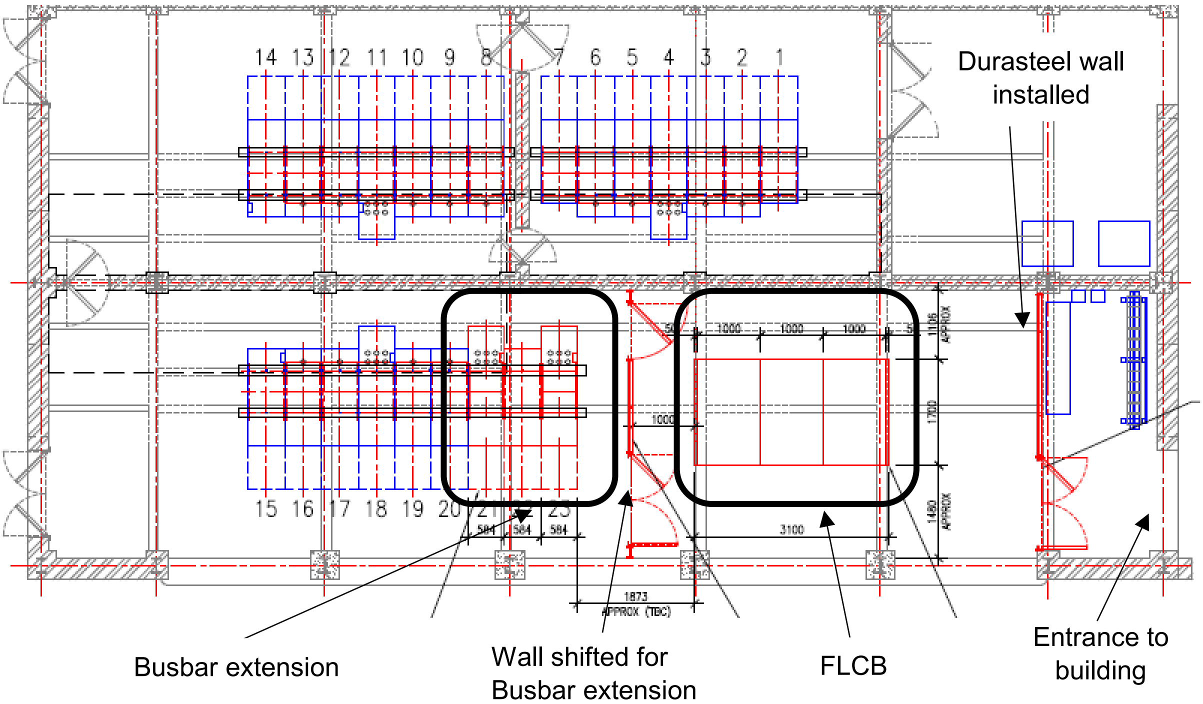

Figure 8 Layout view of Glaucus St substation arrangement

3. Site Preparation Works

Upon the completion of site selection activity, the next step was to prepare the substation for installation and integration into the network. This included preparing the room prior to FLCB delivery, relocation of internal walls, installation of supporting steelwork, installation of cable trays and replacing the building entrance doors as detailed in the following subsections.

3.1 Room Preparation

The substation room earmarked for FLCB installation was previously used as storage space as shown in Figure 9. As such, the general condition of the room was unsuitable for new equipment to be installed without some preparatory work.

The stored equipment in the room was first relocated before any other works were undertaken. The next steps were to level out the floor with screed, paint the walls and to cut holes into the floor to allow access for multicore and HV cable access. The general progress of the room preparation can be seen in Figure 9 below.

Figure 9 General sequence of works to ready the room for FLCB installation. Before works (left), screed poured and levelled, walls painted and holes drilled (middle) and finished floor (right)

As part of the general work to prepare the room for the installation of the FLCB, work was completed to upgrade the small power and lighting. This included the addition of new lighting, installation of heaters to prevent moisture build-up, installation of fire detection equipment and other ancillary equipment.

3.2 Relocation of Walls and New Door

To integrate the FLCB into the network, the existing busbar needed to be extended as there were no spare bays to accommodate the FLCB. Further details on this busbar extension are discussed in Section 4.1 and 4.3.

In order to extend the existing busbar, the internal fire protection walls and doors had to be shifted due to the lack of available space as shown in Figure 10. During site selection and survey, it was observed that the existing walls and doors contained asbestos. It is well known that disturbing asbestos has the potential for serious or fatal health consequences, meaning they are unsuitable for reuse and were required to be removed and disposed of safely. As a result these were replaced with new durasteel walls and doors shown in Figure 11 which are a standard type used for their fire rated properties.

Figure 10 Existing fire protection wall requiring relocation for busbar extension which was replaced due to containing asbestos

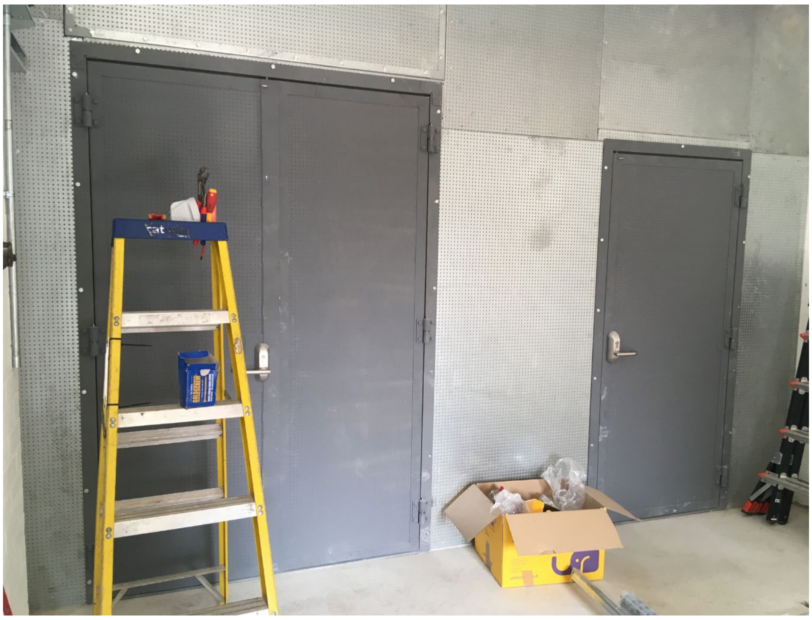

Figure 11 Newly installed durasteel wall and doors to allow for extension of the existing busbar

Similarly a second internal wall near the building entrance was replaced because it was unfit for purpose as it did not meet the requirements for separating switchgear for fire risk and as such was replaced with a durasteel one. The before and after of this work can be seen below in Figure 12.

Figure 12 Second internal wall requiring replacement (left) and newly installed durasteel wall and door (right)

Finally the external door to the building also required replacing as the existing doors were not large enough to allow the FLCB to be delivered inside. The FLCB measures 2200mm in height and each panel is approximately 1000mm so taller doors were installed as per Figure 13 below to allow for delivery of the FLCB panels.

Figure 13 Existing door (left) replaced by larger door (right) to provide access for the FLCB

3.3 Structural Works

In addition to levelling the floor and drilling holes for cable access as seen in Section 3.1, steelwork was installed in the basement to support the weight of the FLCB. Cable trays were also installed in the basement for routing of HV cables between the existing switchgear and the FLCB as well as for multicore cables from the FLCB and other relays used for protection and communications. The left image of Figure 14 below shows the supporting steelwork for the FLCB and the right image shows the cable tray used for newly installed multicore cables.

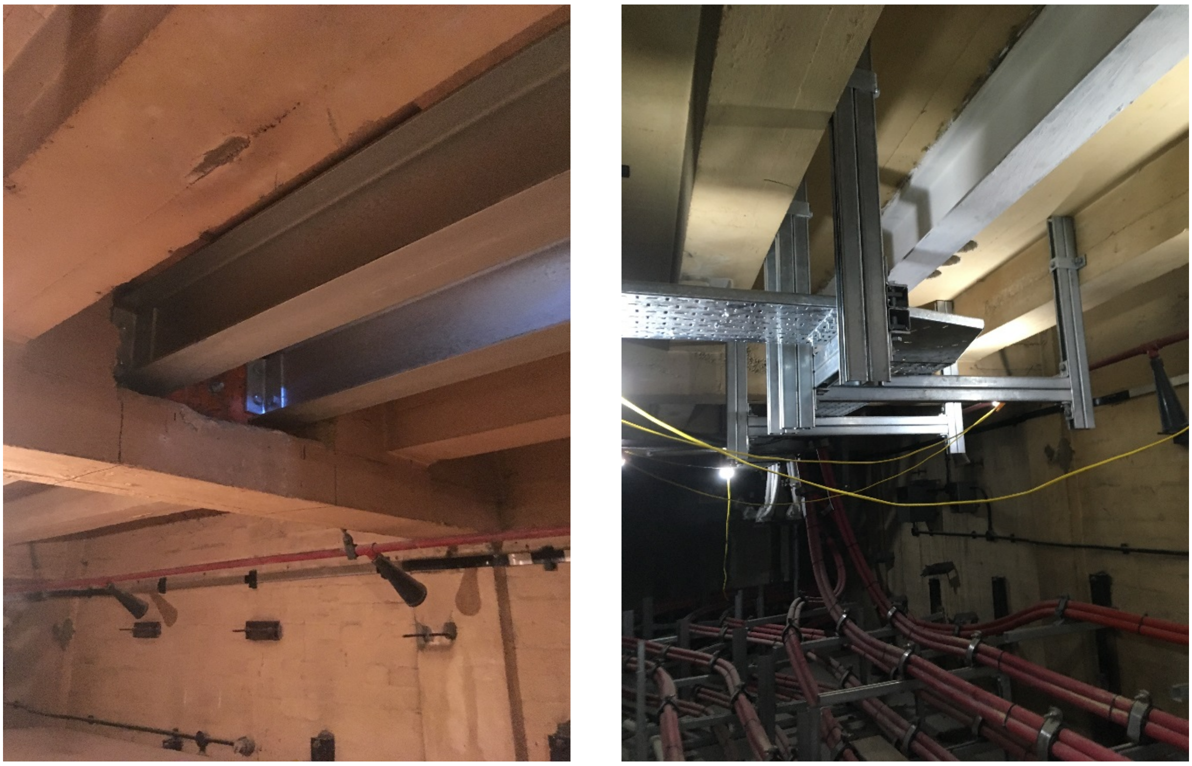

Figure 14 Supporting steelwork in the basement (left) and cable trays added for multicore cables (right)

4. Electrical Works

Integration of the FLCB into the network required electrical works to be carried out on the existing busbar and switchgear along with protection upgrades.

4.1 Busbar Extension

The existing busbars at Glaucus St had no spare bays where the FLCB could be connected and as such, an extension of the busbars was required to connect the FLCB as shown in Figure 15 below. The extension was done by adding three bays, which include two for two additional circuit breakers, PN21 and PN22, and one empty bay as a spacer between them for civil engineering reasons. PN21 and PN22 are also referred to as the adjacent circuit breakers and form the points where the FLCB connects to the existing busbar. These adjacent circuit breakers are required for isolation and backup of the FLCB; refer to Section 4.3 for more details of how PN21 and PN22 are used.

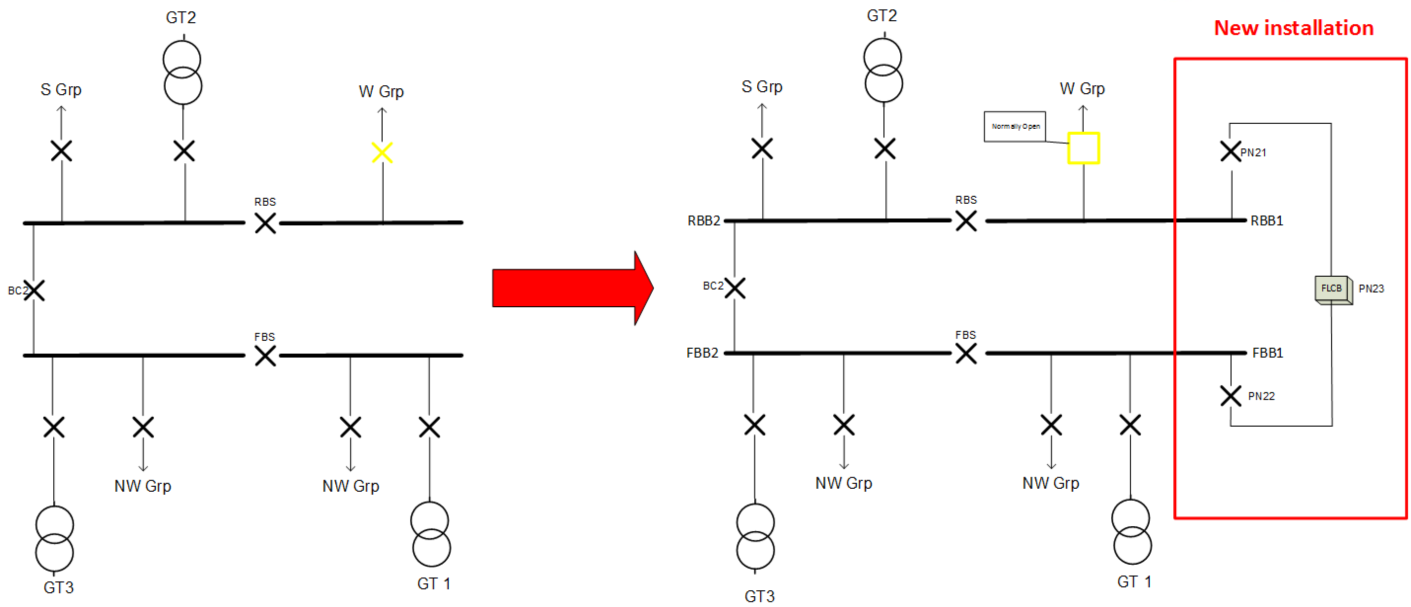

Figure 15 Existing layout of Glaucus St (left) and extension of busbar and addition of FLCB highlighted within red box (right)

In order to complete the busbar extension two types of materials are needed, the bays and the circuit breakers. The specific switchgear bays on site were manufactured in the 1960s and the circuit breakers were retrofitted to vacuum type circuit breakers in 1990s. Production and commercial sale of the switchgear bays and spare parts had therefore ceased. The retrofit service of the original circuit breakers to vacuum is still available. Though a stockpile of circuit breakers of the same type were available, these would need to be repaired and retrofitted to be operational. Therefore an alternative option to extending the busbar considered was the creation of a new small busbar that would be connected to the original via cables and cable end boxes. However during the site selection process, it was identified that another UK Power Networks' substation that had the exact same type of busbar was undergoing an upgrade programme, where the entire busbar and switchgear was replaced with modern equipment. The project team took this opportunity to drive efficiency in delivery by aiming to reuse three bays from this substation for the project.

Although we were reusing the bays, the two being used as the adjacent circuit breakers were sent to ABB to retrofit the bays with new circuit breakers. This retrofit was to ensure the circuit breakers were modernised to have improved reliability and meet the necessary required ratings. The circuit breakers retrofitted into the bays are type VOR-M circuit breakers.

The busbar extension itself was time consuming and complex due to the age of the equipment, and required a lot of the work to be handcrafted. While the circuit breakers were with the manufacturer being retrofitted, the project team worked in parallel to connect the bays to extend the busbar in readiness to receive the retrofit circuit breakers. Figure 16 below shows the installation of the three bays in progress.

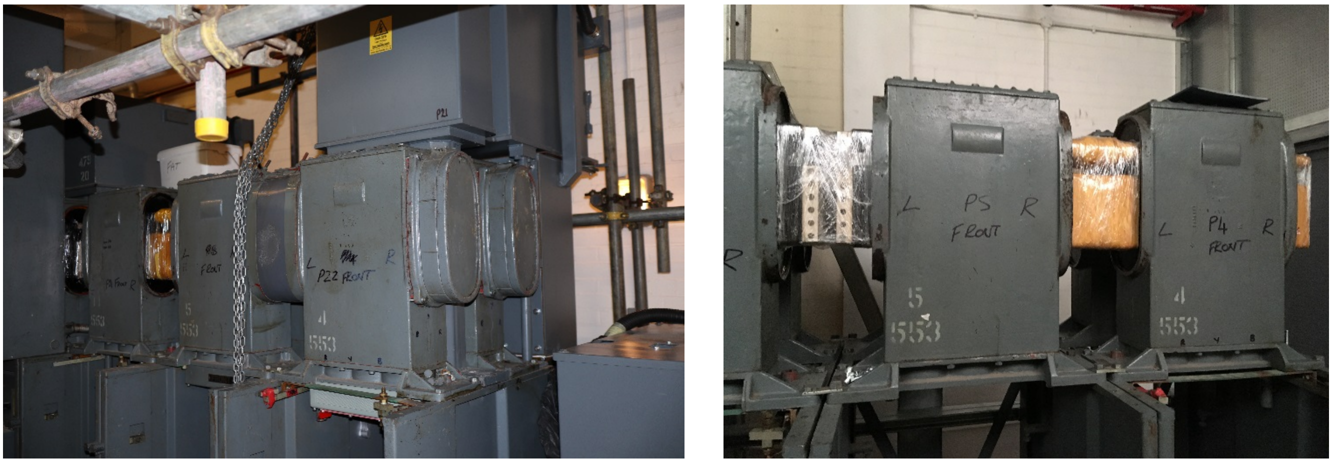

Figure 16 Work required to connect the busbar between additional bays

4.2 Retrofitted Type VOR-M Circuit Breakers

As highlighted in Section 4.1, circuit breakers PN21 and PN22 are type VOR-M circuit breakers. During the busbar extension works, a defect at two other substations was discovered with a batch of retrofit VOR-M circuit breakers of the same type as the ones being used at Glaucus Street substation. There was a defective batch of capacitors used by the manufacturer. The defect meant that there was a possibility for the capacitors to fail and this defect was also raised with the Energy Networks Association (ENA) as part of the National Equipment Defect Reporting System (NEDeRS) with reference “NEDeR 2019/0908/00”. The capacitor failures caused by the defective batch affected the magnetic actuator mechanism. Failure of the capacitor would prevent the circuit breaker from opening/tripping as would a loss in power supply to the VOR-M circuit breakers.

