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Company:

UK Power Networks (Operations) Limited

Powerful-CB

Project Closedown Report

Glossary

Term	Description
ABB	Our technology partner for Method 1
AMAT	Prospective technology partner for Method 2 (Method 2 was de-scoped)
BAU	Business as Usual
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
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
ENWL	Electricity North West Limited
EOS	Engineering Operation Standard
ETS	Engineering Technical Specification
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
Fault Rating	The short circuit current withstand of switchgear against three-phase and single-phase faults to earth
FCL	Fault Current Limiter – a FLMT that attenuates fault current by increasing its impedance (only) during a fault.
FCS	Fast Commutation Switch
FLCB	Fault Limiting Circuit Breaker – a FLMT that blocks fault level contributions from a transformer or 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
FNC	Frazer-Nash Consultancy

Term	Description
GB	Great Britain
HV	High Voltage
HVDC	High Voltage Direct Current
IAC	Internal Arc Fault
IPR	Intellectual Property Rights
L1/L2/L3	Line 1, Line 2, Line 3 of a three-phase power network
LCNI	Low Carbon Networks & Innovation Conference
LPN	London Power Networks plc (one of three UK Power Networks licence areas)
M1	Method 1 – Installation of an FLCB at a substation
M2	Method 2 – Installation of an FLCB at a customer's premises (de-scoped from project following Ofgem approval of change request)
MCB	Miniature Circuit Breaker
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
PM	Project Manager
PPR	Project Progress Report
RA1, RA2, RA3	Running Arrangements 1, 2, and 3
RFI	Request for Information
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
TRL	Technology Readiness Level
UKPN	UK Power Networks
UPS	Uninterruptable Power Supply
VCB	Vacuum Circuit Breaker
VOR-M	Vacuum Oil Replacement Circuit Breaker
WS1, WS2, WS3, WS4	Workstreams 1, 2, 3, and 4

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1. Project Background

UK Power Networks are establishing a Distribution System Operator (DSO) 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. Distributed generation (DG) is a vital enabler of the low carbon transition and over the duration of this project UK Power Networks have seen connected generation capacity increase from 750MW to 9.82GW; however, in urban networks, fault level constraints may hinder DG deployment.

The electricity network is designed to manage the prospective fault levels within its expected load levels, with equipment rated to withstand and clear the prospective fault current. When new generation is added, or the system is expanded in other ways, the prospective current level might increase. The traditional solutions to fault level constraints are: an inhibit agreement (therefore restricting output); connection at a higher voltage level; or network reinforcement, with the latter two resulting in a connection cost which may make generation projects economically unviable. Alternatively, the fault level could be limited so that existing equipment remains within the design rating, thus avoiding the connection costs that inhibit some projects.

The Powerful Circuit Breaker (Powerful-CB) project aimed to demonstrate that Fault Limiting Circuit Breakers (FLCB) can release additional fault level headroom to enable more DG connections to fault-constrained 11 kV distribution networks without the need for network reinforcement. An FLCB is a hybrid (solid-state combined with mechanical switches) circuit breaker that operates 20 times faster than existing Vacuum Circuit Breakers (VCB) to mitigate fault level contributions from new DG connections. The team worked with technology partner and equipment manufacturer ABB Ltd (ABB) to develop an FLCB for trial at an 11 kV primary substation.

The project benefits will also facilitate the decarbonisation of heat, through the connection of Combined Heat and Power plant and decentralised renewable generation which helps in achieving Net Zero and contributes to the transition to a DSO model. 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.

2. Executive Summary

2.1 Scope and Objectives

The Powerful-CB project started in January 2017 and ended in August 2022. The overarching aim of the Powerful-CB project was to demonstrate that FLCBs can enable the connection of more DG to fault-constrained 11kV distribution networks, without the need for network reinforcement which can delay or even prohibit further distributed energy projects.

An FLCB is a hybrid circuit breaker that operates 20 times faster than existing VCBs. It can block 100% of fault level contribution but allows load current to flow normally before and after the fault as soon as the fault has been cleared. This high-speed operation can mitigate fault level contributions from DG, allowing connection of additional DG capacity, including CHP, to fault-level constrained networks.

The Powerful-CB project core objectives were to:

1. Work with the industry to advance new Fault Level Mitigation Technology based on FLCB technology.
2. Trial the technical suitability of the technology including effectiveness and safety considerations for relieving fault level constraints for 11 kV networks.
3. Assess the suitability of the solutions against customers' needs.
4. Share the learning throughout the project with the wider utility industry.

The overall project budget was £4.36m, with £3.43m of funding secured from a NIC funding request, £0.39m contributed by UK Power Networks, and £0.50m provided by project partner ABB.

2.2 Outcomes

Initially, the project investigated two solutions:

- Method 1 (M1) – Installing a device at a substation, to allow multiple generators to connect; and
- Method 2 (M2) – Installing a device at a customer site, to allow a single generator to connect.

Method 1 used technology partner ABB who developed an FLCB for use at a primary substation where they demonstrated an FLCB with a fast commutation switch. This was the only solution to be investigated during the trial and as such all documentation (Workstreams, Successful Delivery Reward Criteria (SDRC), Project Progress Reports (PPRs), Safety Case) is in relation to this method.

Method 2 would have used Applied Materials (AMAT) to develop an FLCB for use at a customer's premises. It was descoped at the early stages of the project as the project partner withdrew from the project. The project team engaged with the Fault Current Limiter (FCL) supplier market by issuing a Request for Information (RFI) to over 50 suppliers but were unable to find a suitable replacement who would have been able to deliver within budget and on time. Subsequently, a change request was submitted to Ofgem to remove M2 from the project.

2.3 Project Performance

The project delivered evidence of a successful network demonstration of the FLCB. The PPRs and SDRCs record the methodology used and results obtained to enable future innovation projects to build on the learning from this project in developing an FLCB.

The project satisfied all of the original aims and objectives as listed in the FSP and all seven SDRCs described in the Final Project Direction relevant to M1 were delivered successfully. Performance against the aims, objectives and SDRCs is summarised in section 6.

2.4 Project Learning

From the project, the following insights emerged that can contribute to the effectiveness and impact of future innovation projects:

- Finalise contractual agreements prior to the project start date where possible. Difficulties with the AMAT contract prevented progress on M2, which resulted in the de-scoping of activities related to M2.
- Define technical, installation and interface requirements early within the project. Changes to various requirements on the FLCB system emerged during the installation and trial phases, outlined in section 8.2. Although the team successfully adapted the FLCB to accommodate these requirements, to prevent re-occurrence, the requirements should be defined as early as possible.
- Ensure early engagement with any resource critical to the project, as skilled internal resources are also used in many network reinforcement projects which can at times take precedence over innovation projects.

A detailed description of the project learning is included in section 9.

2.5 Method Learning

The project has produced an extensive set of learning that can be found in Section 8.2 of the report. The key learnings from the method include:

- Ensuring contractually that equipment delivery plans, routes, traffic management and permits were the responsibility of the supplier and/or any delivery sub-contractor of the supplier.
- Considering signal outputs and channels of transmission during the initial production of device specifications, in order to avoid design changes later on. Alternatively, the standard use of optical fibre communication channels could be further defined within UK Power Networks.
- When connecting to older switchgear, considering the availability of spare equipment for switchgear expansion; availability of skilled resources for specific equipment type; and any potential to re-use equipment from similar sites undergoing refurbishments.

A detailed description of the method learning is included in section 8.2.

2.6 Report Structure

This Closedown Report summarises all activities that were undertaken as part of the Powerful-CB project, broken down into four Workstreams. This report is structured in 15 sections as below:

Section 1. Outlines the project background to provide context.
Section 2. Provides an executive summary of the project scope, objectives, and outcomes.
Section 3. Details the project structure and the work carried out during each Workstream.
Section 4. Summarises the outcomes of each Workstream.
Section 5. Provides information on any extensions or modifications to the initial project plan.
Section 6. Summarises the project performance compared to the initial project aims.
Section 7. Outlines any significant budgetary changes.

Section 8. Summarises the updated Business Case and technical lessons learnt.
Section 9. Summarises any lessons learnt which can be applied to future Innovation Projects.
Section 10. Provides information which may be necessary for a future replication of the project.
Section 11. Provides details on any plans to modify the network based on learning from this project.
Section 12. Summarises the project's Learning Dissemination activities and outcomes.
Section 13. Provides details of all learning documents created during this project.
Section 14. Directs the reader to the UK Power Networks' Data Sharing Policy.
Section 15. Provides contact details for the Powerful-CB and Innovation Team for further questions.

Each of the four Workstreams are summarised within this report and hyperlinks are included to the relevant PPRs and SDRCs that are published on the Powerful-CB website.

Further contact can be made to UK Power Networks regarding the Powerful-CB project using the contact details in section 15.