The project team engaged with the relevant Asset Engineers and Network Operations staff, and with their assistance, contacted the manufacturer who confirmed that the capacitors in the retrofit circuit breakers procured for the project were not part of the defective batch. Although the risk of failure of the circuit breaker was observed to be very low, UK Power Networks requested the development of a portable power pack from the manufacturer that would enable the circuit breaker to be opened in the event of a loss of DC supply to the circuit breakers. Details of additional precautionary measures put in place are discussed in Section 8.

Figure 17 below shows the general sequence of work in extending the existing busbar so that the FLCB could be connected to the network.

Figure 17 Sequence of work to extend the existing busbar – spare bays in place (left and middle) and retrofit circuit breakers ready to be put in position (right)

In order to connect the existing switchgear to the FLCB, new HV cables rated for 11kV had to be installed. Both the existing switchgear and the FLCB use bottom cable entry which means that the cables connect to the underside of the equipment. The cables then enter the basement directly below the existing switchgear and were pulled through the basement to where the FLCB was positioned and are connected to the FLCB via the slots in the floor as seen previously in Figure 9. Figure 18 below shows the HV cables ready to be terminated to the existing switchgear as well as the cables terminated to the FLCB.

Figure 18 HV cables ready to be terminated to the existing switchgear (left) and completed HV terminations to the FLCB (right)

4.3 Protection Works

When trialling new equipment, the typical approach is to have additional protection capabilities as insurance against unexpected malfunctions. Similarly in the case of the FLCB, there were increased requirements on the protection and control design. This meant installing equipment that we would not normally install as part of the BAU deployment and hence the requirement to install the adjacent circuit breakers. The addition of the adjacent circuit breakers on either side of the FLCB meant that these can be used to provide isolation and earthing of the FLCB.

The adjacent circuit breakers will also act as backup protection during the trial, to mitigate any impact of potential FLCB failure to operate under a network fault or failure of the device itself. A portion of the single line diagram (SLD) depicting this arrangement can be found in Figure 19 below. Whenever a trip signal is received by the FLCB, it will open followed by the two adjacent circuit breakers. When an open signal is received by the FLCB, the two adjacent circuit breakers will open followed by the FLCB. Similarly whenever a close command is received by the FLCB, the FLCB will close first followed by the two adjacent circuit breakers.

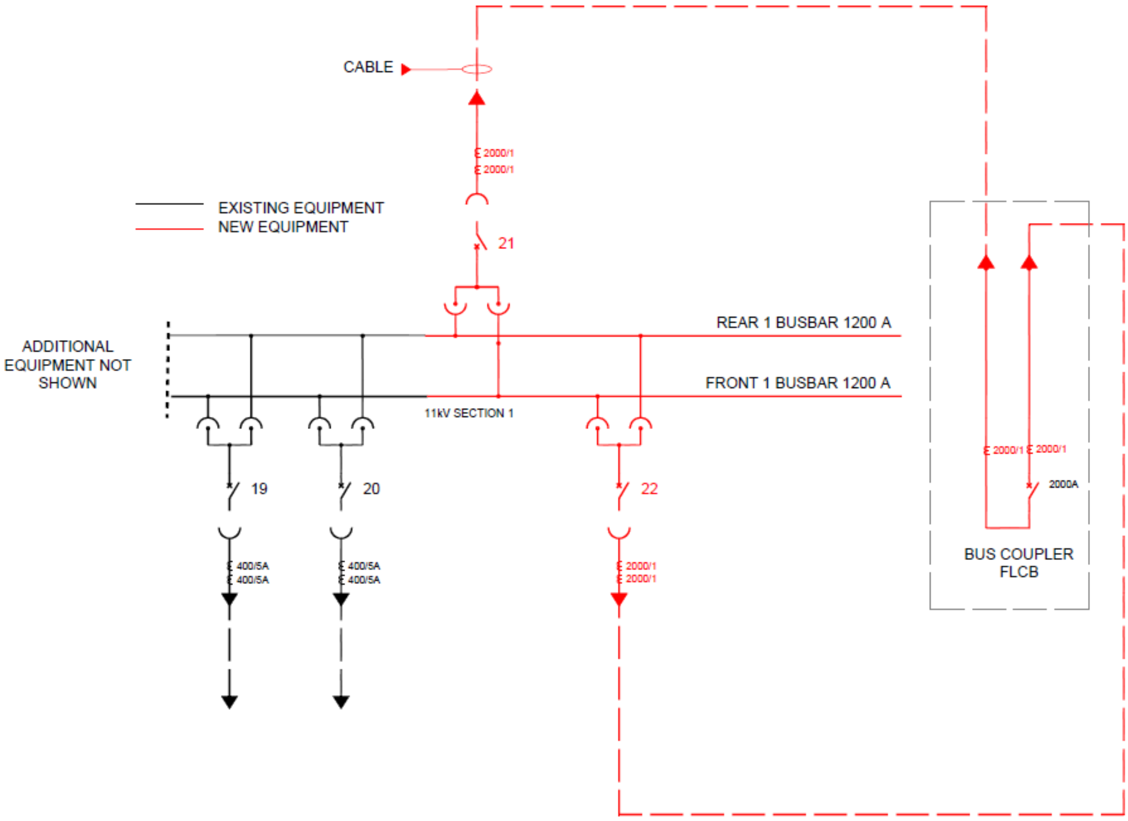

Figure 19 FLCB installation arrangement for network demonstration – circuit breakers PN21 and PN22 are adjacent circuit breakers to provide isolation and back-up protection for the FLCB during the trial

4.3.1 Protection Enhancements

As previously mentioned in Section 4.1, a requirement for the project trial was to use the two adjacent circuit breakers as back-up for the FLCB. The project team worked with UK Power Networks protection and standards experts to review the protection design of the substation and the introduction of the FLCB and concluded that there was a need to implement a fast acting differential protection dedicated to the FLCB branch. As such, differential protection was installed on the FLCB branch between PN21 and PN22, as shown in Figure 20, to have a fast acting backup protection in case the FLCB were to fail to operate.

Differential protection, or unit protection as it is otherwise known, is more advanced, and has faster fault detection and trip initiation than the simpler overcurrent protection commonly used in similar conventional bus coupler arrangements. The limitation of differential protection is that it requires a direct communications channel between the two relays in order for the devices to do the differential calculation and the relays cost more than overcurrent protection relays.

Put simply differential protection monitors current which enters and exits a protection zone. If there is a large difference in measured current, hence differential, the protection detects a fault and trips the necessary circuit breakers. In this case, the zone is between PN21 and PN22 as shown in Figure 20 below and will detect faults in the branch that includes the FLCB and HV cables.

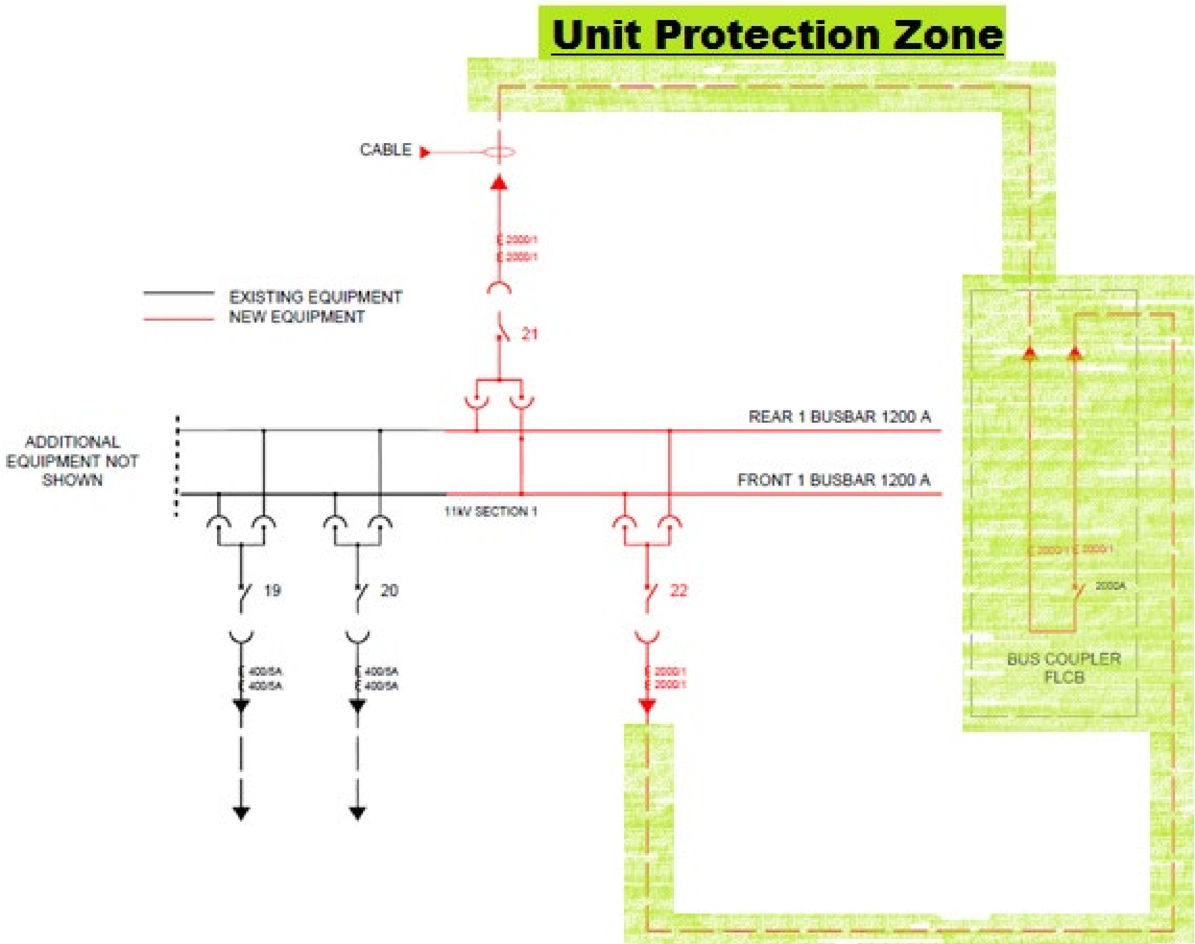

Figure 20 Unit protection/differential protection zone highlighted in green

For further backup protection of the busbar, modern overcurrent protection relays were installed as part of the protection scheme. This is the typical requirement for protection schemes of bus couplers. These relays and the unit protection relays were installed in new wall mounted protection panels in the FLCB room because the busbar bays are unable to house the modern relays.

Figure 21 Protection panels house differential protection relays and overcurrent protection relays for the two adjacent circuit breakers CB21 and CB22

4.3.2 Fault Recorders

One of the key outputs of the project trial is data captured on the performance of the FLCB under real network conditions. It is vital that we capture this data when a fault occurs and as such we have installed external fault recorders in addition to the FLCB also having internal fault recording capabilities. As the FLCB operates at such high speeds, it was important to use equipment that is capable of recording such events. Collaborating with our project partner, ABB, we identified suitable fault recording devices capable of capturing the necessary information at a level of granularity required which was 32 measurements per cycle (i.e. 1.6khz). The fault recorders chosen were Siemens Argus M1 units and were wall mounted in a similar fashion to the protection relays shown in Figure 21.

4.3.3 SCADA Upgrade

The existing protection and control devices at the trial substation were primarily legacy equipment which do not require high capability communication infrastructure to send data back to Network Control. The introduction of the FLCB and other protection upgrades created a need to upgrade the SCADA equipment on site to provide modern digital capabilities in order to take advantage of the full functionality of the FLCB.

Figure 22 Existing SCADA equipment (left) and additional SCADA panel added (right) which includes Human Machine Interface (HMI)

In addition to upgrading the existing SCADA equipment, an important activity was deciding the number of signals and alarms that would be reported to UK Power Networks' central control centre. The FLCB equipment is modern and can provide a large number of data points however the control centre does not necessarily require the visibility of all these data points. Therefore the project team worked with ABB and internal stakeholders to filter out, produce and implement a list of alarms that are critically required for safe operation of the device by the control centre.

The next step in the design process was to select the communications path. According to UK Power Networks' policy, it is required for certain signals including status, alarms and control, to be hardwired. To adhere to this policy, such critical signals were flagged as hardwired and the remaining were marked as digital preferred.

FLCB digital signals to SCADA are transmitted from the ABB REF protection relay in FLCB cabinet, while the hardwired signals are taken from the wiring terminals in the FLCB cabinet. Each hardwired signal requires its own port and cable into the SCADA equipment. Therefore there is a physical limit on the number signals that can be hardwired.

The last step was to verify that the SCADA equipment has the available ports to route all hardwired signals. The project team worked closely with ABB, the electrical design team, the operational telecoms team and the control room engineers to find out a balance between practicality and capabilities. All the control functions, status and alarm signals are carried in hardwire analogue, while all measurements are carried digitally. All these can be seen in the local Human Machine Interface (HMI) and can be seen above in Figure 22. The details of the HMI showing all alarms from the FLCB, adjacent circuit breakers and all measurements from the FLCB is shown below in Figure 23. A mimic of the entire substation is also available through the HMI and is shown in Figure 24 below. The mimic shows the real time status of the substation providing information such as current flowing through each feeder and the status of circuit breakers.

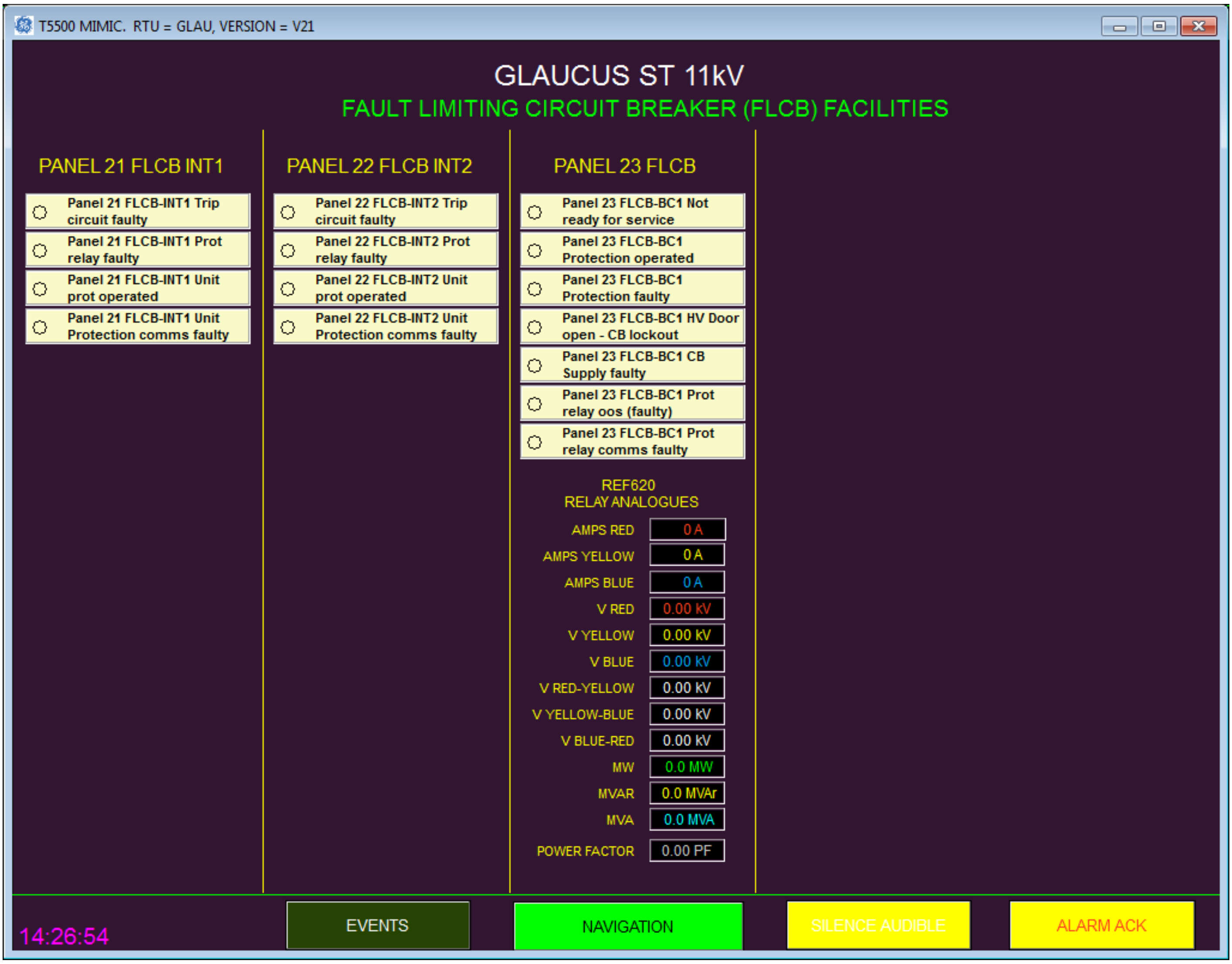

Figure 23 Display screen of HMI showing the alarms/status and analogues from the FLCB and adjacent circuit breakers PN21 and PN22

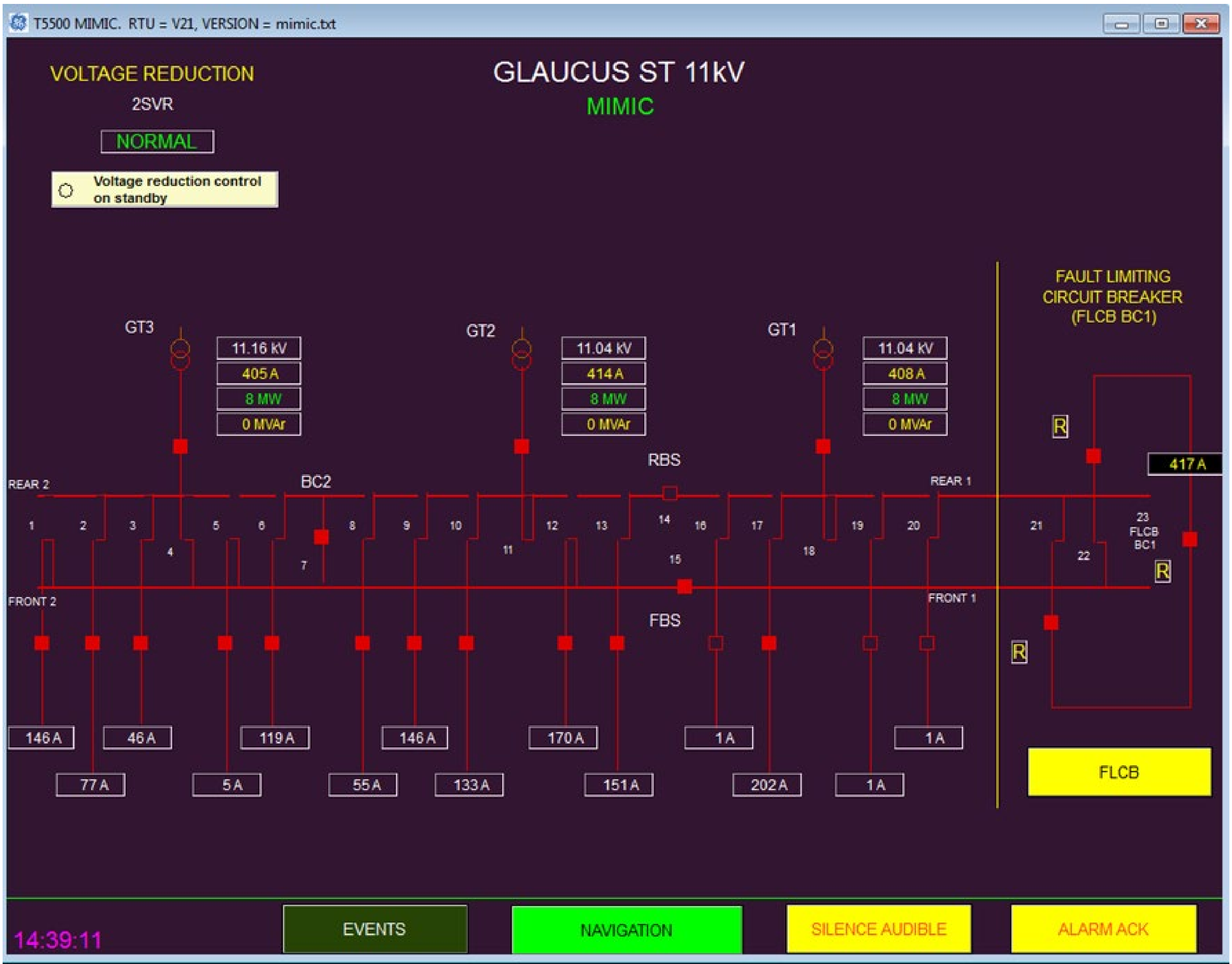

Figure 24 Mimic of substation showing real time status of the substation

An explanation of the signals in our SCADA system reporting back to the control centre are as follows:

- **Panel 23 FLCB-BC1 CB Not ready for service**: This is an alarm to indicate that the FLCB is not ready and typically indicates that capacitors are not fully charged yet so the device cannot be operated;
- **Panel 23 FLCB-BC1 CB Protection operated:** This alarm indicates that the FLCB protection device detected a fault and tripped the FLCB;
- **Panel 23 FLCB-BC1 CB Protection faulty:** This alarm indicates an issue with the FLCB protection relay, QR6, and will trip the adjacent circuit breakers PN21 and PN22 as a result;
- **Panel 23 FLCB-BC1 CB HV Door open – CB lockout:** This alarm indicates that the HV doors are open and the FLCB is locked out of operation;
- **Panel 23 FLCB-BC1 CB Supply faulty:** This alarm indicates that there is no LV supply to the FLCB;

- **Panel 23 FLCB-BC1 Prot relay oos (faulty):** This alarm indicates any detected internal malfunctioning of the FLCB, including:
    - lost charging status of drive capacitors, or if charging time exceeds 3 minutes;
    - unexpected position indication from mechanical switches, either due to any switch being out of position or malfunctioning of position sensors;
    - too long operation time of mechanical switches;
    - issues with semiconductors or gate drive electronics;
    - lost or incorrect communication between FLCB components;
    - failed over-current interruption; or
    - trip signal received during closing of mechanical switches (possible but unlikely).
- **Panel 23 FLCB-BC1 Prot relay comms faulty:** This alarm indicates that there is an issue with the communications equipment, either a wire or a device.

The 'Panel 23 FLCB-BC1 Prot relay oos (faulty)' alarm should not be reset until an investigation that establishes the source of the alarm has been completed by ABB. The options for resetting the alarm are power cycling the control system hardware or using ABB debugging software on a PC that is physically connected to the supervision unit.

4.3.4 Auto-close Scheme

The focal characteristic of the FLCB is the speed of operation and its speed is much faster than existing conventional equipment. The trial substation has 3x15MVA transformers rather than a more conventional four transformer site. Due to this there is a specific scenario under Running Arrangement 3 (running arrangement discussed in Section 6.3), where it is possible to have customers off-supply for three minutes. This three minutes is due to the fact that after a close-open (CO) sequence the FLCB requires three minutes to recharge the capacitors used for opening and closing the FLCB. To mitigate the impact of this, an auto-close scheme has been installed.

In a conventional design the bus coupler protection relay would be slower than the transformer protection. Essentially the bus coupler protection would wait to see if the transformer protection will clear the fault and only operate to open bus coupler if the transformer circuit breaker has not cleared the fault. However in order to be able to limit fault levels the FLCB needs open fast and cannot afford to wait for transformer protection.

The scenario is shown in Figure 25 where a fault anywhere upstream of the 11kV circuit breaker for GT2, the transformer protection will operate to open the circuit breaker or remote upstream protection could send an inter-trip to this circuit breaker. The fault will also be fed from front busbars, FBB1 and FBB2, via the FLCB in Running Arrangement 3 (as BC2 will be normally open in this running arrangement) and as a result the FLCB will detect the fault and trip the FLCB. With both the circuit breaker on GT2 and the FLCB open, this would leave rear busbars, RBB1 and RBB2, dead and hence have no supply.

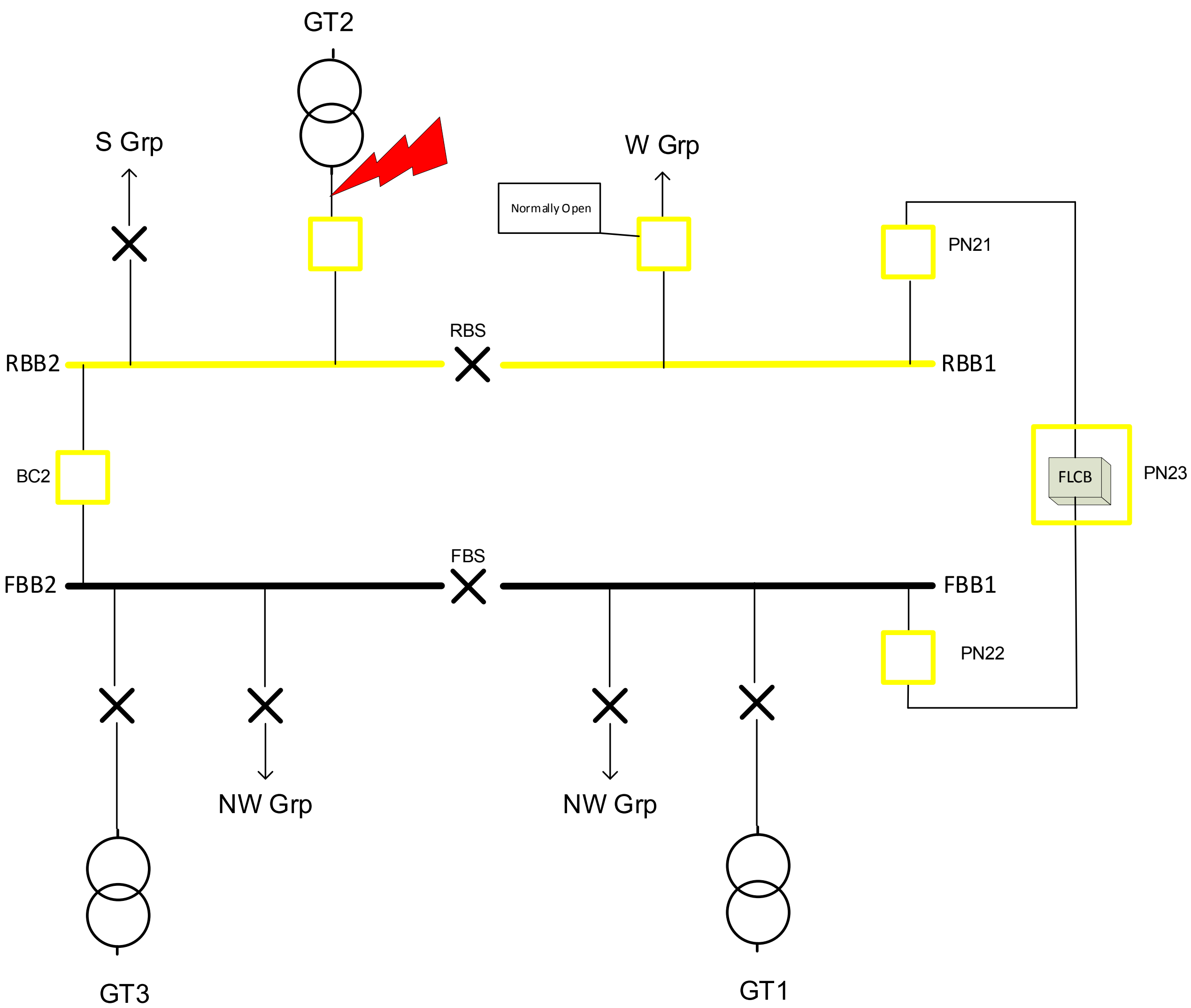

Figure 25 Fault on GT2 in Running Arrangement 3 illustrating the need for an auto-close scheme. Note yellow indicates 'de-energised'

To overcome the issue where under certain faults a loss of supply will occur, the auto-close scheme was installed on the existing bus coupler, BC2. The auto-close relay is monitoring the transformer circuit breakers and if it sees a trip received, it will close the BC2 so that customers stay supplied.

The auto-close scheme shall be initiated by a trip of the GT2 protection or remote protection inter-trip and a simple step by step process of the scheme is below:

1. GT2 transformer protection trip or received inter-trip from remote protection;
2. Check if BC2 is open;
3. Check if FLCB is open;
4. Check if GT2 CB is open; and
5. Send close command to BC2.

This auto-close scheme will be required on all application of the FLCB to substations with three transformers, but is unlikely to be needed on sites with four transformers. Using our trial site as an example if there were a fourth transformer connected to RBB1, there would be a transformer to support the load of RBB1-2 if GT2 were tripped and the FLCB open.

Figure 26 Auto-close panel installed

5. Installation and Commissioning

5.1 FLCB Delivery and Installation

Following the completion of all factory acceptance tests (FATs) and type testing as detailed in the previous learning report, SDRC 9.1.1[4], the FLCB was delivered to site November 2019.

It was transported and offloaded on site by a heavy duty vehicle. Due to the large size of the equipment and carrying vehicle, a parking restriction was required on the road with the entrance to site. The FLCB was disassembled to three bays in the factory for easier transportation, one panel for each phase. Each panel was separately off loaded from the vehicle as shown in Figure 27 and moved inside the building with the assistance of rollers as shown in Figure 28.

[4] https://innovation.ukpowernetworks.co.uk/wp-content/uploads/2019/11/Powerful-CB-SDRC-9.1.1-v1.0-DP.pdf

Figure 27 One panel of the FLCB being offloaded from the transportation vehicle

Figure 28 FLCB panels being shifted into place

After all three bays were placed in the correct position in the room, ABB re-assembled the FLCB including wiring between the panels. The wiring was for communication and control cables as the main control unit, the brain of the system, sits within the middle panel. Each phase is controlled individually by a controller in each panel respectively.

Figure 29 FLCB installed in final position and reassembled

Once the FLCB was installed all the necessary external wiring such as communications and control wiring to integrate it into our protection and SCADA systems was completed by UK Power Networks.

5.2 Commissioning of the FLCB

During the second week of December 2019, experts from ABB visited the site in order to finalise the installation of the FLCB and then to test and commission the device. The ABB team collaborated with UK Power Networks commissioning engineers in order to test full functionality of the FLCB with our systems.

A wide range of testing was completed to confirm the correct functionality of the device and a list of commissioning reports is found in Appendix A. Details of the tests completed are highlighted below:

- Pre-commissioning Checks
    - Ensure equipment to be made live is cordoned off and all non-essential personnel are cleared from test area with permanent and temporary Caution/Warning labels in position;
    - Complete the inter-panel bus wiring in accordance with the associated wiring diagrams; and
    - Check any entries/compartments into live sections of the board are blanked off
- Full Switchboard Insulation Resistance & Dielectric Tests
    - 5kV DC Insulation Resistance Test – The busbars are connected for each test and a 5000V DC Insulation Resistance tester is applied between the connected busbar;
    - AC Insulation Resistance Test – The whole switchboard shall be dielectrically tested with a test voltage of 25kV AC for 1 min for a 11kV Switchgear as per UK Power Networks requirement; and
    - 5kV DC Insulation Resistance Re-test – Repeat the Insulation Resistance Tests as detailed above
- Primary Part Checks
    - Main grounding bar between components and cubicle / main point of grounding; and

  - External. wires and internal wires/tripping lines laid separately
- Electrical Testing
  - Power supply voltages;
  - CTs polarity and magnetising curves;
  - Contacts of panel door;
  - Interlocking panel door; and
  - Operation of FLCB for trip and close commands
- Control Unit Testing
  - Testing according to the testing and commissioning checklist for tripping unit;
  - Signals and alarms (potential-free contacts); and
  - Circuit breaker interlocking/release
- Final Checks
  - CT terminals in service position;
  - Tools, measuring lines, test inserts, etc. removed; and
  - Ensure cleanliness of the units

A minor change requirement was identified during the commissioning process in December 2019; there was a need to complement the power supplies within the FLCB with uninterrupted power supplies (UPS) to ensure the device is as robust, reliable and safe as possible. This required ABB to explore a suitable replacement, ship to the trial site and install the UPS; these were installed in February 2020. Further details of this change are highlighted in Section 8: Challenges and Lessons Learned.

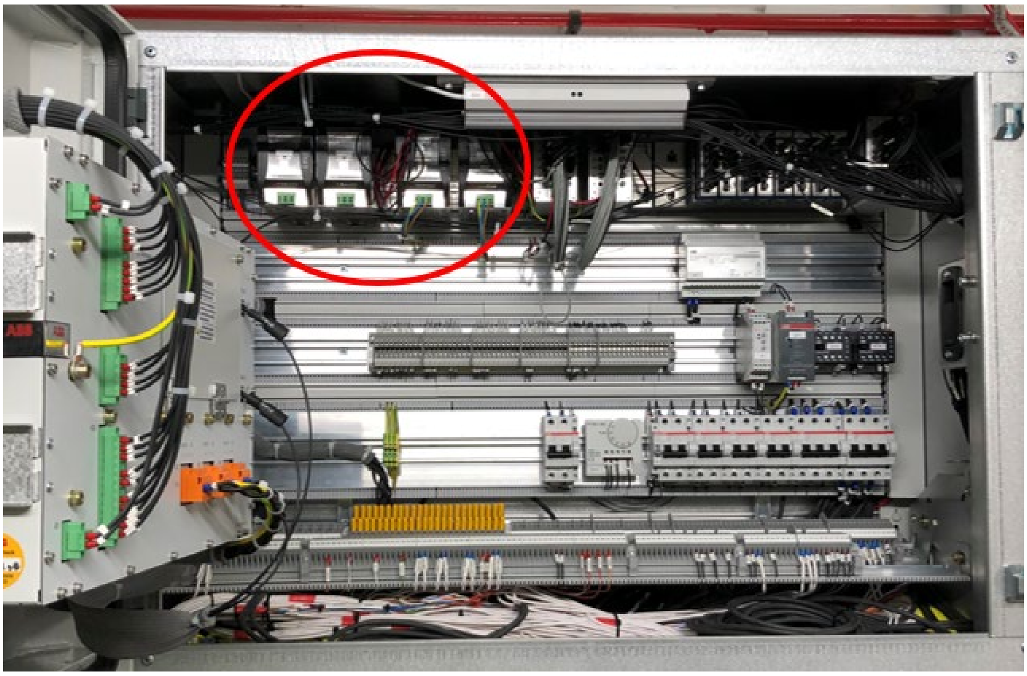

Figure 30 Existing power supplies prior to the addition of the UPS installed in the LV compartment of the FLCB

During the second commissioning visit by ABB in February 2020, it was identified that the magnetic lock which forms part of the HV compartment door interlock was malfunctioning. Following ABB investigations, it was suspected that misalignment of the magnets was occurring due to the weight of the doors on the hinges and the slight slope of the floor. Replacement parts and some minor modifications were made to the HV door and locking mechanism to rectify the issue with further details provided in Section 8.4.

5.3 UK Power Networks Commissioning Works

All the electrical works carried out on site such as the busbar extension, installation of protection relays, HV cabling and SCADA system upgrades required their own testing and commissioning in accordance with UK Power Networks standards. A non-exhaustive list of equipment that was commissioned includes:

- Busbar extension (front and rear);
- Retrofitted circuit breakers including portable power pack testing;
- Commissioning of adjacent circuit breaker protection (CT's, multicore wiring, protection relays);
- HV Cables;
- Fault recorders;
- SCADA modifications and new HMI panel;
- Auto-close scheme; and
- FLCB final commissioning with associated adjacent circuit breaker and energisation;

A list of commissioning reports produced by UK Power Networks is found in Appendix B. These reports are part of the commissioning process to record all the tests completed and their results for future reference.