3. Details of the Work Carried Out

3.1 Project Structure and Governance

The project started in January 2017 and was due to complete in August 2021. The completion date was extended (in two stages) until August 2022 due to COVID-19 pandemic delays and a desire to extend the trial period to continue building confidence in the FLCB. The project was initially extended by five months in a letter to Ofgem in July 2020, which notified the extension of SDRC deadlines due to the COVID-19 pandemic. Ofgem were informed in July 2021 of a further extension of seven months to bring the total extension to twelve months. A non-material change request was submitted for both requests.

Four Workstreams were developed as part of this project, these are covered in detail within section 3.1.1.

3.1.1 Project Structure

Workstream 1 (WS1) – Development of an FLCB Device Prototype

The objectives of WS1 were:

- Design, build and test at least one prototype for M1;
- Design, build and test one prototype for M2 (subsequently de-scoped); and
- Develop preliminary safety cases for both FLCBs.

Workstream 2 (WS2) – Network Demonstration

The objectives of WS2 were:

- Identify use cases for the FLCB trials (e.g. trial sites and trial arrangements);
- Investigate the protection and control philosophy (e.g. FLCB trip setting, reclosing, coordination and discrimination);
- Install and commission the FLCBs at the trial sites (restricted to M1 FLCB and one trial site);
- Collect data and complete analysis to prove that FLCBs are safe and effective (restricted to M1 FLCB only); and

- Update the preliminary safety case to consider data and learning from the field trials.

Workstream 3 (WS3) – Understanding Customers' Requirements

The objectives of WS3 were:

- Understand our customers' needs and requirements;
- Ensure that solutions meet customers' needs; and
- Recruit a trial participant for the M2 demonstration (subsequently de-scoped).

Workstream 4 (WS4) – Knowledge Dissemination

The objective of WS4 was:

- Disseminate knowledge to our key stakeholders.

The progress during the Workstreams was captured in the PPRs and SDRCs which were made publicly available on the UK Power Network website. As part of WS4 and to address Ofgem's requirements, a summary of the key information, learnings and issues from this project is presented in this closedown report.

3.1.2 Project Management

The project management structure was developed to enable successful delivery of outcomes in a timely manner. The key project roles and responsibilities were:

- **The Project Steering Group** comprised of key stakeholders and decision makers within UK Power Networks and chaired by Senior Responsible Owner Ian Cameron (Head of Customer Services & Innovation). This group was ultimately responsible for the project;
- **The Project Manager** was responsible for the day-to-day management of the project. This included but was not limited to, reviewing the project progress against plan, presenting the project progress to the Project Steering Group, updating the project plan, and monitoring project risks and project budget;
- **The Workstream 1&2 Lead** was responsible for the technical delivery of WS1 & WS2;
- **The Workstream 3&4 Lead** was responsible for the technical delivery of WS3 & WS4;
- **The Design Authority** reviewed and approved all key project deliverables. However, ultimate responsibility for the delivery of the solutions rested with the project delivery team; and
- **The Project Management Office** provided support to the Project Manager to achieve project goals and objectives within scope, time, and budgetary constraints.

Throughout the project, various changes occurred within the core project team. These changes are listed within Table 1 below.

Table 1: Detail of Changes in Project Management Roles

Change	Date	Detail
PM Appointed	28 June 2017	-
WS3 & WS4 Lead Appointed	3 July 2017	-

Change	Date	Detail
Ongoing Recruitment for WS1 & WS2 Lead	2017 & 2018	WS1 & WS2 activities were led by the Bid Lead and Project Lead during this recruitment period, with the support of an innovation engineer.
WS1 & WS2 Lead Appointed	23 March 2018	An official handover of activities to the WS1 & WS2 lead occurred.
PM Left the Project	December 2018	PM responsibilities were carried out by an interim PM.
PM Appointed	4 February 2019	An official handover of activities and responsibilities occurred from the interim PM to the newly appointed PM
Reduced Scope for WS3 & WS4 Lead	December 2019	Due to the removal of M2 from the project, the scope of this role was reduced to WS4 Lead.
WS1 & WS2 Lead Left the Project	June 2021	The WS1 & WS2 Lead moved to another team within UK Power Networks during 2021, and so this role was fulfilled by the Project Manager.
PM Left the Project and new PM Appointed	15 March 2022	An official handover of activities and responsibilities occurred from the previous PM to the newly appointed PM
WS1 & WS2 Lead Activities Fulfilled by PM	2022	-

3.2 Customer and Stakeholder Engagement

UK Power Networks signed a collaboration agreement with ABB and intended to sign another with AMAT but were unable to reach an agreement on contractual terms resulting in M2 being descoped from the project as detailed in section 2.2.

During the July – December 2017 reporting period, the project launched the Powerful-CB customer working group, to discuss the trial and future requirements of FLCBs, with a launch event consisting of interested parties and potential trial participants. The project identified key internal stakeholders at UK Power Networks and invited them to join an internal working group to ensure smooth installation and to aid transition to Business as Usual (BAU). Customer engagement activities continued throughout the project, via the project mailing list containing all interested stakeholders and via knowledge dissemination events.

Key learning points from initial customer engagement activities are detailed in SDRC 9.3.1 and included:

- FLCB technology was of interest to a wide range of customer types from a geographic spread;
- Customers expressed a range of potential preferences and business drivers relating to Powerful-CB but some key themes emerged relating to finance and technology maturity; and
- Future success will depend on appropriate commercial and logistical options and arrangements.

A number of challenges that could have prevented achieving wider stakeholder engagement were identified and mitigated by the project team. These challenges included:

- Customers engaging more with the proposed installation at a customer site (M2) than the substation installation (M1);
- The customers who engage not being representative of the wider generator community;
- Customers may not want to engage face to face or only through channels they were familiar with; and
- Reduced interest from customers due to capacity ratings of the device.

A number of methods were implemented to reduce the likelihood and impact of these challenges, these are listed in SDRC 9.3.1, including:

- A plan to hold a customer working group focusing on M1, to increase customer engagement;
- Internal and external communication channels were used to engage with customers from the wider generator community;
- Surveys allowing anonymity were used, to enable customers to avoid face-to-face engagement; and
- Capture of future requirements for product evolution, to address the reduced interest from customers due to the capacity range of the device.

During the project, knowledge dissemination events were held to inform customers of the project's progress. Then, as part the project closedown (August 2022) an event was held with customers to provide an overview of each stage of the project and its findings. The event attendees provided feedback on the project during the session (see section 3.6.6 for more information) and were encouraged to get in touch with the project team with any further questions or to discuss additional topics of interest.

3.3 Workstream 1 – Development of an FLCB Device

The overall development process followed during this Workstream is summarised in Figure 1.

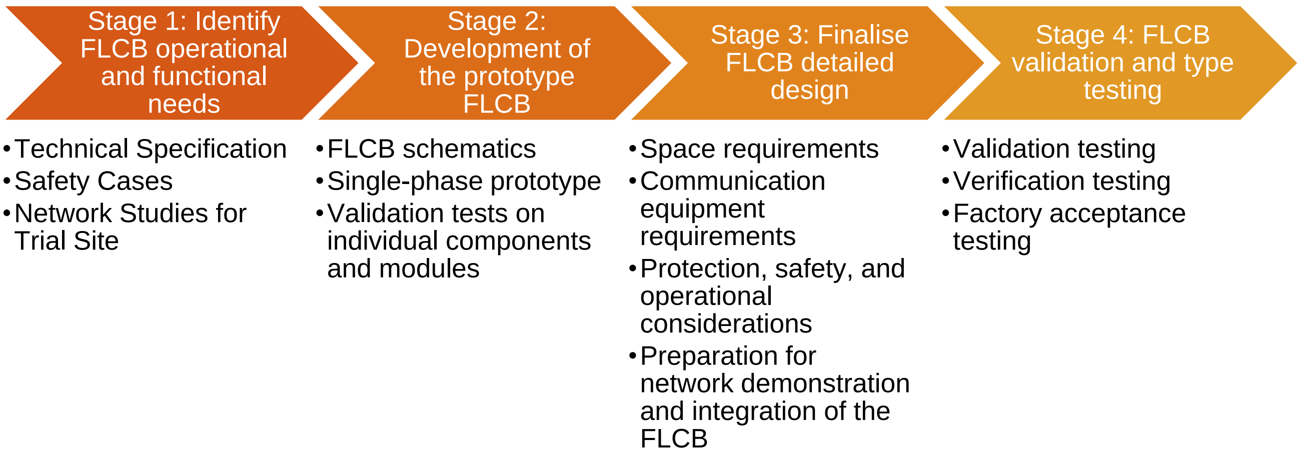

Figure 1: Summary of FLCB Development process

WS1 is captured in further detail in the following documentation which is available on the website:

- SDRC 9.1.1;
- SDRC 9.1.3 and 9.1.4;
- Progress Reports: 2017 to 2019; and
- Safety Case Report Update (2022)

3.3.1 Reporting Year 2017

For the development of the safety case, the project contracted Frazer-Nash Consultancy (FNC), and Imperial College Consultants for expert advice on power electronics.