The functionality of the FLCB with wider protection and SCADA needed to be tested and some of the functionality included:

- When a trip or open signal is received by the FLCB as highlighted in Section 4.3, the adjacent circuit breakers must be opened. Similarly when a close signal is received the FLCB will close followed by the adjacent circuit breakers;
- When the FLCB raises a "FLCB Out of Service/Faulty" alarm, the adjacent circuit breakers are required to be opened to isolate the FLCB. A decision to change the protection logic to enable this was identified during commissioning in December 2019 and these changes were implemented and commissioned during the second site visit from ABB in February 2020;
- An operational safety requirement UK Power Networks is that the HV door of the FLCB cannot be opened unless the adjacent circuit breakers are open and earthed and five minutes has passed since switching off the power supply to the FLCB capacitor banks. Hence the functionality of the HV door interlock was tested; and
- All alarms of the FLCB were generated during commissioning to ensure SCADA could receive them. There was an issue with receiving the trip alarm in SCADA whereby the FLCB would trip however SCADA would not register the alarm; this is discussed further in Section 8.

Once commissioning was finalised and the HV door interlock repaired, the FLCB was energised and hence be running on a live network. Prior to energisation two separate training sessions were held for local Field Engineers who may be called upon to site to respond to any faults on the network. The purpose of these sessions was for familiarisation and to explain the concept of the FLCB, the different alarms raised by the FLCB and any actions necessary to respond to these alarms.

Figure 31 Training session being undertaken by UK Power Networks Field Engineers to familiarise themselves with the FLCB

In addition to these training sessions an internal Engineering Operation Standard, EOS 03-0125, was published to provide information and guidance for Network Operations Field and Control Engineers. This standard includes basic design, physical size/dimensions and arrangement on site of the FLCB. Further information is also provided for the following:

- Various running arrangements for the trial and the purpose of each;
- Operational information about the equipment; and
- A summary/concentrated information for a template to be applied to a pin in PowerOn.

6. Trial Running Arrangements

In collaboration with internal stakeholders, the project team decided to trial three different running arrangements during the project trial. The purpose of having a number of running arrangements was to demonstrate the functionality of the FLCB under different topologies. The existing running arrangement of the trial substation prior to site works is shown in Figure 32 and the site is typically run solid which means that the bus coupler, BC2, was closed. This running arrangement will be referred to as 'standard running arrangement' from this point on.

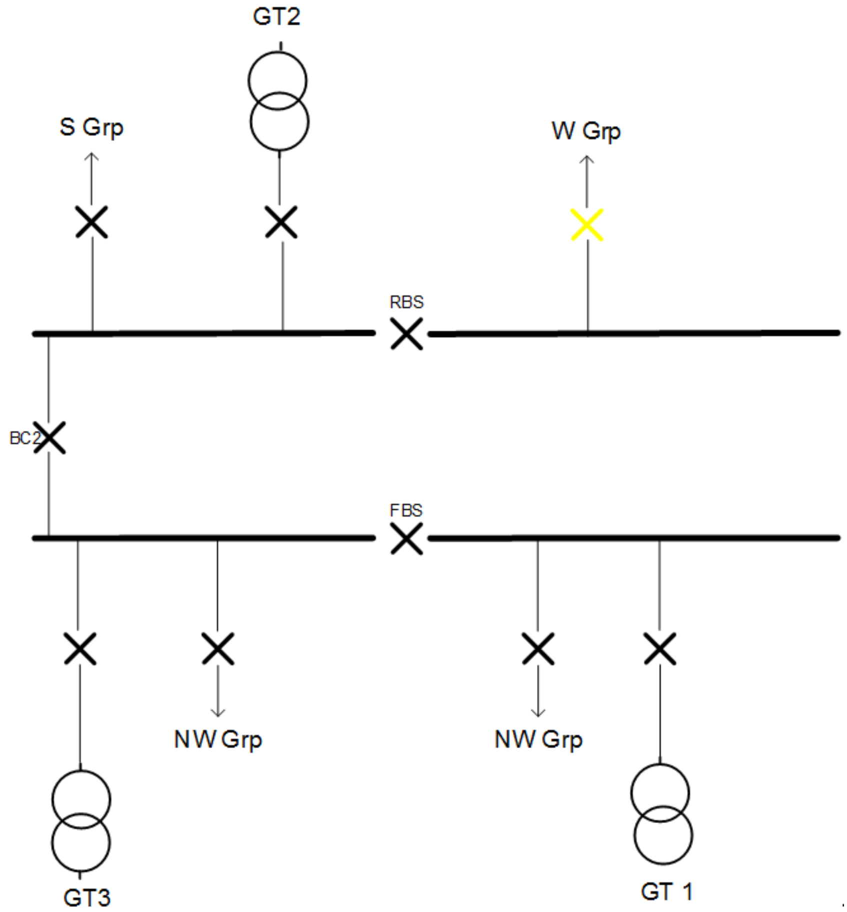

Figure 32 Standard running arrangement of trial substation prior to project work commencing. Note yellow indicates 'normally open'

6.1 Running Arrangement 1

Running Arrangement 1 as shown in Figure 33 is to simply energise the device and let it 'soak' for a short duration to ensure there are no problems. There is no requirement for the FLCB to trip for a network fault under this running arrangement. As previously discussed in Section 4.1 the existing busbar was extended and circuit breakers PN21 and PN22 added to accommodate the FLCB.

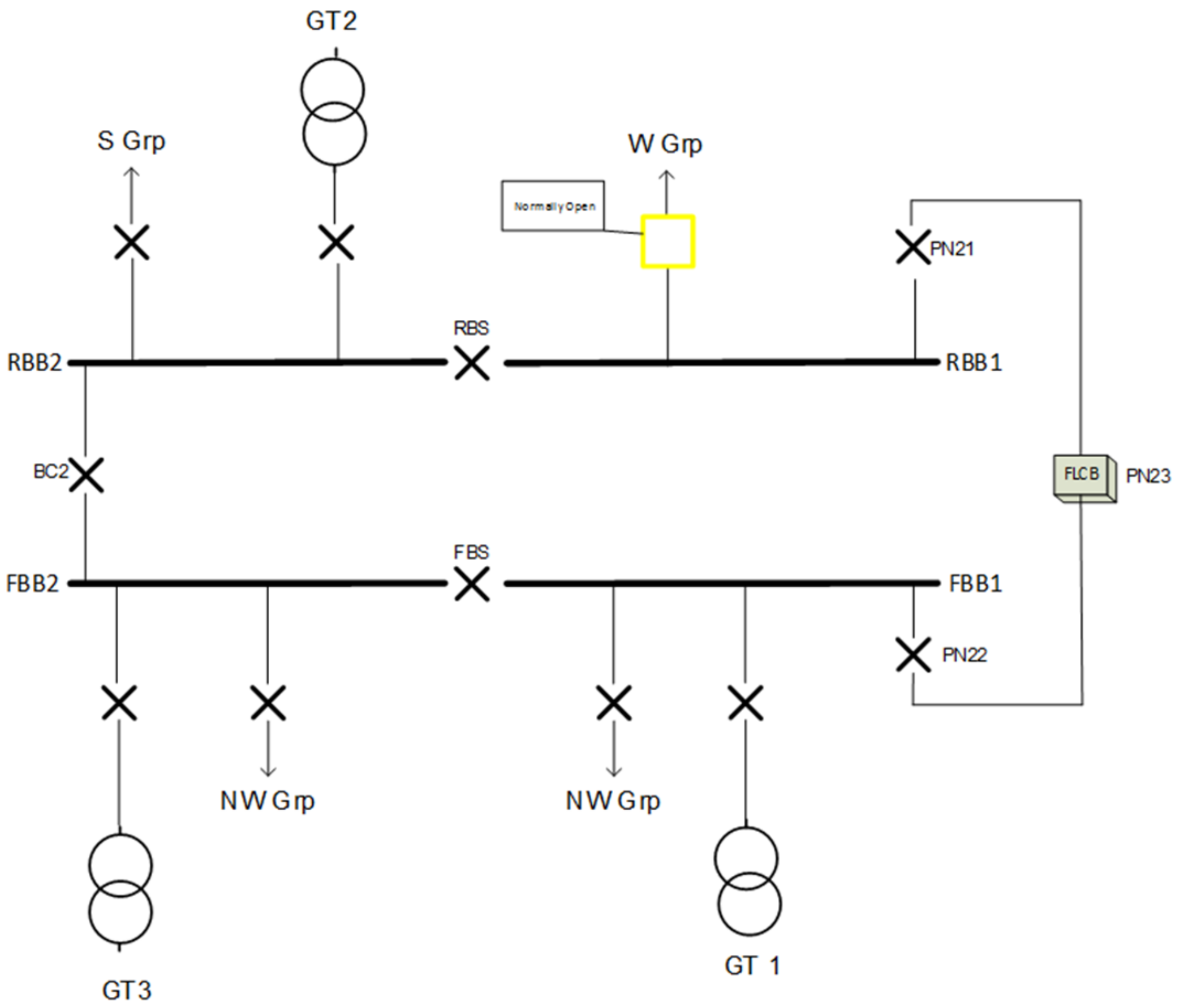

Figure 33 Running Arrangement 1. Note yellow indicates 'normally open'

6.2 Running Arrangement 2

Running Arrangement 2 will simulate the use of the FLCB as transformer incomer feeder breaker. In this arrangement the FLCB will experience fault current fed from a single transformer, in this case GT1. In order to achieve this configuration, GT1 will have to be reselected to the rear busbar when compared to the standard running arrangement. The rear bus section circuit breaker (RBS), will also open.

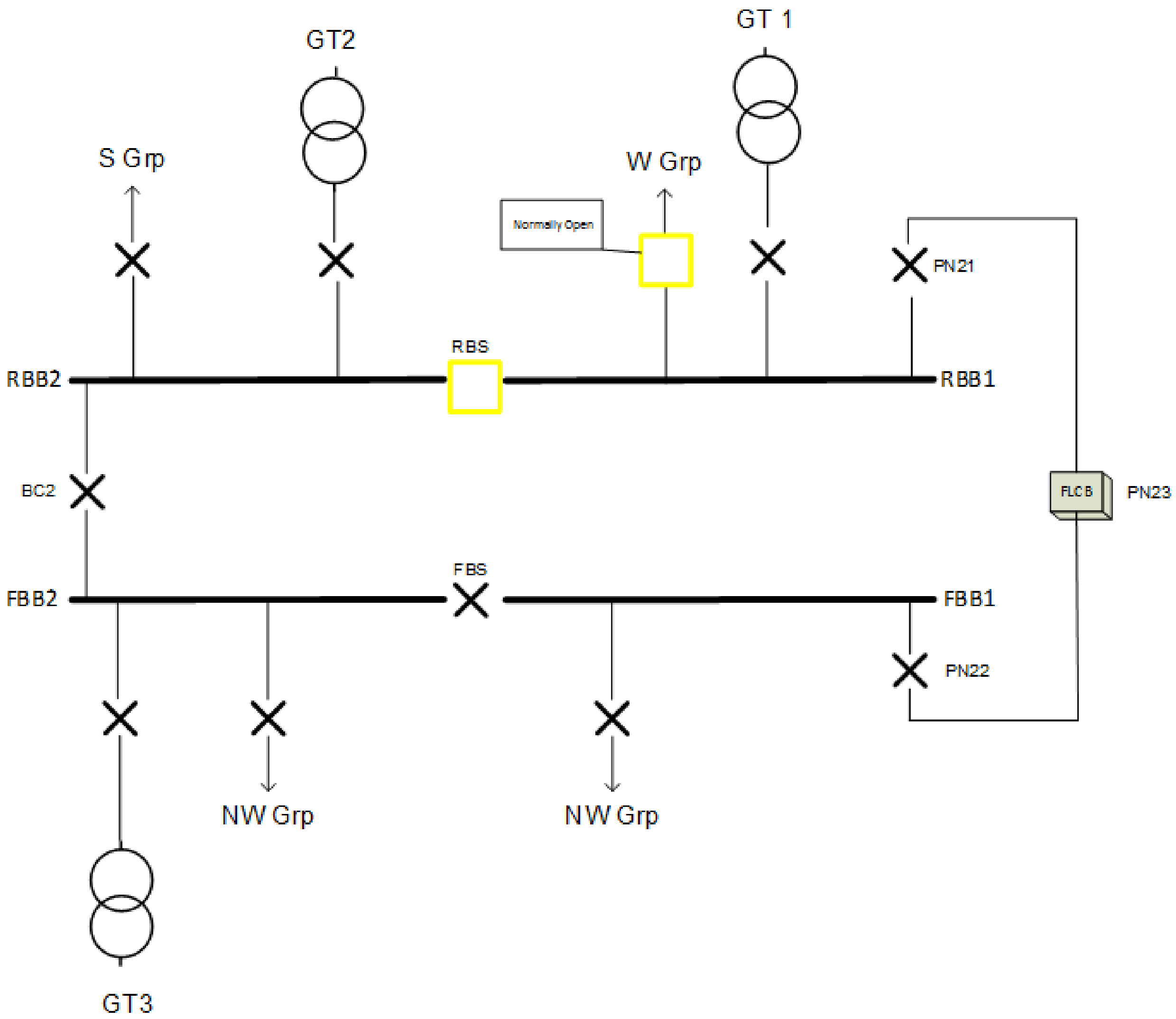

Figure 34 Running Arrangement 2. Note yellow indicates 'normally open'

6.3 Running Arrangement 3

The final arrangement is to trial the FLCB as a bus coupler where it is likely to experience fault level fed from two transformers. Under this running arrangement the bus coupler, BC2, will be open as shown in Figure 35.

Under this running arrangement there is a possibility of busbar outage on the rear busbar in the case of a fault on GT2 feeder as discussed in Section 4.3.4. To mitigate this risk, an auto-close scheme was installed on the existing bus coupler, BC2.

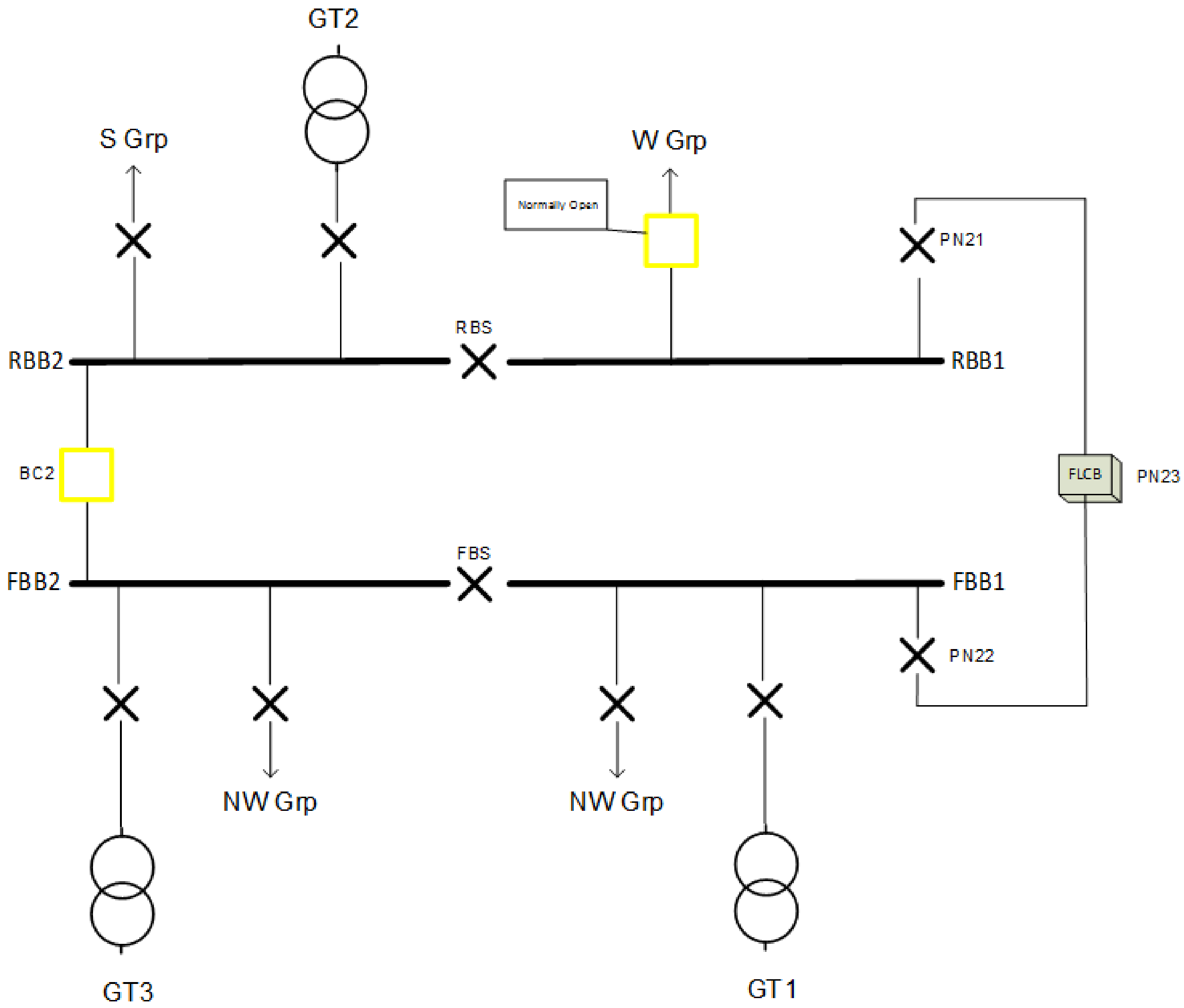

Figure 35 Running Arrangement 3. Note yellow indicates 'normally open'

7. Operation to Date

The FLCB was commissioned in February 2020 with the exception of the HV door interlock which was found to be faulty. Until this was repaired, the FLCB could not have been energised due to safety reasons. Though the arrangements were made to resolve this issue and complete commissioning, including firm dates for ABB engineering team to attend site for completion of remaining works, by the end of March 2020, all site related activities had to be put on hold due to COVID-19 related restrictions. The work recommenced in July 2020 once the restrictions were lifted and safety measures placed for COVID-19. The device was subsequently energised, commencing the project trial period.

7.1 Remote Monitoring of the FLCB Health and State

The FLCB has a control system that continuously monitors the state and health status of relevant FLCB components. The purpose of monitoring is similar to conventional equipment; to gather operational data and to detect any faults with the device. If a problem is detected the FLCB will send out an alarm and perform a safe shutdown procedure. One of the important tasks of the control system is to monitor the exact position of the mechanical switches because the distances travelled between the open and close position are only a few centimetres. Lastly for the purposes of the trial, the collected data can be made remotely accessible for development and fault-tracing purposes by ABB.