Initially the FLCB engineering technical specification was finalised (ETS 03-6511 Specification for Indoor 12kV Power-Electronic Fault Limiting Circuit Breakers), which defined the technical requirements for both M1 and M2 FLCBs. The project published the Safety Case Processes and Principles document which can be found here and explains the development of the safety case for FLCBs.

The safety case work continued throughout the July-December 2017 reporting period, moving to mitigations and cost benefit analysis. During this time the project also signed a collaboration agreement with ABB.

3.3.2 Reporting Year 2018

During the January – June 2018 reporting period, the project completed detailed network studies for the M1 trial site which was assumed to be a typical 11 kV urban substation. Outputs were used by ABB for protection calibration purposes and by UK Power Networks to monitor the trial's effect on the surrounding network. Outputs from the safety case activities were utilised to provide an independent review of the upcoming trials and potential BAU use. SDRC 9.1.3 and 9.1.4 were submitted on time, including further information regarding the safety case process and report.

ABB completed validation testing of M1 single phase prototype at their corporate research facility in Sweden in June 2018 (June – December reporting period). The testing proved that the single-phase prototype aligned with the desired characteristics of a fault current limiting device deployed for Powerful-CB. ABB also successfully completed FLCB panel integration and preliminary temperature rise testing of the single-phase prototype.

3.3.3 Reporting Year 2019

During the January – June 2019 reporting period, the FLCB schematics were completed, including general electrical schematics. These schematics were used in WS2 to facilitate the design for FLCB integration into the trial site. Similarly, the mechanical drawings showing the exact dimensions and cable entry points were finalised and used for WS2. Successful verification testing of the FLCB was undertaken in this period. These verification tests included:

- Electromagnetic Compatibility (EMC) tests in accordance with IEC 61000-4 of the complete panel and selected critical components;
- Endurance testing to build confidence that the FLCB can operate successfully during mechanical stresses and for up to 2,000 operations (defined as the design target). This was especially critical for the Fast Commutation Switch (FCS) which was developed for this application.

Type testing of the FLCB was also undertaken during this period. The type tests were delayed by two months due to issues with the independent test laboratory generator; however, the project team worked closely with ABB to mitigate the impact and reschedule the tests as early as possible at an alternative certified laboratory. Selected type tests were completed in the presence of an external observer from PEHLA (the Association of High Power Laboratories in Germany and Switzerland) and in the presence of UK Power Networks. The following type tests were completed at accredited high power test labs in Germany and the Netherlands:

- Dielectric testing in accordance with IEC 62271-200;
- Temperature rise testing in accordance with IEC 62271-200;
- Breaking and making testing in accordance with IEC 62271-100;
- Short time/peak current withstand testing in accordance with IEC 62271-100; and
- Internal arc testing in accordance with IEC 62271-200.

All type tests were completed successfully with the exception of internal arc testing which did not pass. Initial investigations by ABB indicated that only minor modifications to the device panel would be required to resolve the issue, and a second set of internal arc testing was planned for the next period.

During the July – December 2019 reporting period, ABB finalised type testing by completing the necessary modifications to the FLCB panel in order to pass the Internal Arc Fault (IAC) re-test. Details of the modifications can be found in SDRC 9.1.1. ABB also completed Factory Acceptance Tests (FATs) at ABB in Ratingen, Germany which were witnessed by UK Power Networks. These tests confirmed that the FLCB had been built, assembled, and operated in accordance with the specification, and gave confidence that the FLCB was ready to be shipped to site. The project also produced an installation manual for the FLCB, and operational documentation for the engineers in the UK Power Networks control centre as well as field and operational staff. Finally, in October 2019 SDRC 9.1.1 was submitted to Ofgem and published on the project website – this deliverable included the development of an FLCB for substations.

All WS1 activities for the development of the FLCB were completed by the end of 2019. 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 was as robust, reliable and safe as possible. This required ABB to explore a suitable replacement, ship to the trial site, and install the device. Due to the lead-time of the UPS and resource unavailability, these were installed in February 2020.

3.4 Workstream 2 – Network Demonstration

The overall process followed during WS2 is shown in Figure 2.

Figure 2: Summary of FLCB Network Demonstration Workstream stages

WS2 is captured in further detail in the following documentation which is available on the project website:

- SDRC 9.2.1;

- SDRC 9.2.3; and
- PPRs: 2017 to 2022

3.4.1 Reporting Year 2017

The first steps included progressing site selection and preliminary design of the M1 trial site, as well as undertaking a feasibility study on a sample of primary substation sites to confirm the applicability of FLCBs to the network. The project selected a representative sample site that met the following criteria:

- Site experienced fault levels above threshold;
- Located within the LPN licence area in a dense urban environment and at 11kV rated primary substation;
- No physical and operational constraints;
- Existing fault level did not exceed fault rating under normal conditions or N-1 conditions;
- No asset replacement were planned or likely before the end of the trial;
- History of faults on outgoing circuits;
- Ideally, had existing non-firm generator connections; and
- Evidence of a high demand for future DG connections was also considered for site selection.

Following this selection, the project planned to conduct a high-level study to determine whether the FLCB would be a feasible solution.

3.4.2 Reporting Year 2018

During the January – June 2018 reporting period, the M1 trial site selection was completed and a preliminary design for the M1 trial site was progressed. Appropriate internal stakeholders were engaged to ensure the trial site was ready for installation by summer 2019. Preparations began for detailed design as well as updating the project plan according to expected civil and electrical enabling works. The technical partner, ABB, provided valuable data relating to the trial safety – see SDRCs 9.1.3 and 9.1.4 for more information. Site inspection visits were performed during this period, and potential M2 trial sites were shortlisted. A detailed assessment of each potential trial site was progressed during this reporting period to determine the most suitable location for the M2 trials.

The Glaucus Street 11kV substation was selected as the preferred trial site as per the M1 selection criteria. Glaucus Street is within the LPN licence area in east London. The site selection was based upon thorough criteria prepared to ensure that the device could be successfully demonstrated to maximise learnings for BAU installation, commissioning, and operation.

During the July – December 2018 reporting period, appropriate internal stakeholders, including Capital Programme & Procurement, Outage Planning and Network Operations, were engaged with the target that the trial site was ready for device installation by summer 2019. The first electrical running arrangement of the trial site was agreed following a series of workshops with the internal stakeholders. Further trial arrangements were decided later in the project. At the first trial arrangement, it was decided that the FLCB device at Glaucus Street would be installed in parallel with the existing bus coupler. The project team worked with internal stakeholders to complete the detailed civil design for the trial and commenced the electrical design and procurement activities for the trial site preparation.

3.4.3 Reporting Year 2019

During the January – June 2019 reporting period, the civil design, mechanical design and cable routing was completed, in addition to the following electrical items at Glaucus Street:

- Switchgear design drawings;
- Protection drawings;
- Multicore cable schedules;
- Autoclose relay drawings;
- Procurement of materials;
- Retrofitted circuit breakers that would be used to extend the existing switchboard;
- Additional CTs needed for unit protection of the FLCB branch were ordered;
- All the protection relays and panels were ordered;
- Supervisory Control and Data Acquisition (SCADA) panel request to the internal manufacturing team was placed; and
- The demonstration-specific drawings were pending feedback from commissioning engineers.

An auto-close philosophy for an operational scenario was developed after it was identified there was a potential for an unwanted dead busbar (causing loss of supply to customers). This assessment was produced in collaboration with internal subject matter experts to agree the running arrangements during the trial. See section 8.2.6 for a summary of the lessons learnt during this task.

Site preparation work to ready the site for installation of the FLCB was completed: stored equipment in the room was relocated and the existing wall replaced as it contained asbestos. The civil, mechanical and small power and lighting works were all completed including modifying the fire suppression system and adding a new set of substation batteries.

During the July – December 2019 reporting period, the existing switchboard was extended including the addition of the retrofitted circuit breakers. New unit protection panels were installed as well as fault recording relays, SCADA panel and all the wiring for signalling. The FLCB was also delivered to site and the following activities were completed:

- Installation of steelworks in the basement for power cables;
- Installation of the FLCB and control cabling;
- Installation of power cables from the busbar to the FLCB and back including terminations;
- Commissioning of the busbar extension including the retrofit circuit breakers; and
- Commissioning of the FLCB.

In parallel with completing type testing and site works, a number of documents were created including the FLCB Installation Manual, Commissioning Plan and Resource Plan for the network demonstration period.

3.4.4 Reporting Year 2020

During the January – June 2020 reporting period, the portable power pack was tested. This was designed as a mitigation for the defect warning issued for the type of retrofit Vacuum Oil Replacement (VOR-M) CB (further details are in July – December 2019 PPR). The portable power pack allowed for the CB to be opened following a capacitor failure in the operating mechanism. The power pack is shown in Figure 34.