The diagnostic data is gathered by the control system for each of the three phases and is collected by a supervision unit in the FLCB. The supervision unit stores this data on its local hard-drive and transfers the data periodically to a remote file server managed by the ABB. This data is transferred through a private encrypted virtual private network (VPN) tunnel over the internet using a cellular router that provides mobile internet access. In this way, the FLCB is physically isolated from the UK Power Networks' data network, which is important for the purpose of cyber-security. The VPN-tunnel terminates at a firewall located within a private network inside of ABB's corporate network. The transferred data is stored on a file server within the private network and the data can be accessed only by physically connecting to the file-server.

It is important to note that the remote monitoring by ABB is done only for the trial to maximise learning, minimise downtime by predicting internal faults and to provide the ongoing view of the device to the manufacturer's experts. This is particularly important to ensure effective trouble-shooting and maintenance, especially due to the distance between the device development location (Vasteras – Sweden) and the trial site (London – UK). Between completing commissioning of the FLCB and energisation the remote monitoring system of the FLCB continuously reported on the health and state of the device.

The overall setup of the system is illustrated in Figure 36.

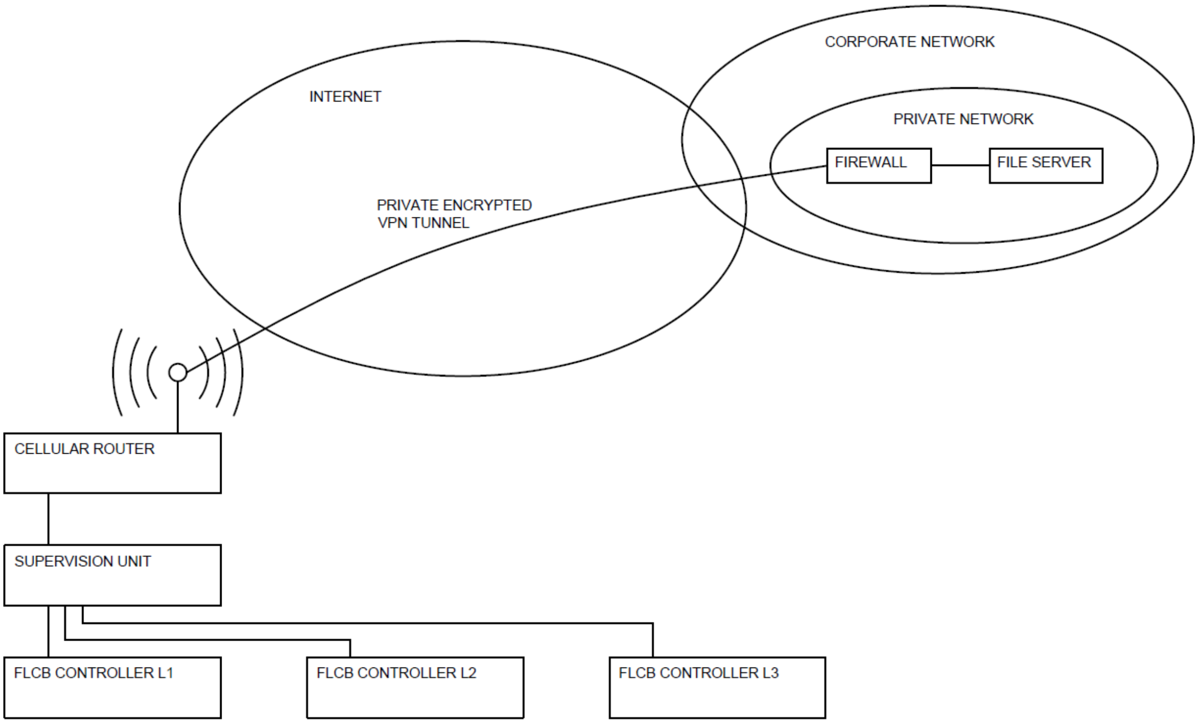

Figure 36 Setup of the remote monitoring system

In ordinary circumstances, when the FLCB is energised, ready and waiting for a protection operation or switching command, the following parameters are monitored:

- The states of the mechanical switches are continuously monitored to immediately detect unexpected position indications, either due to switches moving or due to malfunctioning of position sensors;
- The charging status of the drive capacitors for the mechanical switches are monitored continuously; and
- The power semiconductors' state (i.e. conducting or non-conducting) and health status, and the internal status of the gate drive electronics is checked once every 12 hours, using a status request from the control system to the gate drive units. This interval is as a trade-off considering both the probability and severity of potential errors as well as the required overhead communication with the gate-drive units.

Furthermore, in the case of a switching event or safe shut-down due to a detected error, the following parameters are monitored:

- The operating time of the mechanical switches;
- Different aspects of the power semiconductors' switching operation are monitored by the gate-drive units to assess whether the switching was successful, and the result is communicated to the control system;
- The time required for re-charging the drive capacitors;
- The line currents are recorded at a sample rate of one million samples per second, starting 20 ms before and ending 100 ms after the detection of the event.

One example of a remotely accessible data file is shown in Figure 37, where the data indicates that the entire FLCB is healthy and in the closed state, ready to perform a protection operation. This type of data file is collected once every 12 hours if the FLCB is healthy and ready, and promptly following a switching event or a detected malfunctioning leading to safe shut-down.

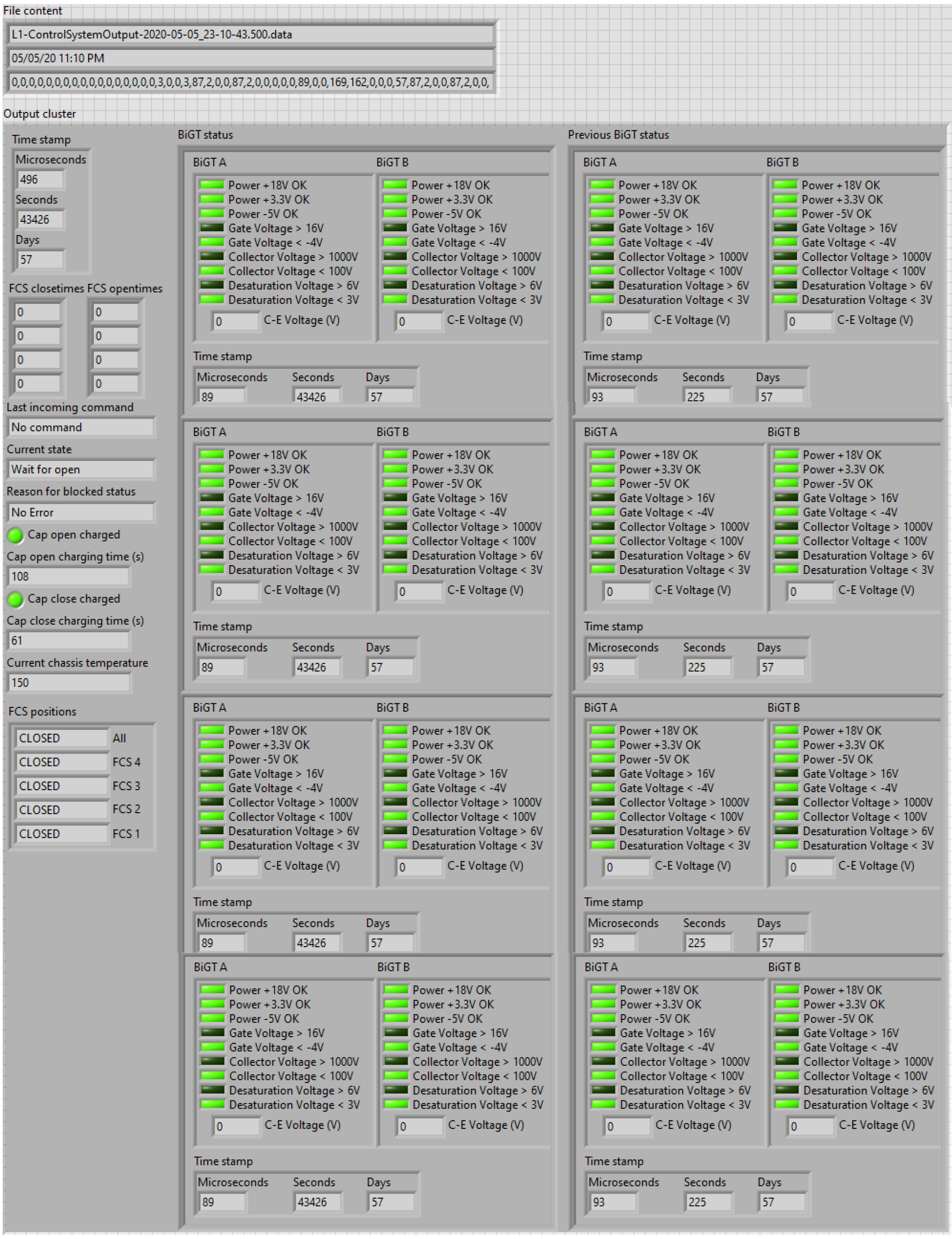

Figure 37 Contents of a remotely available status file where the FLCB reports healthy status in closed state, ready to perform a protection operation

7.2 Confidence Switching

In an effort to increase the understanding about the device use and test its durability, the project team, ABB and technical experts from UK Power Networks have decided to program regular confidence switching of the device.

Confidence switching is when a network circuit breaker is remotely switched to its alternate position and then back to normal within a few minutes. For example a circuit breaker that is typically closed will be switched open and the closed again. This is done to verify the good operation and provide 'confidence' so that for example when called upon to operate for a fault, the circuit breaker should trip as expected.

A regular confidence switching schedule has been setup with the Outage Planning Team of UK Power Networks so that it takes place starting from October 2020 in the first week of each month for the duration of the trial. The data captured from confidence switching is captured through remote monitoring as explained in Section 7.1 above.

7.3 Running Arrangement 1 Demonstration

Following energisation the demonstration of Running Arrangement 1 as described in Section 6.1 commenced. In this running arrangement when the device is energised and connected in parallel with the existing bus coupler, it is unlikely to put a great strain on the device. This approach is typical when introducing new equipment to the network and by following this approach, some minor problems can be identified during this "soak" phase.

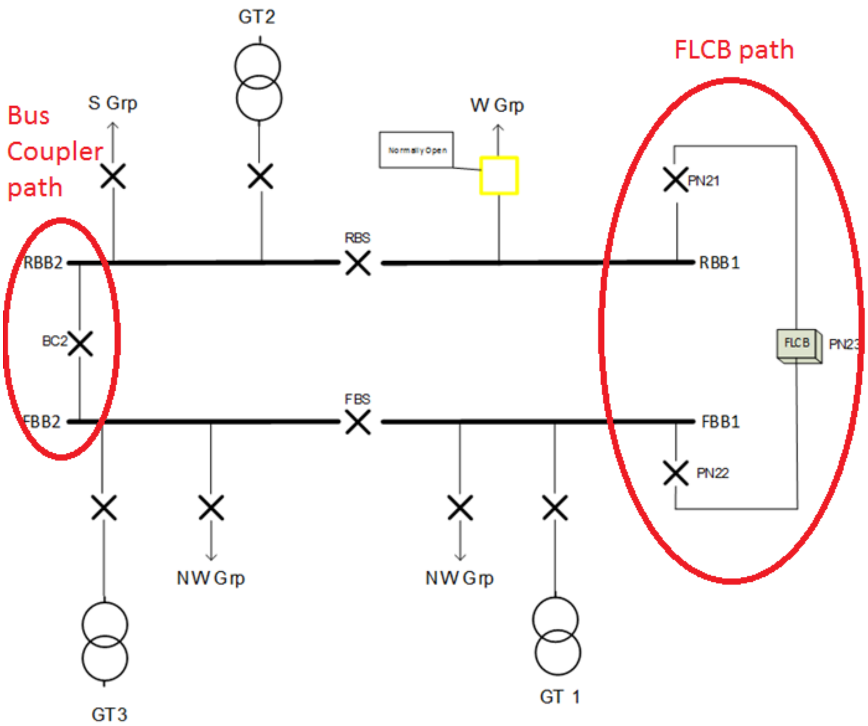

Figure 38 Running Arrangement 1 substation configuration highlighting the parallel paths between the existing bus coupler, BC2, and the FLCB

During this trial phase, the FLCB continued to report healthy with no issues including when confidence switching took place or when outages of transformers and circuit breakers were taken to complete wiring of the auto-close scheme and external fault recorders. As can be seen in Figure 39 below, a relatively small amount of current has been flowing through the FLCB with the exception of when outages took place. The most interesting to note is that from 24-26 August 2020 there was an outage of circuit breakers BC2 and RBS to complete wiring for the auto-close scheme. Here we can see the current flowing through the FLCB has increased significantly as there is no parallel path for the current to flow.

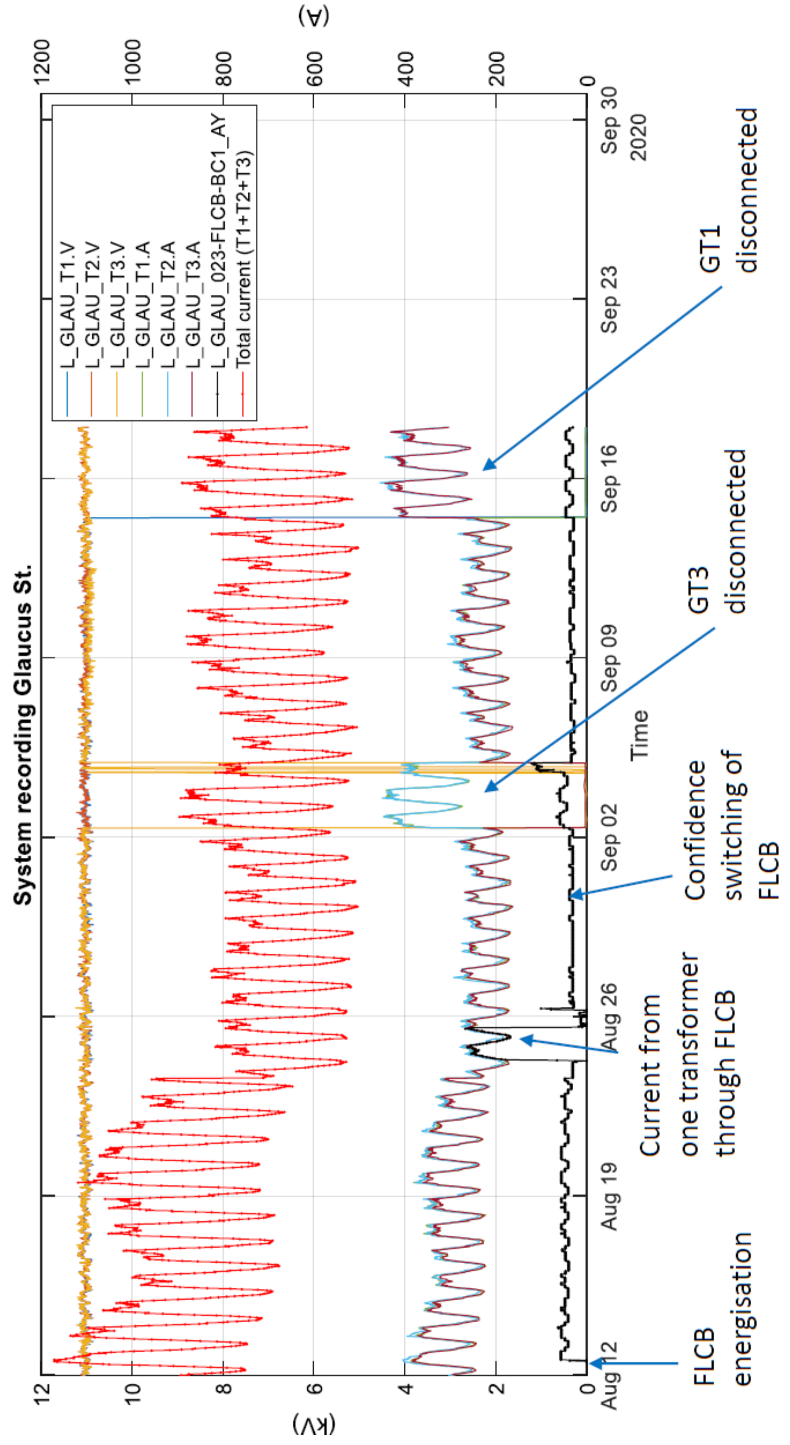

Figure 39 Operation to date in Running Arrangement 1 highlighting various outage events

Based on the healthy status of the FLCB being reported throughout Running Arrangement 1, the ‘soak’ test was completed successfully and no issues observed.

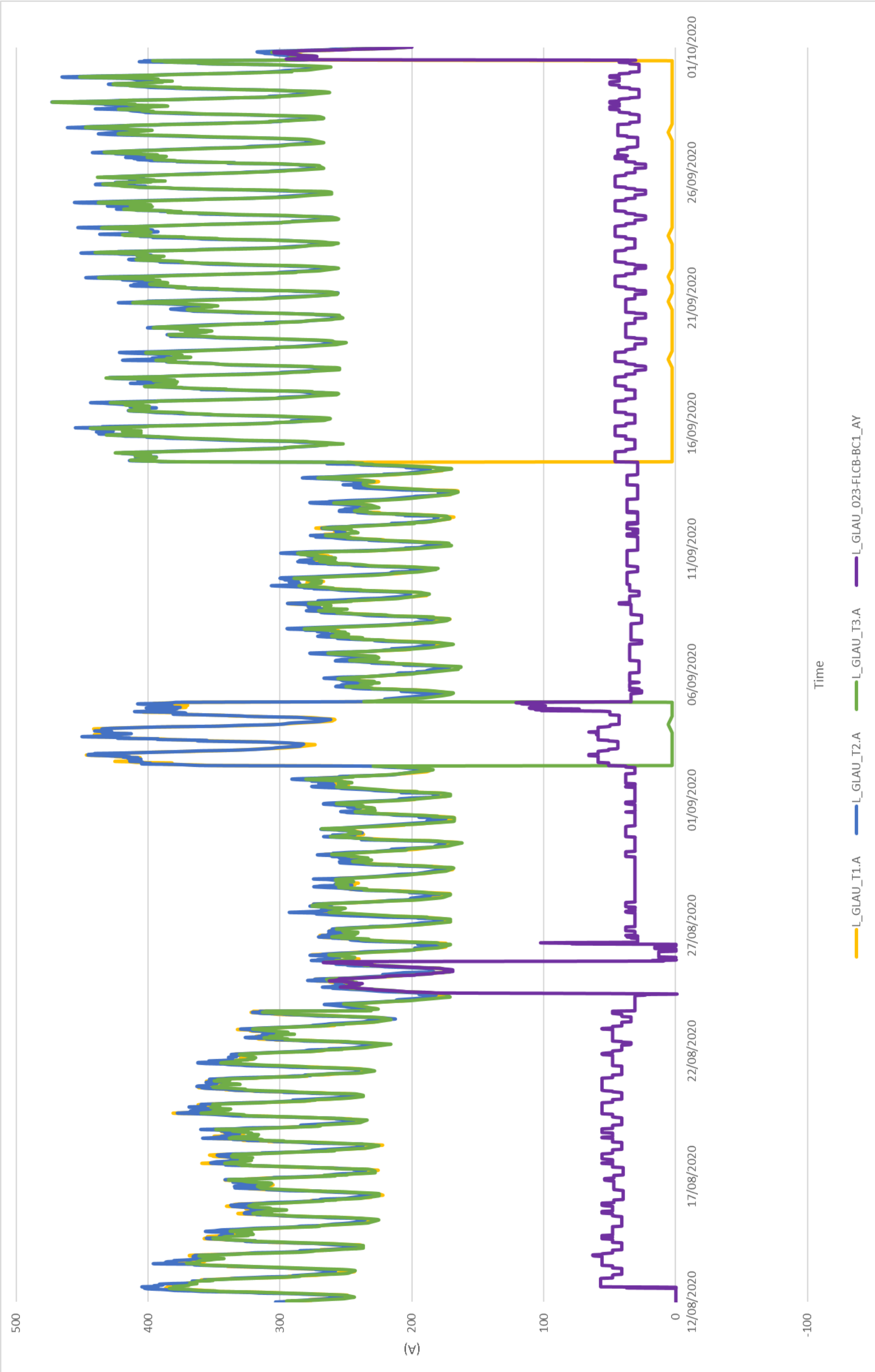

Figure 40 Full dataset of Running Arrangement 1 with current running through the FLCB coloured in purple

7.4 Running Arrangement 2 Demonstration

Following the successful 'soak' test of the FLCB, the project team worked with UK Power Networks' Outage Planning teams to transition to Running Arrangement 2. The switchover was executed on 30 September 2020. As described in Section 6.2, this arrangement simulates the scenario were the FLCB would be used as a circuit breaker for a specific transformer, also known as a transformer incomer, rather than a bus coupler. To change to this running arrangement the circuit breaker RBS was opened and GT1 was shifted to the rear busbar, RBB1. By switching over to this running arrangement, the current flowing through the FLCB increased when compared to Running Arrangement 1 as there is no parallel path. To illustrate this, indicative current paths can be found in Figure 41 and shows current flowing from GT1 through the FLCB to the load groups located on busbar FBB1-2.

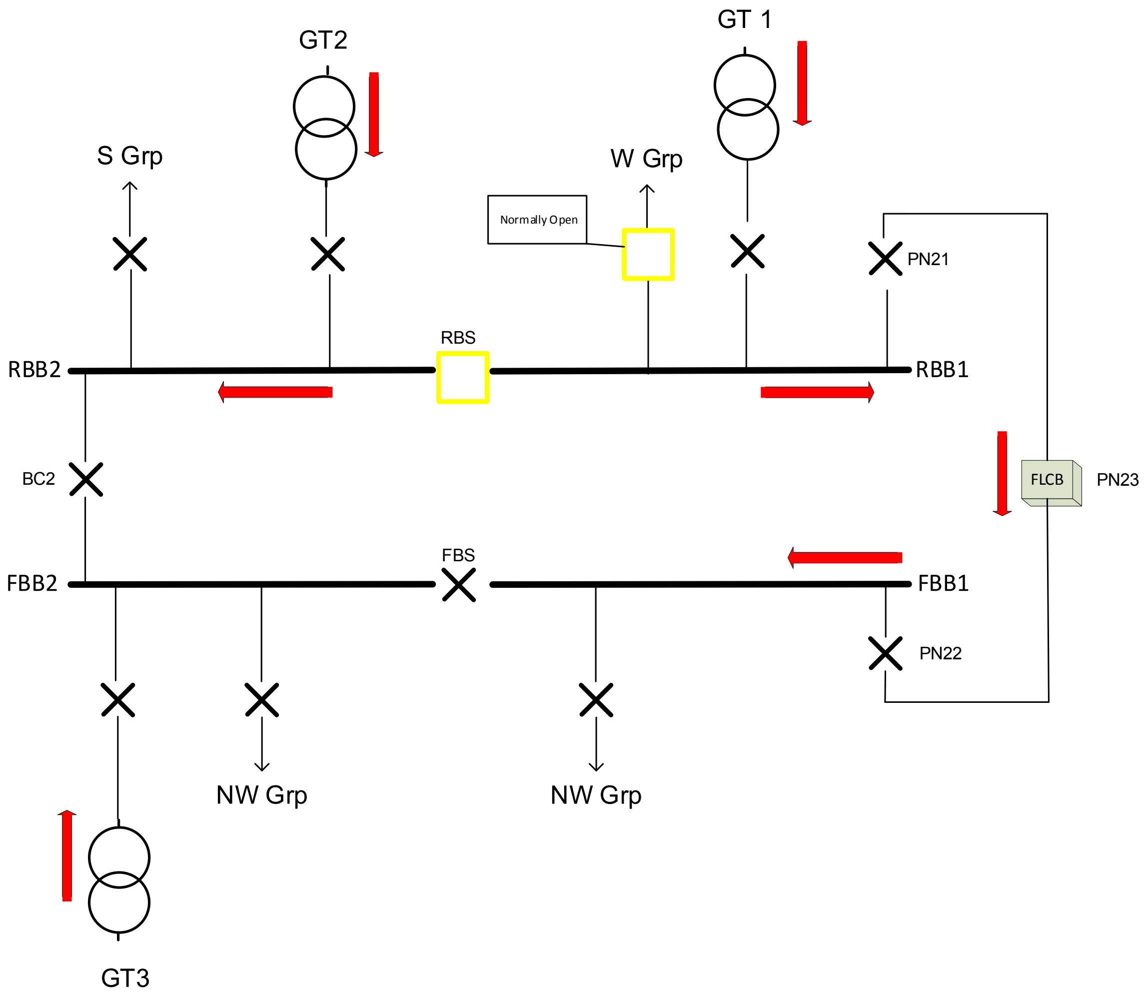

Figure 41 Running Arrangement 2 with indicative current flow direction shown with red arrows

The full operational data to date of the FLCB is shown below in Figure 42. It is also possible to see the step change in current flowing through the FLCB when the transition from Running Arrangement 1 to Running Arrangement 2 was completed at the end of September. The average current flowing through the FLCB in Running Arrangement 1 was 45 A whereas the average current to date in Running Arrangement 2 has increased to 327A.

On 2 October 2020 a step change can be seen in both the total current of the substation and the FLCB itself. The reason for this increase is the restoration of two feeders that taken out of service as part of the outages arranged for the completion of auto-close scheme works. This is a typical approach to planned outages, whereby demand is transferred to reduce the single circuit risk under N-1 outage conditions. Following completion of works and the outage restoration, the total load of the substation was restored.

Although the FLCB passed type testing, the strategy the project team and ABB agreed was to gradually increase the potential fault current the FLCB would be required to interrupt. This is achieved as the magnitude of fault current the FLCB may see under Running Arrangement 2 is lower than the potential fault current under Running Arrangement 3.

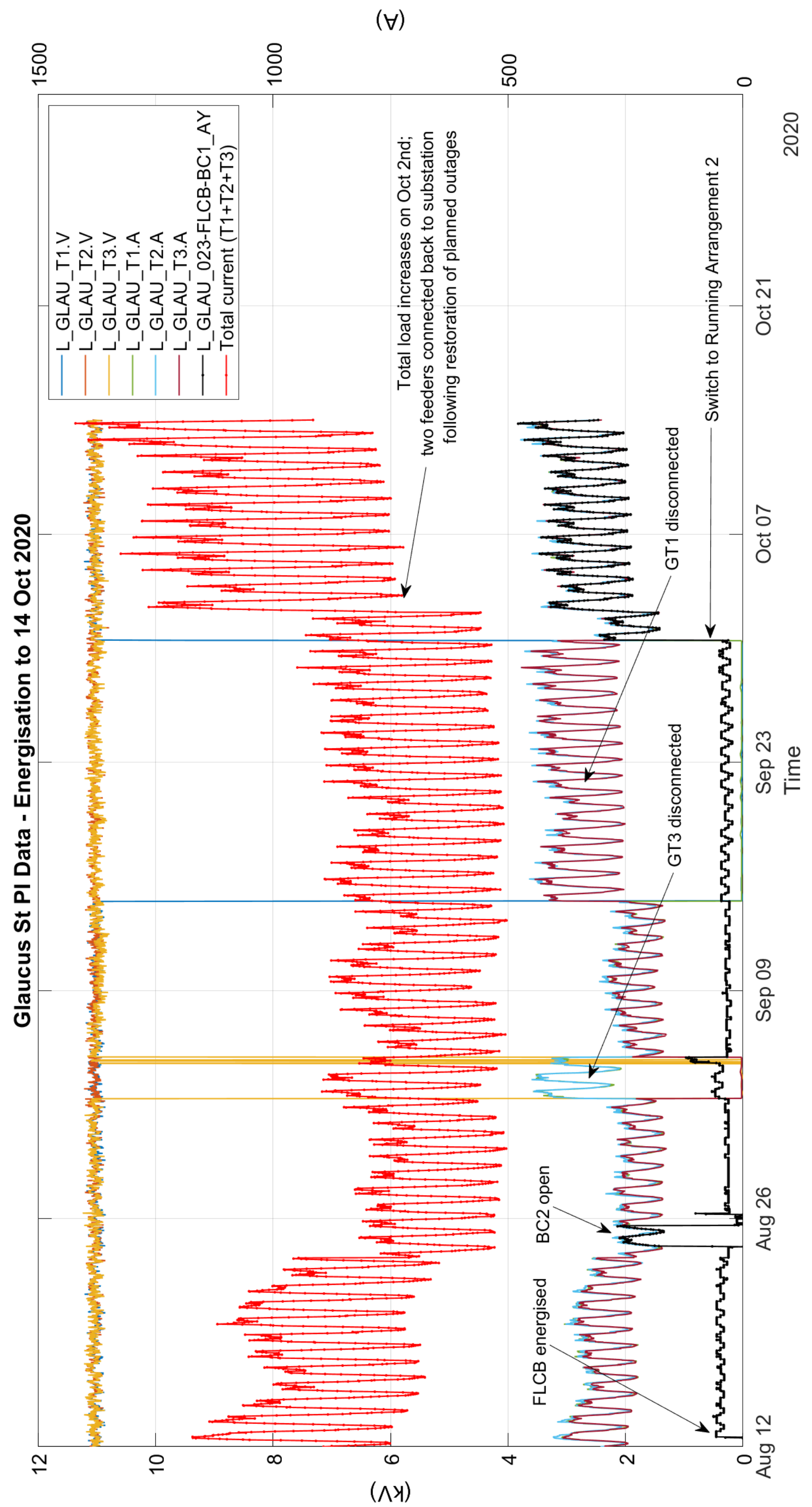

Figure 42 Operation to date of the FLCB through Running Arrangement 1 and Running Arrangement 2

8. Challenges and Lessons Learned

As part of any innovation project, there are often technical challenges to overcome but this offers unique lessons for the future development and application of the solution in the network. The below subsections outline some of the key challenges faced and learnings generated from the installation and commissioning of the FLCB for the Powerful-CB project.

8.1 Busbar Extension

The project has identified bus coupler arrangement as the most cost effective way to use the FLCB. However as the FLCB is a first of its kind, it was decided that adjacent circuit breakers be installed not only to isolate the FLCB but to also act as back-up protection in case the trial device fails to operate. As the solution is better suited for existing substations that have reached the fault level capacity, it is unlikely that spare bays will be available for additional equipment; just as there was no spare bay available to connect the FLCB at Glaucus St. The device could possibly be connected via cable end boxes; however, this would limit the capabilities to isolate the FLCB and hence required the existing busbar to be extended.

The busbar at Glaucus St is of considerable age and meant it was challenging to find materials for the expansion. During the site selection process, it was identified that another UK Power Networks' substation that had the exact same type of busbar was undergoing an upgrade programme. The project team took this opportunity to drive efficiency in delivery by aiming to reuse three bays from this substation for the project rather than installing a new separate busbar for the FLCB. There are also considerable lead times in retrofitting older circuit breakers and CTs into the older equipment. Finally due to the age of the equipment, there were limited resources who had the skills to work on and expand such assets, which required a lot of manual and handcrafted work.

The learning in this instance is that when connecting to older switchgear, the following should be considered:

- Availability of spare equipment for switchgear expansion;
- Availability of skilled resources for specific equipment type; and
- Potential to re-use equipment from similar sites undergoing refurbishments

When the FLCB is made commercially available in the future, the need to install adjacent circuit breakers may be removed and hence decrease the complexity in installing the device into existing substations.

8.2 Retrofit Circuit Breakers Portable Power Pack

As discussed in Section 4, a defect was discovered with a batch of retrofit VOR-M circuit breakers of the same type as the ones being used for the trial site. The defect caused capacitor failures and form part of the magnetic actuator mechanism. Failure of the capacitor would prevent the circuit breaker from opening/tripping.

The manufacturer confirmed that the capacitors in the retrofit circuit breakers procured for the project trial are not part of the defective batch however UK Power Networks still wanted to mitigate this risk of the retrofit circuit breakers failing to operate; either due to a failed capacitor or a loss of power supply to the circuit breakers. The proposal to overcome this issue was to design a portable power pack which contained capacitors to provide charge to the magnetic actuator coils of the circuit breaker. Subsequently Asset Management team issued an instruction to delay the energisation of all such retrofit circuit breakers until the portable power pack have been developed and deployed.

To operate the portable power pack, access is gained to the actuator connection by removing the front panel of the circuit breaker. Following this, the four-way connector for the magnetic actuator connection is unplugged and replaced by a connection from the portable power pack. Once this is done, the remote trip reel can be taken to another room and the circuit breaker safely opened or closed.

Figure 43 Portable power pack (left) plugged into retrofit VOR-M CB (right) during testing of the power pack

8.3 Requirement for UPS in FLCB

The original power supplies provided with the FLCB for the control system were suitable for use as the substation site has an 110V DC battery backup supply. However, it was identified during commissioning, in December 2019, that in case of a loss of supply to the FLCB control system, the FLCB would be connected in the network but unable to react to a fault. Although the probability of this occurring was observed to be low, the impact could be significant on the wider connected network. As such, the project team decided to mitigate this by complementing the existing power supplies with UPSs in order to make the FLCB as robust, reliable and safe as possible. With the UPS, the control system remains powered up and can perform a safe shut down and disconnect the FLCB from the network by opening the adjacent CBs as well as triggering the FLCB faulty/ out of service alarm. When the 110V DC power is restored, the FLCB and its control system need to be switched off and then switched back on again to return to normal operation.

8.4 HV Door Interlock

During commissioning in February 2020, it was identified that the magnetic lock which forms part of the HV compartment door interlock was malfunctioning. It was observed that even when the electromechanical locking mechanism would be locked in place, the door could still be opened with brute force. As this is a vital safety feature, the energisation of the FLCB could not have taken place until this issue was rectified. Following investigations by ABB, mechanical modifications to the interlock were required to resolve the issue.

The interlock of the FLCB panel works as described below in Figure 44 and Figure 45.

The door handle moves a rail that runs the full height of the panel door. There are circular studs on the panel housing side which engage in the circular cut-outs of the rail, hence securing the door in place. The door handle pushes the rail downwards so that the smaller circular cut-outs are moved behind the studs.

At the same time, the rectangular cut-out circled in red in Figure 44 below engages a lever on the opposite side of the panel housing. The rail in the door pushes it downwards when the door handle is operated.

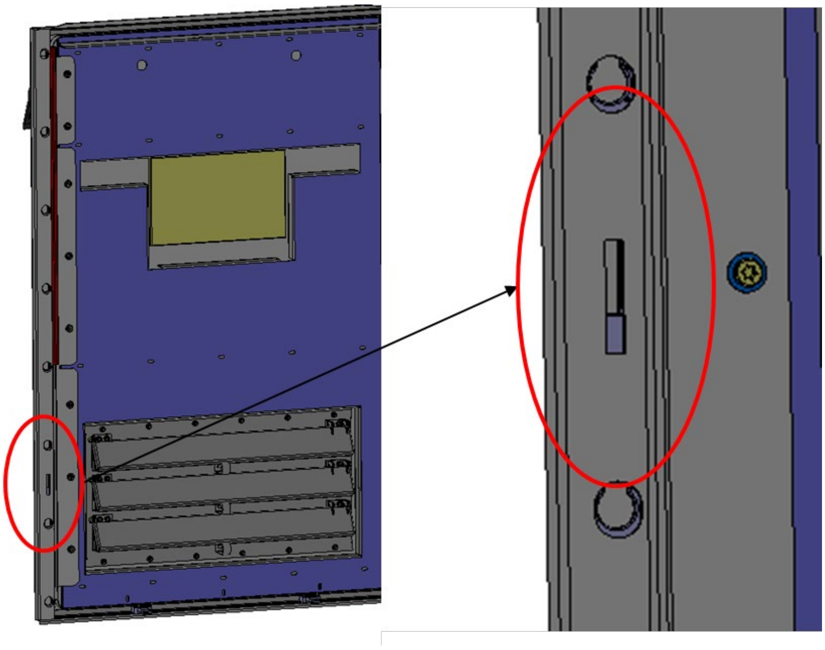

Figure 44 FLCB HV door detailing the rail running in the door which moves up and down as the door handle is engaged

On the right side of the panel a lever (circled in red in Figure 45), is pushed down when the door is closed. The electromechanical locking mechanism is located behind the cover (circled in green in Figure 45). When the lever is pushed down from the outside, a stud moves into the locking mechanism. This prevents the lever from being pushed upwards when the door is locked, so that the handle on the door and thus the rail cannot be operated.