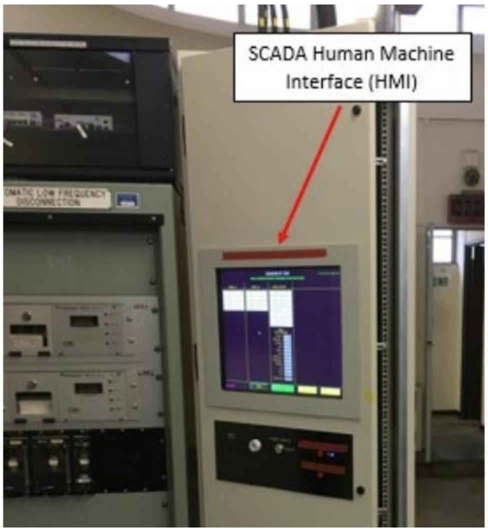

Figure 4: SCADA panel with HMI screen which shows alarms from the FLCB and other protection equipment

Figure 3: Portable power pack (left) plugged into retrofit VOR-M CB (right) during testing of the power pack

The main change made during January to June 2020 was due to the SCADA system being unable to display the high speed FLCB trip alarm signal. To overcome this, ABB latched the alarm to a spare relay contact, and a software updated was performed by the manufacturer of the SCADA equipment to detect the high speed alarm signals – the SCADA panel with HMI screen is shown in Figure 4. Information on the lessons learnt during this activity can be found in section 8.2.9. While retesting all alarms and functions during commissioning, a fault with the HV door interlock of the FLCB was identified. As the interlock is a critical safety mechanism, energisation was postponed until site works could resume with a safe approach following the introduction of restrictions due to COVID-19.

The commissioning of adjacent retrofit CBs was finalised following approval to energise from Asset Management after the portable power pack was successfully tested. The standalone commissioning of the FLCB was then completed before the installation and commissioning of HV power cables from the busbar to the FLCB, shown in Figure 5. At this time, the asset registration was completed as well as continued training of LPN field staff. In addition, the Engineering Operation Standard (EOS) 03-0125: Fault Limiting Circuit Breaker Operational Information, to be used by control engineers, was completed. Finally, the safety case was updated by Frazer-Nash Consultancy.

During the July – December 2020 reporting period, the remaining Glaucus Street site works interrupted in the previous reporting period due to COVID-19 restrictions, were completed. Final commissioning checks and tests prior to energisation were completed as well as commissioning of the fault recorders and auto-close scheme. Energisation of the FLCB took place in August 2020, and the trial of Running Arrangements 1 and 2 was initiated – see Figure 6 for an illustration of these running arrangements.

Figure 5: Completed HV cable terminations to the FLCB

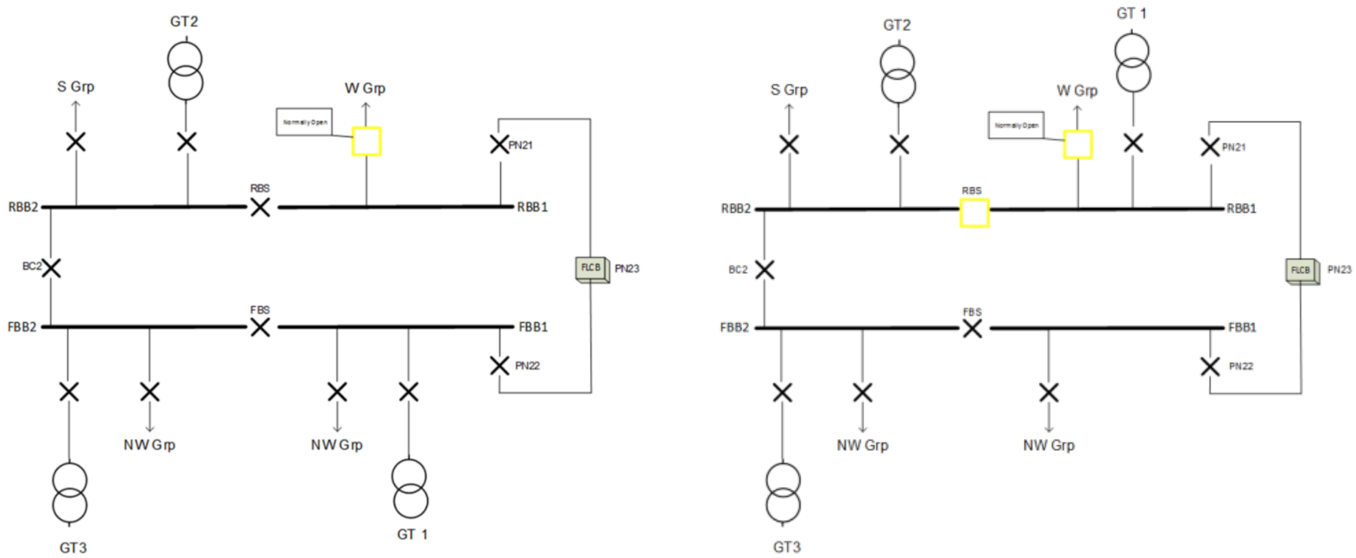

Figure 6 Running Arrangements 1 (left) and Running Arrangement 2 (right). Note that yellow indicates "normally open"

Running Arrangement 1 saw the FLCB undergo a 'soak' test, during this time there was no requirement for the FLCB to trip for a network fault. A 'soak' test is typical for all new equipment in order to avoid early failures, and this approach allowed the project team to identify any early issues before the FLCB would be required to operate for a network fault. Data collection and analysis was ongoing during the trial period.

Figure 7 shows the FLCB's operation during Running Arrangement 1.

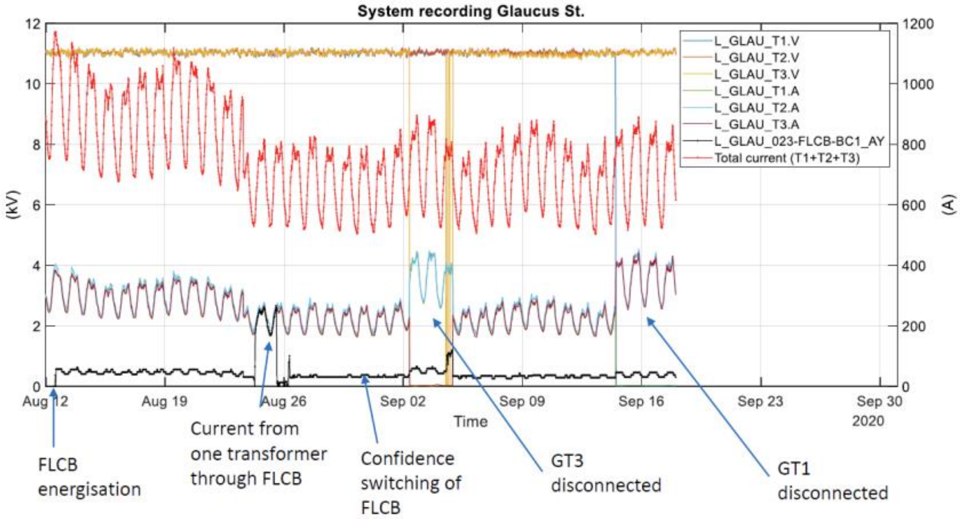

Figure 7: Running Arrangement 1 highlighting various outage events

The FLCB transitioned to Running Arrangement 2 on 30 September 2020 where it operated as transformer incomer circuit breaker for Grid Transformer 1 (GT1) by opening circuit breaker RBS and switching GT1 to the busbar RBB1 (Figure 6 and 8). The FLCB continued to report healthy with no issues during this time, including when confidence switching took place and during outages of transformers and circuit breakers. Monthly confidence switching was performed to demonstrate that the FLCB would functionally operate the isolated device upon receiving an open command and increased the number of operations seen by the FLCB as part of the continuous monitoring. It demonstrated that the FLCB was responsive and would react to a command, giving confidence that it would operate correctly during a network fault on the system.

Finally, the FLCB transitioned to the Running Arrangement 3 (RA3) on 3 December 2020 which was the final arrangement to be trialled. More information on this can be found on section 3.4.5.