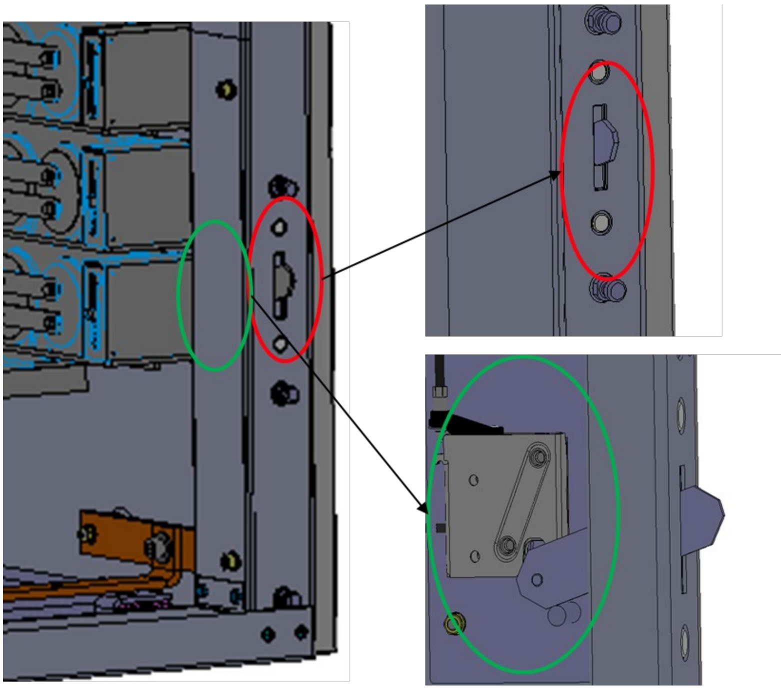

Figure 45 FLCB panel detailing electromechanical locking mechanism used to implement the interlock and prevent opening when conditions are unsafe

ABB's investigation concluded that the rail in the door had most probably been bent in such a way that the rail could be pushed past the lever of the electromechanical locking mechanism and hence allowed the door to still be opened, albeit with strong force exerted, even though the lever was locked into position and should have prevented opening. Replacing the rail in the HV panel door (shown in Figure 46), the door handle and some other mechanical parts resolved the issue and the interlock performed as required, i.e. the HV door could not be opened when unsafe to do so.

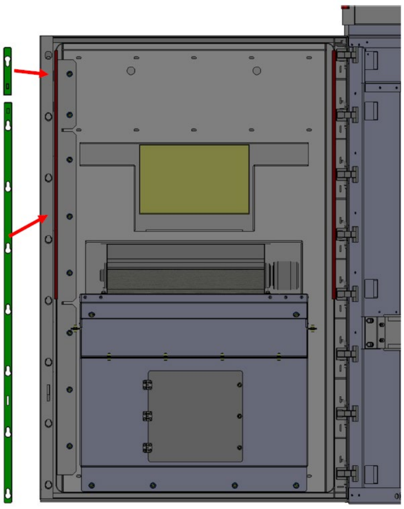

Figure 46 Rail replaced in FLCB HV panel door

8.5 Protection Challenges

During commissioning we identified a few instances where protection logic changes were required and unexpected issues arose. These include:

- The FLCB has an alarm labelled “FLCB Out of Service/Faulty”, which shall be raised when any internal problems associated with the FLCB and its control system are detected. On a conventional circuit breaker if a faulty alarm is raised, the typical response from control engineer is to switch the circuit breaker off, reset the alarm and raise a maintenance job. However for FLCB trial period, the alarm should not be reset until ABB maintenance teams have completed an investigation. Although UK Power Networks’ control engineers could respond to this alarm by operating the two adjacent circuit breakers manually to isolate the FLCB, the project team had added additional features to ensure safety of the network; a protection logic has been incorporated in the scheme, which will initiate a trip of the two adjacent circuit breakers to automatically isolate the FLCB as a precaution upon the receipt of this alarm;
- When testing the tripping of the FLCB, the SCADA system could not pick up the trip signal from the REF620 protection relay in the FLCB although the FLCB operated correctly. Further investigation identified that the signal was too quick for the SCADA system due to the speed at which the FLCB operates; we found the signal was present for approximately 100ms whereas SCADA needed it to be persistent for roughly 150ms. To overcome this problem, ABB used a spare relay contact and latched the signal so that it would remain present for the SCADA system to pick-up. In parallel with this we consulted GE, the manufacturer of the Remote Terminal Unit (RTU), who provided a patch fix for SCADA not displaying short-duration fleeting alarms. The fix allowed the mimic to display alarms greater than 30ms and this patch was applied to the RTU during the commissioning visit in February 2020. The valuable lesson learned here for wider rollout of the FLCB is to check the RTU is capable of displaying short-duration fleeting alarms; and
- On the display of the REF620 protection relay installed in the FLCB you can see the state of the FLCB along with the two adjacent circuit breakers by toggling the display. During the commissioning stage upon noticing this behaviour, a requirement was put on the display of the REF620 to always return to a default view showing the current status of the FLCB and the interconnecting circuit breakers. This was deemed critical as the FLCB has no other visual indication of its state.

8.6 Energisation Challenge

During energisation of the FLCB in August 2020, a seemingly unexpected set of behaviours was observed by UK Power Networks commissioners regarding the joint operation of the FLCB and the adjacent circuit breakers PN21 and PN22.

As part of the final energisation commissioning process, it was required to operate the FLCB independently from PN21 and PN22. In particular, the intended energisation sequence was to:

1. Close PN21;
2. Close the FLCB;
3. Perform a phase control at PN22; and
4. Finally close PN22 and hence energisation complete.

As mentioned in Section 4.3 the FLCB relay is not programmed to perform any independent operation of the FLCB and adjacent circuit breakers, so therefore the independent operations were enabled by disconnecting the wires carrying the operation commands from the FLCB to PN21 and PN22 (these wires are referred to as “the links” in the following passage). The wires carrying the status signals from the circuit breakers to the FLCB were kept connected.

The following behaviour was then observed:

- When the FLCB, PN21 and PN22 are all closed, the FLCB refuses to open when the links are disconnected; and
- When the FLCB is open and either PN21 or PN22 is closed, the FLCB refuses to close.

The behaviour above can be explained by considering how the FLCB relay is programmed to operate the FLCB and PN21/PN22 jointly to achieve the agreed behaviour with all wiring connected in the following situations:

- At tripping of the FLCB due to overcurrent detection, the FLCB will open firstly to provide the desired fast current limitation, and subsequently PN21 and PN22 will open to disconnect the FLCB from the network;
- At opening of the FLCB (either by external command or via the relay button interface), the committed sequence is to first open PN21 and PN22, and subsequently open the FLCB when both PN21 and PN22 are confirmed open. In this way, the current in the circuit will be interrupted by the circuit breakers and not by the FLCB. With this logic in place, when the links are disconnected, PN21 and PN22 will then not operate and hence no change to the required open state will be observed. As the two adjacent circuit breakers will not be open, the FLCB will not operate as was experienced during the energisation process; and
- At closing of the FLCB, the committed sequence is to first close the FLCB and subsequently close the circuit breakers. In this way, the circuit breakers will close the circuit allowing current to flow, and not the FLCB. This requires that both PN21 and PN22 are initially in the open state, so if any either of the adjacent circuit breakers is closed at the time of the close command, the close operation of the FLCB will be blocked. This explains why the FLCB refuses to close if either PN21 or PN22 have been manually closed before the close command is sent to the FLCB.

The energisation commissioning steps required were accomplished by deploying a work-around: First, only the FLCB was closed while both PN21 and PN22 were open with the links disconnected. Subsequently, PN21 was closed manually to end up in the desired state with PN21 and FLCB closed and PN22 open. Subsequently, the phase control was performed at PN22 before finally closing PN22 and hence the FLCB energised.

In Engineering Operation Standard, EOS 03-0125, which the project team developed, the following text is included, “In order to avoid problems in the sequence of operation, engineers (control or field) shall not directly operate the adjacent circuit breakers. They shall only operate the FLCB and it will send the appropriate command to the adjacent circuit breakers. Only if the FLCB device is faulty, shall the adjacent circuit breakers be operated directly.”

In summary, the switching steps required for energisation were not explicitly considered while defining the committed behaviour of the FLCB relay, which prompted for an ad-hoc solution at site. A lesson learned from this issue is therefore to also consider rare switching scenarios occurring e.g. at commissioning in the requirements, so that the manufacturer can provide this functionality in a more well-controlled manner.

Another solution for this issue could be a change in the closing sequence so that the adjacent circuit breakers close first and then the FLCB. Closing the FLCB in this manner would allow the full utilisation of the semiconductors within the FLCB. If for example, closing in this way onto a fault, the FLCB will interrupt the current in 10 microseconds after the fault current level is detected and hence minimises the stress on the system. It was decided early in the project not to use this sequence for the trial to reduce the burden on the FLCB until it is approved for BAU. However this ability was proven during the type testing for future needs and possibilities.

9. Summary and Next Steps

This report forms the key evidence for the fourth Powerful-CB SDRC, SDRC 9.2.1: Install and Commission Solution at an 11kV Substation. The project has successfully delivered on the requirements of SDRC 9.2.1, and this report provides an overview of the installation, commissioning and energisation of the FLCB ready for network demonstration as well as information on operation to date of the FLCB.

The report captures the following activities undertaken by the Powerful-CB project to commence the network demonstration:

- Site preparation of the room to accommodate the FLCB;
- Busbar extension works and HV cabling required to connect the FLCB to the network;
- Protection and SCADA upgrades;
- Installation of the FLCB;
- Commissioning of both the FLCB, protection, SCADA and other equipment installed as part of this project;
- Energisation of the FLCB; and
- Operation to date

In August 2020 the FLCB was energised and since that time the project has successful demonstrated Running Arrangement 1, including confidence switching, with the FLCB reporting a full healthy status throughout. At the time of publication has transitioned to demonstrating Running Arrangement 2. The project team will continue to remotely monitor the FLCB and awaits any network faults to further analyse the FLCB's performance.

The project builds on learnings from other projects including Electricity North West's (ENWL's) Respond project and Western Power Distribution's (WPD's) FlexDGrid project. This report ensures future innovation projects can build on the learning from Powerful-CB in developing a FLCB.

For further questions on the evidence provided in this report, commissioning or more general questions about the project, please contact Powerful-CB team at: Powerful-CB@ukpowernetworks.co.uk, the UK Power Networks' Innovation team at: innovationteam@ukpowernetworks.co.uk or visit our project website.

9.1 Next Steps

Following the successful development, installation, commissioning and energisation of the FLCB, the project is currently in the network trial period. The project team will continue to monitoring the performance of the FLCB and carryout any necessary analysis following a network fault and/or trip of the FLCB. The key outputs over the next phase of the project include:

- Continued trial of a number of different running arrangements;
- Delivery of SDRC 9.2.3 – Demonstration of solution at an 11kV substation (Method 1); and
- Updating the safety case that formed part of SDRC 9.1.3 and 9.1.4.

Appendix A ABB Commissioning Reports

ABB visited the trial site thrice as part of the installation and commissioning process. The third visit was purely to repair the HV door interlock of the FLCB, and no further commissioning tests completed other than testing if the does remain closed after a relatively high manual force is applied.

For the first two visits that included testing and commissioning activities, ABB have supplied commissioning reports that are presented below.

Site works December 2019 – Protection device QR6 On-site testing checklist

ABB	ABB AG	DEABB	ELDS
	Calor Emag Medium Voltage	Page 1 of 2	
	Integrated Management System	Q	
	On-Site Testing Checklist	PP	
		1VBA500169P0102-02	

Equipment under Test

Type QR6-B
Serial No. 1VB9002016R0101-00_A_1829_0002

Test

Test Procedure QR6-B On-Site Testing
Report Number 5DE8DDBA

Customer Specific Values

Order No 204005993

Instantaneous current 3.20 A
Inhibit current 4.80 A
Frequency 50 Hz

Further Applicable Documents

1VBA500155P0101

Result

Test Conclusion ok.
Date of Certificate 11/12/2019
Approved by [signature]
Sign

Index	Date	Dept	Created Changed	Sign.	Date	Dept	Checked	Sign.	Date	Dept	Approved	Sign.
02	2019-07-26	GST	Dziwuk		2019-07-26	GST	Ott		2019-07-26	GSQ	Grüneberg	

ABB	ABB AG	DEABB	ELDS
	Calor Emag Medium Voltage	Page 2 of 2	
	Integrated Management System	Q	
	On-Site Testing Checklist	PP	
		1VBA500169P0102-02	

Mesuring Procedure	QR6-B On-Site Testing
EUT Type	1VB9002199R0101-00
No. of Measuring Procedures	24

No.		Mesuring Procedure	Min	Value	Max	Result	Operator
1	59662092	Visual Inspection	1	✓	1		
2	59D4DC6D	Voltage Uaux	2	✓	2		
3	93DA8FD1	Function of Uaux1 LED	1	✓	1		
4	F9E10DBE	Function of Uaux2 LED	1	✓	1		
5	58681E67	Function of IRF LED	1	N.A.	1		
6	EC5DE21C	Function of Trip Circuit Fault L1 LED	1	N.A.	1		
7	E0A5E6ED	Function of Trip Circuit Fault L2 LED	1	N.A.	1		
8	64E285AA	Function of Trip Circuit Fault L3 LED	1	N.A.	1		
9	D8683AE3	Function of Externally Blocked	12.00 V	✓ V	20.40 V		
10	2E734A74	Function of First LEDs	1	L1, L2, L3	1		
11	D4CAF71F	Function of Reset	1	✓	1		
12	19FBAE98	Connect QTD600 L1	1	✓	1		
13	5E1A40B9	L1 (+) INS Value	3.10 A	3,20 A	3.30 A		
14	72039686	L1 (-) INS Value	3.10 A	3,20 A	3.30 A		
15	C75DD98F	Connect QTD600 L2	1	✓	1		
16	35B5B824	L2 (+) INS Value	3.10 A	3,20 A	3.30 A		
17	0961B655	L2 (-) INS Value	3.10 A	3,20 A	3.30 A		
18	1C3D6AF2	Connect QTD600 L3	1	✓	1		
19	A761388B	L3 (+) INS Value	3.10 A	3,21 A	3.30 A		
20	70A3D270	L3 (-) INS Value LZK	3.10 A	3,20 A	3.30 A		
21	67DC9DB1	Note QTD600 Serial (last 8 digits)	1	– (FLC3)	000000		
22	9E367852	Function Impulstransformer L1	1	N.A.	1		
23	BA2CD26B	Function Impulstransformer L2	1	N.A.	1		
24	C2AD1ED0	Function Impulstransformer L3	1	N.A.	1		

___ End of Measuring Procedures ____

UK Power Networks Delivering your electricity

Site works December 2019 – Testing and commissioning checklist

ABB	ABB AG Calor Emag Medium Voltage Products	DEABB/EPDS	
	Integrated Management System	**Page 1 of 2**	
	Testing and Commissioning - Checklist **Type: FC-Protector, type: ZS-P and QR6**	Subject: Q	
		Type	no.:
		AA	1VBA500185P0102

Order no. : 24445087 Date : 12/12/2019
Customer : ABB SE for UKPN ~~[illegible]~~
Place of Installation : Substation Glasshouse St, London Inspector : Greke

Item.	Steps of Testing	N.A.	Checked yes	Checked no
1	~~**FC-Protector**~~ FLCB **primary part / cubicle**			
1.1	Integration of ~~FC-Protector~~ FLCB components / build-in direction of CT´s (P1-P2)		✓	
1.2	Main grounding bar between FC-Protector components and cubicle / main point of grounding Station grounding bar welded connections!		✓	
1.3	Ext. wires and internal wires/tripping lines laid separately		✓	
2	**FC-Protector insert-holder** Not applicable!			
2.1	Insertability of the FC-Protector inserts	✓		
2.2	Correctness of FC-Protector inserts	✓		
2.3	Pulse transformer plug connectors are completely engaged	✓		
2.4	Information- and type-labels	✓		
2.5	FC-Protector mounted in cubicle / on truck of customers design	✓		
3	**Current transformer**			
3.1	Mounting place		✓	
3.2	Build-in direction (P1-P2)		✓	
3.3	Allocation of CT cores		✓	
3.4	Transmission ratio (acc. type-labels)		✓	
3.5	Performance data (acc. type-labels)		✓	
3.6	Spring contact	✓		
3.7	Wiring		✓	
3.8	Grounding and shielding		✓	
4	**Electrical testing**			
4.1	Power supply voltages		✓	
4.2	Heater (tripping unit)		✓	
4.3	Compartment lighting		✓	
4.4	Fan	✓		
4.5	Contacts of panel door		✓	
4.6	Interlocking panel door		✓	
5	**FC-Protector control unit**			
5.1	Testing according to the testing and commissioning checklist for FC-Protector tripping unit QR6		✓	
5.2	Signals and Alarms (potential-free contacts)		✓	

Create /Modification:	*Dept.:*	*Name:*	*Sign.*	*Checked:*	*Dept.:*	*Name:*	*Sign.*	*Release:*	*Dept.:*	*Name:*	*Sign.*
08.08.18 / Index 00	GST			08.08.18	GST			08.08.18	GS		

File: FC-P type ZS-P Testing & Commissioning.doc

ABB	ABB AG Calor Emag Medium Voltage Products	DEABB/EPDS	
	Integrated Management System	Page 2 of 2	
	Testing and Commissioning - Checklist **Type: FC-Protector, type: ZS-P and QR6**	Subject: Q	
		Type	no.:
		AA	1VBA500185P0102

Item.	Steps of Testing	N.A.	Checked yes	Checked no
5.3	Circuit breaker interlocking/release		✓	
5.4	Inspection plate fitted		✓	
6	**Final works**		✓	
6.1	CT terminals in service position		✓	
6.2	Tools, measuring lines, test inserts, etc. removed		✓	
6.3	Cleanness of the units		✓	
7	**Miscellaneous**			
Remarks and Details				
5.2	Protection Blocked" Alarm to be re-programmed in "REF Relay. This been done!		✓	

The correctness of item 6.1 and 6.2 has been validated by the customer.