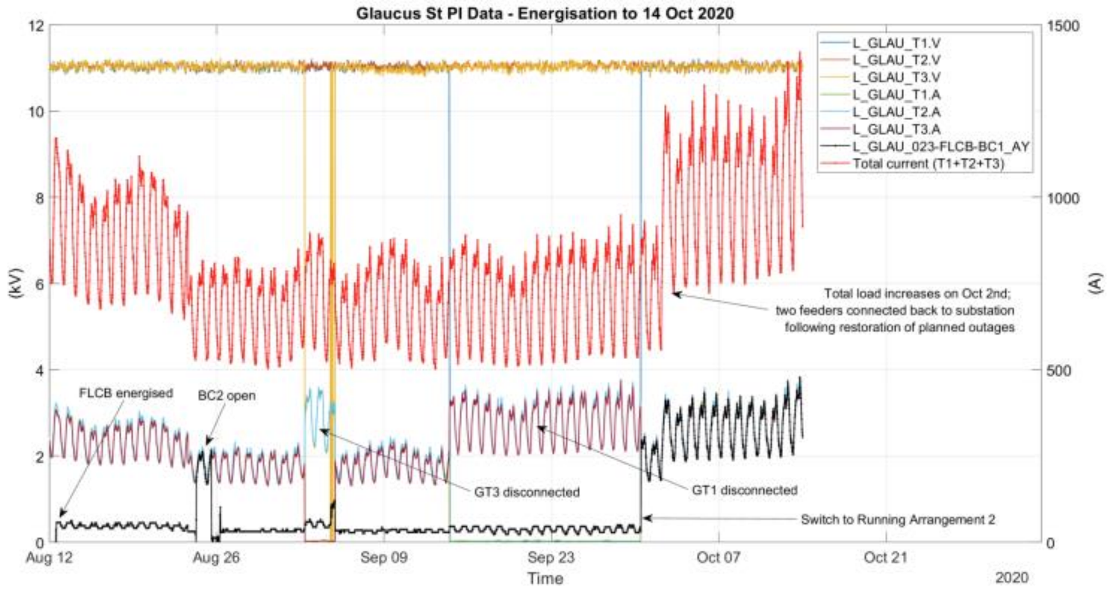

Figure 8: Operation to date of the FLCB through Running Arrangement 1 and Running Arrangement 2

3.4.5 Reporting Year 2021

During the January – June 2021 reporting period, WS2 focused on continuing the trial period under the Running Arrangement 3. This arrangement, shown in Figure 9, saw the FLCB operated as a bus coupler by opening the existing bus coupler BC2 and required the FLCB to break the short circuit current fed from two transformers during certain faults. In RA3 the purpose of the FLCB was to separate the busbars in the event of a fault to ultimately decrease the fault current by a factor of two in a four-transformer running arrangement.

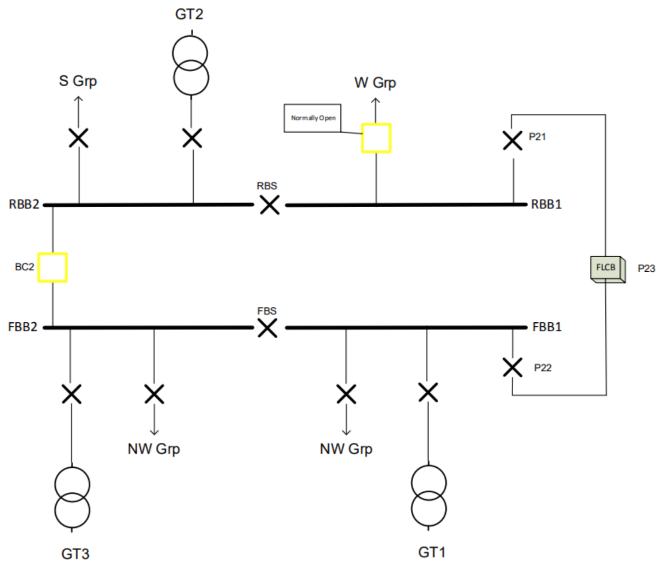

Figure 9: Running Arrangement 3. Note that yellow indicates "normally open"

During RA3 data was gathered to monitor the health of the FLCB. Twice per day, the supervision unit within the FLCB received a data cluster, from the control system of each phase of the FLCB. The data in the cluster was used to monitor all the components in the FLCB including the control system itself, the mechanical switches, and semiconductors. In the event of an operation, an updated data cluster and a transient recording of the currents through the FLCB were recorded. The project team scheduled a monthly confidence switch where Network Control sent an open command to the FLCB and then closed it a short time later.

In this reporting period two network faults above the threshold were experienced, both caused by cable faults on the network, and in both cases the FLCB operated as expected.

A site inspection and annual maintenance was carried out by ABB in September 2021. This inspection and maintenance included:

- Visual inspection of all parts of the FLCB – no issues were found;
- Measurement of the contact resistance for all mechanical switches – found to be within expected values;
- Measurement of the capacitor charging time for each individual drive unit – found to be within expected values;
- Verification of the tripping set point of the QR6 protection relay in the FLCB;
- Updating the software of the supervision unit to enable continuous monitoring of load current levels in the FLCB and to trigger the recording of current waveforms for overcurrent events with insufficient amplitude to trip the FLCB. This action was identified as necessary during the previous reporting period.

During maintenance, one of the mechanical switches (FCS L3-3) was replaced – Figure 10 shows images from this site visit. Diagnostic data collected during the preceding months had shown its opening and closing times beginning to deviate from expected values. The FLCB was de-energised as a precautionary measure during August 2021 until the switch could be replaced, to mitigate the risk of a mechanical failure. The replacement switch was confirmed to be working correctly following installation and the FLCB was re-energised in October 2021. The old switch underwent accelerated testing at ABB to investigate its remaining life as this knowledge may help the judgement of similar trends observed in the future.

Figure 10: Site Inspection and Maintenance (left) and the mechanical switch replacement (right)

3.4.6 Reporting Year 2022

In the January – August 2022 reporting period, two network faults above the threshold were experienced: a two-phase fault and a single-phase fault. In both instances the FLCB operated correctly. During May 2022, SDRC 9.2.3 – Demonstration of solution at an 11 kV substation (M1), was submitted to Ofgem and published on the UK Power Networks website. This SDRC included results and learnings from operating and maintaining a substation containing an FLCB, in addition to the technical performance of the FLCB and overall solution under real network conditions.

The FLCB was taken out of service on 27 June due to a fault reported on the UPS, which acted as back-up power for the control system in phase L2. The issue was related to the UPS' battery status which was used to provide the requested back-up power in the event of a problem with the primary 110 V DC supply. Even though the FLCB was operating correctly, it was decided to switch it out as the faulty UPS would require maintenance in order to continue with the FLCB trial, and decommissioning was due to commence shortly.

Decommissioning activities of the FLCB took place in July 2022 and an update of the Safety Case and Risk Assessment Report was performed by Frazer-Nash Consultancy in order to incorporate learnings from the FLCB trial.

3.5 Workstream 3 – Understanding Customers' Requirements

The overall process followed during this Workstream is shown in Figure 11.

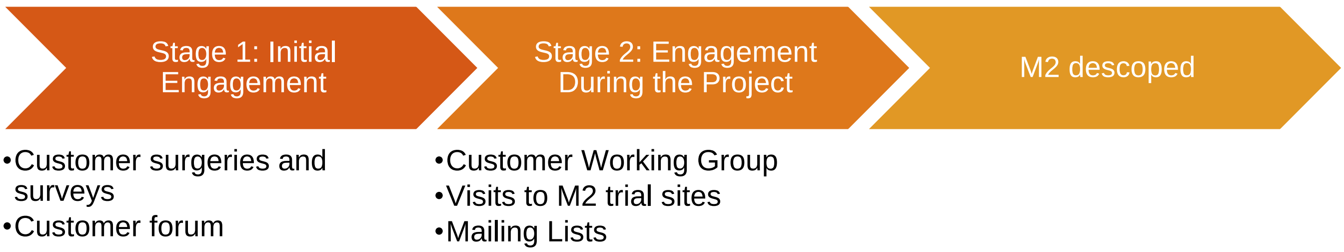

Figure 11: Summary of FLCB Understanding Customers' Requirements Workstream stages

WS3 is captured in further detail in the following documentation which is available on the website:

- SDRC 9.3.1; and
- PPRs: 2017 to 2020.

3.5.1 Reporting Year 2017

During the 2017 reporting period, the project held a number of customer surgeries, submitted SDRC 9.3.1 (Understanding Customers' Requirements) to Ofgem, and presented the project to potential M2 trial participants at the following events:

- Presentation to potential M2 trial participants in February 2017. Slides from this presentation are available here;
- UK Power Networks DG Customer Forum in July 2017;
- The Association of Decentralised Energy District Heating Cooling Forum in October 2017; and
- The Association of Decentralised Energy Commercial Forum in October 2017.

3.5.2 Reporting Year 2018

A shortlist of M2 trial participants was generated, the selection process involved a matrix of essential and desirable criteria, and each interested M2 trial participant was assessed against these. At this stage, the required commercial and legal arrangements for each shortlisted site were considered.

Site visits of the three shortlisted locations were undertaken to understand the available footprint, how the trial would impact on critical business activity and willingness of the customer to be involved with media/outreach. One site was discounted due to a space constraint, the other two sites were owned by the same company and so the customer was given an option to select the most appropriate site to suit their needs. At the end, a 4.2 MW CHP was selected as the preferred trial site for M2.

The team contacted the customer in September 2018 to inform them about the withdrawal of AMAT and asked if they were willing to be considered should an alternative device be found. When no replacement supplier was found, the customer was informed and the change request was submitted to remove M2 from the project.

3.5.3 Reporting Year 2019

During the June and December 2019 reporting periods, the project team were working with Ofgem regarding the removal of M2 from the project.

3.5.4 Reporting Year 2020

During the January – June 2020 reporting period, the project team received approval from Ofgem for the removal of M2 from the project. As a result, SDRC 9.3.2 – Assess the (commercial) business case based on the technical and customer findings, was no longer produced and published. This SDRC was intended to focus on investment decision criteria and trade-offs such as cost, time to connect, space, and impact on security of supply.

3.6 Workstream 4 – Knowledge Dissemination

The overall process followed during this Workstream is shown in Figure 11.

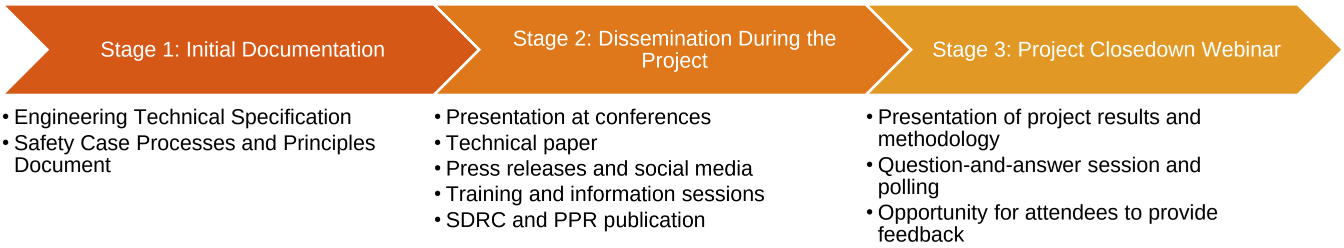

Figure 12: Summary of Knowledge Dissemination Workstream stages

Progress for WS4 is captured in further detail in the following documentation which is available on the website:

- SDRC 9.4.1; and
- PPRs: 2017 to 2022.

3.6.1 Reporting Year 2017

In July – December 2017 reporting period the project team finalised the FLCB ETS (ETS 03-6511 Specification for Indoor 12kV Power-Electronic Fault Limiting Circuit Breakers) and Safety Case Process and Principles Document, which were then published on the Innovation website.

The purpose of the Safety Case Process and Principles Document was to define the scope of the safety case for M1 and M2, and the process for their creation. The document includes definition of the safety management process, review and approval process for the safety case, discussions with relevant stakeholders, and definition of the safety case principles and acceptance criteria.

3.6.2 Reporting Year 2018

During July – December 2018 reporting period, the project team presented the project's learnings and achievements at technical forums and innovation conferences, including the Low Carbon Network Innovation Conference (LCNI), as shown in Figure 13. The project team also presented the findings on trial recruitment at the Chartered Institute of Building Services Engineers (CIBSE) Technical Symposium 2018.

Internally the project obtained input and feedback from the Distribution Planning Engineers who are a key internal stakeholder group.

Figure 13: Presenting Powerful-CB to Distribution Planning Engineers, and discussions at the LCNI

The project team then visited Electricity North West (ENWL) to explore collaborations on the development of the safety cases between Powerful-CB and ENWL's Respond innovation project. Respond is ENWL's innovation project addressing fault level constraints. During this visit, project outcomes were presented and the stakeholder engagement challenges and safety case methodology were discussed; at the conclusion a collaborative approach was agreed. The team also reviewed the project closedown report from the ENWL project Respond and provided feedback. Similarities were identified and the Respond project learnings were taken into account to avoid similar issues during the Powerful-CB project.

3.6.3 Reporting Year 2019

During the June – December 2019 reporting period, a technical paper for the FLCB, titled, "Fault Current Limiting Circuit Breaker in Distribution Systems" was submitted for review and participation at the CIRED international conference. The paper detailed the drivers behind the device development, the unique characteristics of the device compared to existing fault level mitigation technology (FLMT) and the implementation plans. The paper was approved and it was presented at the conference in Madrid. The project team also updated the project website in readiness for the launch of the new UK Power Networks' innovation website.

During the July – December 2019 reporting period, SDRC 9.1.1 was submitted to Ofgem and published on the UK Power Networks Innovation website. The project was also presented at the LCNI held in Glasgow in October 2019 – shown in Figure 14. The conference was a great opportunity to raise awareness of the project to the wider community and to share key learnings from the development of the FLCB. During this reporting period the project team also attended Utility Week Live to discuss progress to date with interested stakeholders.

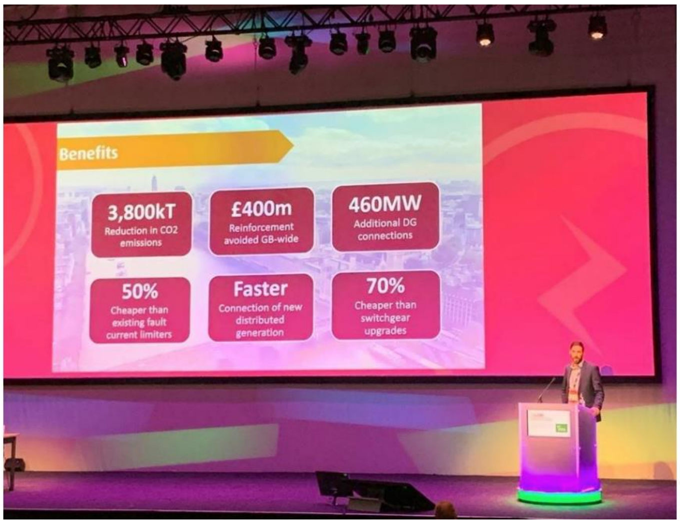

Figure 14: Presentation at LCNI Conference 2019

In addition, valuable engagement with UK Power Networks' internal stakeholders was ongoing, firstly to ensure the FLCB met the operational requirements, and secondly to ensure that the business understood the benefits for a successful BAU transition. Workshops were held with control engineers and presentations were made to the LPN commissioning team. These were opportunities to explain how the FLCB operates, the different network arrangements the FLCB was planned to be trialled, and an explanation of alarms. Feedback and considerations for the project team were also provided through these workshops and presentations.

A press release was also published during this reporting period to inform the industry and general public, raise general awareness about the innovation project as well as its benefits, and more specifically, to share the project progress including installation of the FLCB at the trial site.

3.6.4 Reporting Year 2020

Over the January – June 2020 reporting period, the team strategically focused on internal knowledge dissemination for increased awareness and understanding. The project was included in an innovation newsletter which was circulated throughout UK Power Networks. This was further shared on internal communications platforms to facilitate interactive discussions. A second training and information session was also delivered to LPN field staff in February following the keen interest from the first session held in the previous period. This provided opportunities to explain how the FLCB operates, the different network arrangements the FLCB was trialled under, and an explanation of alarms. Feedback and considerations for the project team were also provided during this session.

Figure 15: FLCB installation in Glaucus Street site

Externally, the project was presented at the UK Power Networks Developer's Forum in March 2020. A press release was also issued during February 2020, to share the project progress. Figure 15 shows an image used in the press release. In addition, a project update newsletter was issued in February to the project mailing list. The newsletter provided an update on project progress, notification of the M2 removal change request approved by Ofgem, and directed recipients to learning report, SDRC 9.1.1, published in 2019. Following this newsletter, the project team engaged further with individuals who had expressed interest in the technology.

During the July – December 2020 reporting period, the project focused on preparing SDRC 9.2.1 – Install and commission solution at an 11 kV substation. Stakeholders were kept informed of the project progress and an update newsletter was issued informing recipients of the energisation of the FLCB and publication of SDRC 9.2.1.

Three internal sessions were held with the Network Planning Teams from each of the UK Power Networks licensee areas where details of the project, including specific technical details, were provided so that the FLCB could be taken into consideration for deployment into BAU.

Further afield, in July 2020 the project was introduced and presented to experts from an Australian DNO; South Australia Power Networks (SAPN), as they expressed interest in the solution. The project also featured in UK Power Networks' 2019/20 Annual Review highlighting the great work and progress of the project team.

The project was highly commended at the Business Green Leaders Awards in the category for Green Infrastructure project of the year for 2020. The project was also nominated for the Institution of Engineering and Technology (E&T) Innovation Awards in the category of Outstanding Innovation in Future Power and Energy Award.

3.6.5 Reporting Year 2021

During the January – June 2021 reporting period, UK Power Networks delivered a webinar to ABB stakeholders focusing on FLCB concept, development, installation, and performance to date. The webinar was an opportunity to discuss next steps with ABB and any changes to the FLCB strategy following the project.

Following the network faults experienced, as discussed in section 4.2, the project team engaged with colleagues from Asset Management, Capital Programme, Procurement and Network Operations to share the data captured, the performance of the FLCB, and interaction with existing protection.

During the July – December 2021 reporting period, two external webinars were delivered with ABB to share knowledge gained from the installation work, commissioning, and operation of the FLCB. During the maintenance site visit in September 2021, a training and information session was delivered for operational staff, following a positive response to similar sessions delivered in previous reporting periods. The session included an update on project progress and learning to date, and demonstrated how feedback from operational staff had been incorporated into the trial.