Place: London Date: 12.12.2019

Signature: (customer) [signature] Signature (ABB) [signature]

Create /Modification:	Dept.:	Name:	Sign.	Checked:	Dept.:	Name:	Sign.	Release:	Dept.:	Name:	Sign.
08.08.18 / Index 00	GST			08.08.18	GST			08.08.18	GS		

Site works December 2019 – Commissioning Report

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OUR REFERENCE	ELDS_GST-Gr/VG, MOM_244445087 IBN-2019-12-12_Report-In00_2019-12-16-Gr[en].docx
PAGE	1/4
DATE	January 13, 2020

Commissioning report

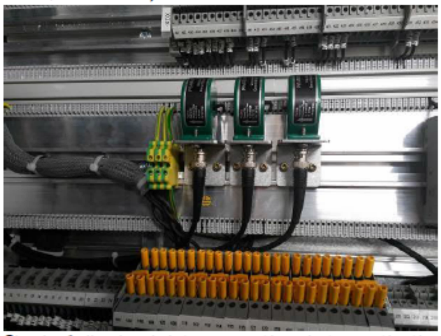
DEABB order no. 244445087
FLCB for UKPN via ABB R&D, Sweden

The FLCB mentioned above is installed at UK Power Networks, substation 42 Glaucus Street.

From 09/12/2019 till 12/12/2019, ABB Germany (Volker Grafe) together with ABB Sweden (Thomas R. Eriksson, Jesper Magnusson) and ABB UK (Hardeep Khangura) visited the site for checking and commissioning of the device.

09/12/2019

- Arrival at site
- Optical check of the installation
- Safety & site induction by UKPN (Dan Johnson)
- Installation of the requested sealings for the holes of the crane hooks (6 pieces at the rear, 2 at the front done; 4 pieces at the front still open -> done on 10/12/2019)
- Installation of the current sensors for the FLCB supervision unit according to schematic drawings (1VB2497622 Rev. 3, 31/07/2019) -> done!



- Check of all galvanic interconnections between the three panels -> ok!

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ABB

Page 2/4, January 13, 2020

10/12/2019

- HV test and resistance check of the primary part of the panels by ABB UK -> ok; remarks:
  - due to the VTs, meggering was done with disconnected VTs
  - power frequency withstand voltage test was firstly done with 25kV/1min (VTs disconnected)
  - After re-connection of the VTs, power frequency withstand voltage test was repeated with 6.35kV/1min
- Power supply (24VDC) was connected to the FLCB supervision unit and the modem (fed from =A01, -PS1; schematic drawings to be revised)
- External 110VDC supply to "Control Circuits 2" (terminals -XDI1:21-24, supply voltage for charging of the Thomson drive capacitors) was missing. It was decided that this supply input should be interconnected to that input, which feeds "Control Circuits 1" (terminals -XDI1:1-4, supply voltage for the FLCB controller, REF620 and interlocks) and "Main Supply UAUX1" (main supply for QR6 tripping electronic). This interconnection was done in panel =A01 -> schematic drawings to be revised.
- Optical alarms and commands between the FLCB controllers, the optical/electrical converter boxes and REF620 were checked -> schematic drawings to be revised.
- Time relay -K1 (delayed release of the HV doors) checked and finally adjusted (function AV – delay on energisation, 5:00 min) -> adjustment: 4:55 min.

11/12/2019

- External 230VAC supply to "Heating/Lighting" (terminals -XDI1:17-20) was missing. It was decided that this supply input should be interconnected to that input, which feeds "Auxiliary Supply UAUX2" (terminals -XDI1:13-16, auxiliary supply for QR6 tripping electronic). This interconnection was done in panel =A02 -> schematic drawings to be revised.
- Check of the QR6 (please cf. "On-Site Testing Checklist", document no. 1VBA5000169P0102, Rev. 02) -> ok.
- Door interlocks checked -> ok, remarks:
  - At the time of the visit, the door interlock was realized by an auxiliary switch "CB open", as a "Interconnector grounded" indication is not available. It was discussed that the contact "CB isolated" could be used for an increase of safety.
  - It should be noted that in case of a loss of supply, the door locks store their last condition! In case opening of the doors was released prior to disconnection of the "Control Circuits 1"-supply, the locks remain open until supply is restored.
  - As UKPN used the schematic drawings from a former revision, interconnections to CB1 were revised.
- Signals "CB1 ready" / "CB2 ready" to REF620 are missing. In order to enable further testing, links were inserted between terminals -XDX:340 & -XDX:372 (CB1) and -XDX:339 & -XDX:375 (CB2). These signals must be provided by UKPN in order to give a proper release for REF620 to operate CB1 and CB2.
- Intertrip of CB1 and CB2 (in case of trip from QR6) checked, ok.
- Check of alarms to UKPN's Scada system:
  - UKPN expected at terminals -XDC:544/557 a signal "Protection blocked"; this signal should appear in case at least one FLCB controller indicates a "blocked for operation" status. This was changed in the software of the REF620.
  - UKPN expected to get analog signals from the REF620 via RS485-protocol. This was not wired from ABB; UKPN made these connections. All requested signals (13 signals as per signal list, version A) were implemented in the REF620 and confirmed by UKPN.
  - Some of the alarms show reverse logic at the Scada system.
  - Alarm "Protection tripped" (coming directly from QR6, terminals -XDC:513/508) was not recognized by the Scada system. Reason is that this signal is lasting only for 100ms, which is too short for the current configuration of the Scada system.

Page 3/4, January 13, 2020

12/12/2019

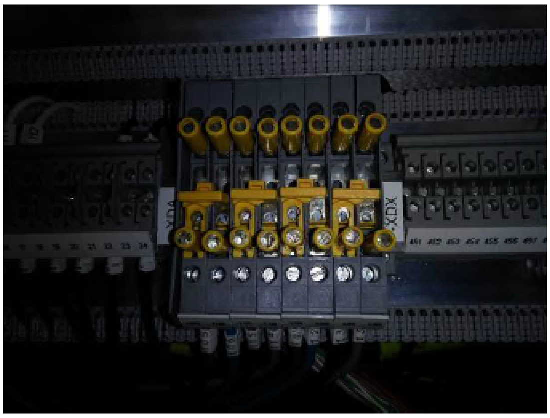
- Training and discussion with UKPN:
  - Explanation of the device and its handling
  - Actions for DEABB (please refer also to Jack McKellar's e-mail dated 12/12/2019):
    - Modification of the REF620 software to trip CB1 and CB2, if "Protection blocked" signal is received.
    - Confirm which signal triggers fault recording in the REF620.
    - Check if "Protection tripped" alarm can be latched to a REF output to create an impulse long enough to be picked-up by Scada.
    - Check if SLD (showing open/closed condition of FLCB and CBs) can be displayed permanently as default page; otherwise, another solution for indicating the FLCB status must be engineered.
    - All alarms should be re-checked together with UKPN.
    - Label for doors to be re-designed in suitable size, using UKPN's wording.

All MCBs (except that for the VTs) were switched off when leaving the site.
All CT terminals were in service position:
Panel =A01:

Panel =A02:

Page 4/4, January 13, 2020

Panel =A03:



The "Testing and Commissioning Checklist" (for the FLCB-panel, document no. 1VBA500185P0102, Rev. 00) as well as the "On-Site Testing Checklist" (for the QR6, document no. 1VBA5000169P0102, Rev. 02) are attached.

DEABB/Grafe

Site works February 2020 – Commissioning Report

ABB	Technical Note Corporate Research		2020/SECRC/E/TN/271
Issued by department SECRC/E	Create date 10/22/2020		Page 1/7
Doc. Title	Commissioning Report		
Project name/ID	Powerful CB	Status of document	Published
Creator name	Johan Nohlert Jesper Magnusson		
Attested by Reviewer			
Approved by	Thomas Eriksson	Approval Date	10/22/2020

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Commissioning Report

Final commissioning of FLCB at UKPN Substation Glaucus Street, London, February 11-13 2020

Powerful CB Project

TABLE OF CONTENTS

ABB	Corporate Research	2020/SECRC/E/TN/271
Doc. title Commissioning Report		Page 3/7

1 SITE ACTIVITIES

From 2020-02-11 to 2020-02-13, ABB Sweden (Jesper Magnusson and Johan Nohlert) together with ABB UK (Johnny Valencia) visited Glaucus Street substation for completing the final commissioning steps for the FLCB. People present from UKPN were Dan Johnson, Jack Lee, Alan Edwards, Jack McKellar and John Moutafidis.

1.1 2020-02-11

- Arrival at site.
- Site and safety introduction by site manager Dan Johnson.
- Drive capacitor charging cable connectors were fixed in place by glue as an extra safety measure to ensure that spontaneous disconnection due to creeping cannot occur.
- Attachment of updated labels on the outside of the panel doors with instructions for accessing the HV compartment.
- Re-wiring according to revised FLCB schematic (1VB2497600 INDEX 05 244445087):
  - For incorporating 50V CB READY signals from CB1 and CB2 to REF620.
  - For latching of the TRIPPED signal in REF620.
- Installation of UPS devices (QUINT-UPS/24DC/24DC/10/3.4AH) and switches (SFS2) adjacent to PS1 in L1, L2 and L3 including wiring and wire labelling. The ferrule labels used for different modules and their supply connection as implemented on site is shown in Figures 1-3 and stated below:
  1. Control System NI-9149 in L1, L2 and L3 – UPS backed.
  2. Position sensor interface in L1, L2 and L3 – not UPS backed, connected directly to PS1. Schematic needs revision.
  3. Sibel isolation transformer in L1, L2 and L3 – Not UPS backed, connected directly to PS1.
  4. Supervision Unit and cellular router in L1 – UPS backed. Schematic needs revision.
  5. Optical/Electrical converter boxes 1 and 2 in L2 – Not UPS backed, connected directly to PS1.

ABB	Corporate Research	2020/SECRC/E/TN/271
Doc. title Commissioning Report		Page 4/7

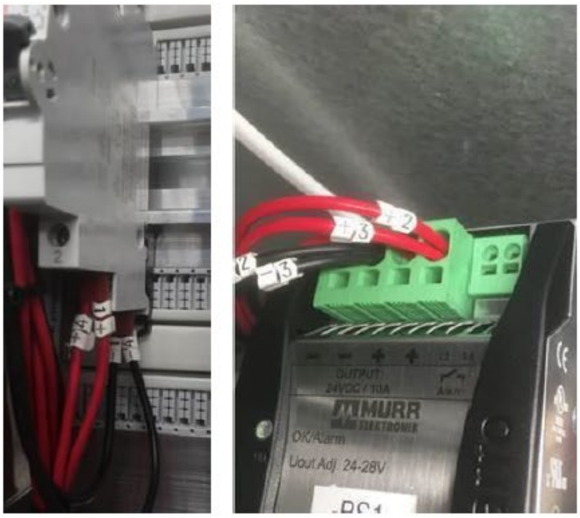

Figure 1. In L1, modules 1 and 4 are connected to SFS2 and hence UPS-backed. Modules 2 and 3 are connected to PS1.

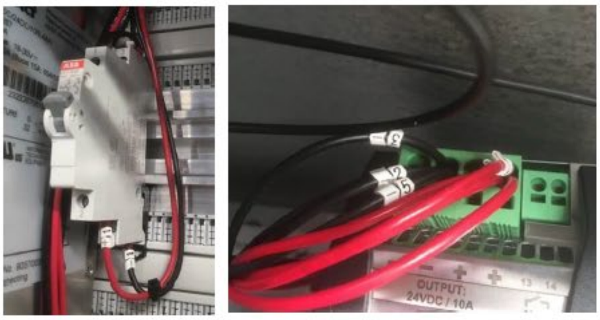

Figure 2. In L2, module 1 is UPS-backed and modules 2, 3 and 5 are connected to PS1.

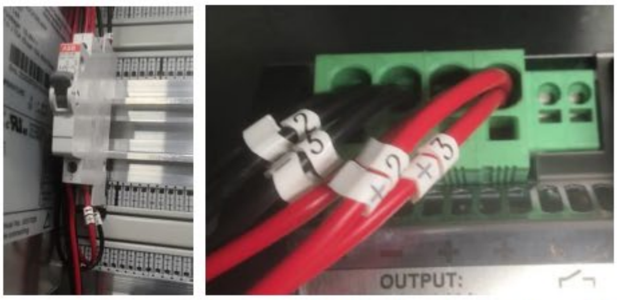

Figure 3. In L3, Module 1 UPS-backed and modules 2 and 3 connected to PS1.

1.2 2020-02-12

- Uploading of revised control logic into REF620 with the following program changes:
  - Prolonging the FLCB tripped signal by means of latching in REF620 to ensure correct registration in SCADA.
  - Automatic opening of interconnectors (CB1 and CB2) at tripping of FLCB and at "protection out of service" alarm.
  - Single-line diagram showing the state of the FLCB and interconnectors always shown by default on display.
  - Joint coordinated opening and closing of FLCB and interconnectors upon open and close commands.
    - At opening (not trip) the interconnectors open firstly and the FLCB opens secondly when CB1 and CB2 are confirmed open.
    - At closing, the FLCB closes firstly (if CB1 and CB2 are both open), and the interconnectors close secondly.
- Testing of alarms registration in SCADA. Results confirmed by UKPN (Jack Lee and Alan Edwards).
  - Alarm "HV door open" in L1, L2 and L3: Alarm generated and cleared.
  - Alarm "FLCB supply fault" (redundant U-AUX alarm): Initially, this alarm was nominally true due to SCADA being connected to -XDC 553 (normally closed). By re-wiring to -XDC 554 (normally open) the alarm is generated upon switching off FCM5 (AC supply) and cleared when FCM5 is switched back on.
  - Switching (CLOSE and OPEN) of FLCB tested by remote command and locally from REF620. The joint coordinated opening and closing of FLCB and interconnectors was verified.
  - Alarm "Spring not charged/FLCB not ready" verified after OPEN operation (due to drive capacitors recharging). The alarm is cleared after approx. 2 minutes as the capacitors become re-charged.
  - Alarm "Protection operated" triggered by Johnny Valencia using Omikron instrument to inject the CT's. The CT ratio of 1250 leads to that a secondary current of $3.2A_{peak}$ ($2.26\ A_{RMS}$) should correspond to a primary trip current level of 4 kA. A current ramp was therefore applied from 0.1A to 2.5A (RMS), leading to confirmed tripping of the FLCB and generation of the SCADA alarm.
  - Alarm "Trip system faulty/QR6 Internal Relay Fault (IRF)/Protection faulty" triggered by short-circuiting QR6 output terminals 11 and 12. Alarm confirmed and cleared.
  - Alarm "FLCB Protection out of service/Faulty" triggered by opening FCM2.2 to disconnect capacitor charging. The alarm was confirmed and the interconnectors open automatically. The FLCB control system goes into a blocked mode and needs to be manually restarted.
- Verification of analogue readings in SCADA by CT current injection using Omikron instrument. Result confirmed by UKPN (Jack Lee and Alan Edwards).
- An issue with the HV door interlock mechanisms was revealed by UKPN (Jack Lee) being able to open the door with moderate force. Energisation of the FLCB is not allowed until this issue has been resolved.

1.3 2020-02-13

- Demonstration of FLCB to UKPN staff.

- Verification of Supervision Unit log file registration and file transfer to ABB server.

2 PACKING OF FLCB SPARE EQUIPMENT IN DESIGNATED LOCKED STORAGE AT SITE FOR POSSIBLE USE AT FUTURE ABB SERVICE VISITS.

ABB	Corporate Research	2020/SECRC/E/TN/271
Doc. title: Commissioning Report		Page: 7/7

CHANGE HISTORY

Rev.	Chapter	Description	Date / Dep. / Name
01	All	Initial document	20-10-22/ RDE2 / Johan Nohlert

Appendix B UK Power Networks Commissioning Reports

As part of the standard testing and commissioning procedures a variety of tests were done to the adjacent circuit breakers and the SCADA system. A non-exhaustive summarised list is shown below.

Panel 21&22 – Interconnector 1&2 tests

The tests below were repeated for each of the two panels.

1. *Argus protection relay tests*

   The Argus protection relay is providing back-up protection capabilities. These are Overcurrent and Earth Fault protection and blocking elements. Additionally it has a CB Fail protection element. The tests check if:
   - the correct settings are applied,
   - the wiring was done correctly for the inputs and outputs,
   - the LED's are functioning correctly and
   - the functionality is as expected

2. *Solkor N unit protection relay tests*

   The Solkor N relay is providing the main protection for the cables connection the FLCB and the adjacent circuit breakers. The tests check if:
   - the correct settings are applied,
   - the wiring was done correctly for the inputs and outputs,
   - the LED's are functioning correctly,
   - the communications path between the two relays forming the unit protection scheme is intact and robust and,
   - the functionality is as expected

3. *CT tests for both overcurrent and differential relays for all three phases*

   These are extended test of the CTs to verify their operation and accuracy of results for different current ranges and load burden.

4. *Insulation resistance tests*

   As per the title these tests measure the insulation between the electronic equipment in the panels (relays) and the earth.

5. *Pressure tests*

   The adjacent circuit breakers are vacuum circuit breakers and therefore some tests are required to verify the vacuum pressure is intact before commissioning.

6. *Tripping and auxiliary relays tests*

   An interposing relay was used to overcome a limitation of the adjacent circuit breakers outputs. The interposing relay functionality was tested and verified.

7. Primary injection tests

These are tests where current is injected in the primary side of the equipment to verify the ratio and performance of all CTs across all phases. The measurements read from the protection relays are also verified to confirm the end to end correct operation.

8. Telecontrol tests

These are tests to verify all the remote control functionality of the CB and protection relays. These tests additionally verify all signals and alarms are correct.

Portable power pack for retrofit CB test

The portable device used as a backup for tripping the retrofit circuit breakers (as explained in chapter 8.2) was tested on site to verify that it is safe to use and to confirm the functionality. Those tests were witnessed by the Asset Management Technical Standards representative and Asset Management Asset Strategy representative.