Figure 16: Winning the "'Energy Tech - Innovation' Award

Additionally, a Q&A session on the project was delivered at the Energy Networks Innovation Conference in October 2021. The project won two awards during this reporting period: the 'Energy Tech – Innovation' award at the Better Society Energy Awards – see Figure 16 and the 'Electrify our world Award – first in innovation.' These awards aim to highlight exceptional examples of projects that embody the qualities "First for Customers"; "First for Innovation" and "First in Digital".

The project also featured in UK Power Networks' 2020/21 Annual Review highlighting the achievements and progress to date.

3.6.6 Reporting Year 2022

During the January – August 2022 reporting period, an external closedown webinar was delivered with ABB to share knowledge gained from the design, installation, commissioning, and operation of the FLCB. Following the webinar, SDRC 9.4.1 was prepared and submitted to Ofgem in August 2022 as part of the project deliverables.

SDRC 9.4.1 contains a brief summary of the event agenda in addition to materials and feedback obtained during the external closedown webinar. An analysis of the project attendees is included as well as examples of the questions asked during the event. In summary, the event provided a good overview of each stage of the project as well as its findings. A total of 100 stakeholders joined the webinar, which included a diverse mix of professionals and customers from different industries ranging from manufacturers, utilities and engineers to consultants and developers. The webinar attendees scored the event with an overall 8.3/10 rating.

The project was shortlisted for one award during the reporting period: the 'Energy Tech – Innovation' award at the 2022 Better Society Energy Awards and the project website was updated with relevant information and deliverables to ensure these were easily accessible to all stakeholders.

4. The Outcomes of the Project

4.1 Workstream 1 – Development of an FLCB Device

The objectives of WS1 were:

- Design, build and test at least one prototype for M1;
- Design, build and test one prototype for M2 (subsequently de-scoped); and
- Develop preliminary safety cases for both FLCBs.

Firstly, ABB conducted a number of validation tests on individual components and modules prior to commencing type testing. Validation tests included a First Assembly functional test, where a complete single-phase FLCB was assembled, and functional verification performed. This was performed together with representatives from UK Power Networks present at SECRC in Västerås, Sweden. The functional verification was performed through mechanical operation of the switches and interruption of low currents in the 1kA range and very limited voltage. The first assembly is shown in Figure 17.

Figure 17: First test assembly of the FLCB

A short time current (STC) withstand test was also performed. During this test, the critical component was the FCS, since the main path during nominal operation is through the low loss mechanical switch. The critical factors for the FCS during the STC test were that the FCS remained in the closed position, i.e. resisted the current forces, and that damage to the contact system was avoided. Therefore, it was important to verify the STC capability of the FCS. This was tested on a single FCS, and one setup for this test is shown in Figure 18.

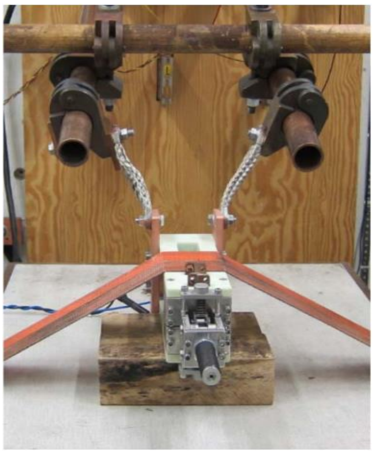

Figure 18: Set-up for one of the 25 kA 1s short time current tests of the FCS

Other verification and functional tests included:

- Bi-mode insulated Gate Transistor (BiGT) Interruption Testing;
- FLCB Endurance Testing;
- Short Time Current (STC) Test, 25kA 1s Single FCS;
- Temperature Rise Test (Validation Testing);
- Interruption, Close-Open (C-O) and Short Time (STC) Test on FLCB Integrated in Panel;
- Insulation Testing;
- Energy/Redundancy Capability at Multiple Operations;
- EMC Testing
- FCS Endurance Testing; and
- Dielectric Withstand;

Five main type tests were carried out, including a short time/peak current withstand testing in accordance with IEC 62271-100. In this test, the FLCB's ability to withstand the full prospective fault current in closed position for 3s was tested. No load operations and resistance measurements before and after the test were performed to confirm that the device was not damaged during the short circuit. The FLCB passed the test without any remarks. The FLCB after the short time/peak current withstand testing is shown in Figure 19.

Figure 19: FLCB panels after short time current withstand testing

Full detail of the tests performed and their results can be found in Appendix A of SDRC 9.1.1. This includes the following additional type tests:

- Temperature rise test in accordance with IEC 62271-200 clause 6.4 and 6.5;
- Making and Breaking Test;
- Dielectric testing in accordance with IEC 62271-200; and
- Internal arc testing in accordance with IEC 62271-200.

The overall development process was completed successfully with ABB finalising type testing at KEMA Laboratories (an accredited high power test laboratory) in July 2019. This followed initial failure of the initial internal arc test, which required modifications to the switchgear panels and subsequent retesting of internal arc withstand capabilities. Finally, completion of Factory Acceptance Tests (FATs) occurred in August 2019, with the FLCB delivered to UK Power Networks' trial site in October 2019.

The Safety Case Report was successfully produced, the preliminary safety case can be found in SDRC 9.1.3-4, published in May 2018, and the final Safety Case Report can be found here, updated in August 2022.

4.2 Workstream 2 – Network Demonstration

The objectives of WS2 were:

- Identify use cases for the FLCB trials (e.g. trial sites and trial arrangements);
- Investigate the protection and control philosophy (e.g. FLCB trip setting, reclosing, coordination and discrimination);
- Install and commission the FLCBs at the trial sites (restricted to M1 FLCB and trial site only);
- Collect data and complete analysis to prove that FLCBs are safe and effective (restricted to M1 FLCB only); and
- Update the preliminary safety case to consider data and learning from the field trials.

The interfaces between the FLCB and the existing network were designed successfully, and installation and commissioning were completed as detailed in SDRC 9.2.1. The installation and commissioning process resulted in a number of insights regarding modifications which could be made to improve the FLCB safety, reliability, or robustness. These modifications were recorded in SDRC 9.2.1 and consisted of:

- Installation of UPS modules into the FLCB to improve reliability and robustness;
- Addition of protection logic to automatically isolate the FLCB as a safety precaution when a "FLCB Out of Service/Faulty" alarm is raised, in the case of an internal FLCB problem;
- Ensuring proper latching of the FLCB trip alarm so that the SCADA system could register the alarm, and applied software update to SCADA equipment to record this; and
- Repair of a fault with the FLCB HV door interlock so that energisation could take place.

The three running arrangements chosen for the network demonstration were successfully trialled:

- During RA1 the FLCB continued to report healthy with no issues – including when confidence switching took place or during outages of transformers and circuit breakers.
- The FLCB was successfully operated throughout RA2, no faults were observed throughout the running period.
- During RA3, the FLCB experienced multiple network faults and tripped as required. As intended, it did not trip for faults lower than its set-point.

Results from the network demonstration are recorded within SDRC 9.2.3, and summarised in Table 2.

Table 2: Summary of Recorded Fault Study Data

Fault Date	Fault Type	FLCB Triggered? (i.e. > 4 kA)	Peak Fault Current (kA)
24 March 2021	Cable fault	Yes	4.4
15 April 2021	Cable fault	Yes	5.3
14 June 2021	Unknown	No	3.7
28 June 2021	Unknown	No	3.0
25 July 2021	Unknown	No	0.68
3 February 2022	2ph Ground Fault	Yes	4.4
30 March 2022	1ph Ground Fault	Yes	1

The tripping value in the FLCB was set to 4 kA and analysing the performance of the FLCB showed that when the fault current reached this level, the peak was limited and was then forced down to zero. Figure 20 below provides two examples of the data captured during network faults, illustrating this fault limiting and interruption behaviour.

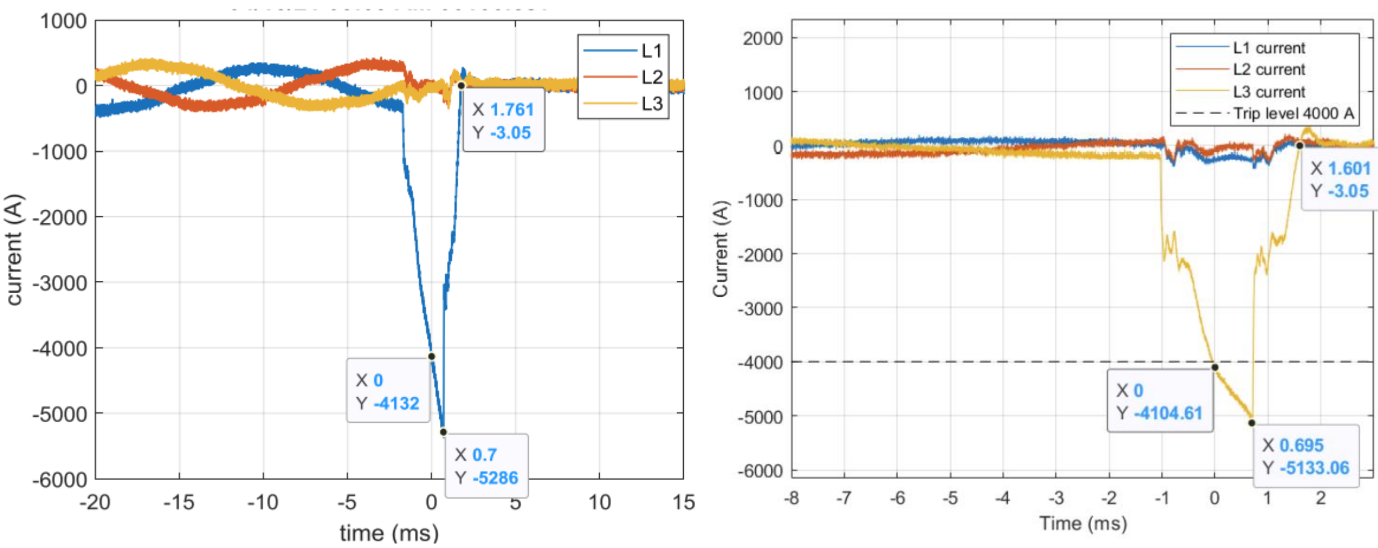

Figure 20: Fault current measured by the FLCB during network fault in April 2021 (left) and March 2022 (right)

The April 2021 figure depicts a typical fault current waveform where there was a rapid increase in current magnitude. Prior to the fault, the system measured symmetrical currents in the order of hundreds of amperes in the three phases. When the fault occurred in phase L1, the current rapidly rose with a negative value. When the current passed 4 kA, the FLCB tripped and the interruption sequence began. The peak fault current was reached after 0.7 ms, (in this case 5.3 kA) and was limited within approximately 1 ms. The March 2022 figure depicts a similar fault current waveform, where the fault current was successfully limited at a peak current of 5.1 kA.

The data collected built significant operational confidence in the FLCB concept over the trial period from August 2020 to the end of May 2022. Throughout this time the device was continuously operating with exception of a few weeks, in Q3 2021, when it was decided to de-energise the FLCB awaiting a scheduled service visit by ABB staff.

The monthly switching demonstrated the responsiveness of the FLCB and that it would react to a command, and built confidence that it would operate correctly during a network fault. Only one inspection activity was performed, in September 2021, due to the COVID-19 travel restrictions which were in place during the majority of the project. The scope of this inspection site visit included the following:

- Visual inspection of all parts of the FLCB
- Measurement of the contact resistance for all mechanical switches
- Measurement of the capacitor charging time for each individual drive unit
- Verification of the tripping set point of the QR6
- Replacement of switch three in the Line 3 (L3) with a new switch. The used switch was returned to ABB for further investigation.

Two preliminary Safety Case Reports were produced, one for M1 and one for M2, and these can be found here. The M1 Safety Case Report and Risk Assessment Workshop Report were both updated in 2022 to incorporate learnings from the FLCB trial; the updated document can be found here.

4.3 Workstream 3 – Understanding Customers' Requirements

The objectives of WS3 were:

- Understand our customers' needs
- Ensure that we design the solutions to meet our customers' needs

As described in SDRC 9.3.1, all WS3 Customer Understanding objective for M1 were met. Understanding customer requirements was an important activity in the project and the project team held discussions and received feedback from customers and other stakeholders on the FLCB device cost, operation, maintenance, and BAU rollout plans amongst other topics. Various engagement activities were performed via surveys, customer working groups, webinars, and external events, and mailing lists.

An online survey was created and distributed to 780 DG stakeholders, in order to obtain stakeholder views on Fault Level Constraints. A second survey, the Powerful-CB survey, was circulated via internal and external mailing lists and social media, to assess customer interest in and understanding of the project, the technology, and the trial.

A customer working group was held in September 2017, with seven stakeholders from various backgrounds. They were presented with information on: previous tried-and-tested fault level limiting technologies; how the UK Power Networks 11 kV London network operates; the current mitigation solutions offered; an introduction into power electronics; and terms of reference for the group.

Webinars and external events such as the project closedown event were instrumental in developing an understanding of customer concerns and requirements for an FLCB. Attendees were engaged via a poll, a question-and-answer session, and a feedback form. More information on this event can be found within SDRC 9.4.1.

4.4 Workstream 4 – Knowledge Dissemination

The objectives of WS4 were to disseminate knowledge to our key stakeholders, such as:

- Internal stakeholders – Major Connections teams, Distribution Planners, Service Development team.
- External stakeholders – customers, regulators, other utilities, other manufacturers, consultants, developers, engineers, and academia.

Knowledge dissemination and learning are critical aspects of the project and capturing these aimed to ensure that DNOs across GB can build on Powerful-CB learnings, avoiding unnecessary duplication of work. Key learning reports, PPRs, and SDRCs were published on the UK Power Networks innovation website.

Multiple knowledge dissemination activities were successfully held during the project, such as presentations to operational staff and external events and conferences, a paper publication, one internal and three external webinars, and an external closedown event with ABB. Internal stakeholder engagement activities were also prioritised as they play an important role in guiding the development and deployment of the new FLCB within the business and support the successful transition into BAU.

The final knowledge dissemination activity, the project closedown event, was held in August 2022. Project process and achievements were shared during this event, and attendees were encouraged to provide feedback and ask any questions to the project team.

5. Required Modifications to The Planned Approach

This section lists the changes to the planned approach which were required for the project to progress.

5.1 Summary of Changes during 2019

During the January – June 2019 reporting period, the following notable changes were made to the project plan.

For WS1 the prototype development progressed as per plan, the device prototype was developed and assembled in time for the scheduled type test. However, risks R4 (referring to delay in prototype development) and R41 (relating more specifically to the delays in type testing and/or FAT) materialised and impacted the programme.

- The high-power test laboratory in Ratingen, Germany had a fault with the generator used for high power tests and as a result three of the five type tests could not be completed. ABB were informed of this fault one day before the scheduled test dates;
- The number of accredited high power test laboratories was limited and as such, the lead-times for booking were long – the slot for Powerful-CB was booked four months in advance. In addition to long lead-times, the costs to book a test laboratory were high so booking multiple laboratories was not practical;

- To minimise the impact on the delivery of the FLCB to site, the project team worked with representatives of the laboratory in Ratingen to find an alternate laboratory to complete the remaining type tests. The type tests were conducted at KEMA in the Netherlands in May 2019. Although the delay was minimised as much as possible, a two month delay in type testing occurred; and
- Failure of internal arc testing affected the readiness of the FLCB and hence the delivery to site was delayed until November 2019.

For WS2, the project team identified in the January – June 2019 reporting period that delivery of the electrical design of substation and resourcing for the electrical site works was open to risks R40 (Delay in completion of electrical design) and R17 (UK Power Networks not able to deliver on commitments because other teams supporting the project are under-resourced) respectively. These risks were mitigated by working closely with capital delivery teams and the works were subsequently rescheduled from January to mid-May for the electrical design works. However, the following events resulted in a further delay to the start of the trial:

- The increased time and effort required for the completion of the site electrical design;
- The capital delivery team requested an increased time period for the test and commissioning of the site due to the increased complexity of the scheme. This time increased beyond the initial agreement during concept design.

During the July – December 2019 reporting period, the following notable changes were made to the project plan:

- For WS1, the completion of the FLCB and readiness to be shipped to site was delayed due to the failed IAC test in the previous reporting period. ABB had to modify the panel and completed a re-test in July. This was linked to risk R41 (Delay in testing and/or FAT of FLCB device) and resulted in approximately a further two month delay in completion of type testing. The FLCB was delivered to site in November 2019, however a combination of both these issues resulted in a delay of four months against the plan;
- For the busbar extension works, risk R17 (UK Power Networks not able to deliver on commitments because other teams supporting the project are under-resourced) materialised as the specialist resource was required to work at alternative sites on both network projects and network faults. In order to recover some of the delay in completion it was agreed by the project team for some overtime work to be completed.

5.2 Summary of Changes During 2020

During 2020, the project received Ofgem approval to formally remove M2 (and the associated budget) from the project scope by issuing an amended Project Direction. The removal of M2 from the project was caused by the M2 project partner being unable to sign a collaboration contract which aligned with the NIC Governance.

In terms of delays, firstly the UK Government COVID-19 restrictions began in March 2020. Due to this, it was predicted that all future planned activities and deliverables for the project would be delayed by four months, including the project completion date. Ofgem was then formally notified with a non-material change letter on 8 July 2020 detailing the impact of COVID-19 on project progress. As a result, all remaining SDRC delivery dates were delayed by four months and the project completion date was delayed by five months compared to the Project Direction.

Energisation of the FLCB was delayed from the end of December 2019 and planned for the beginning of August 2020 due to a number of issues including: Risk R42 (delay in energisation due to defect identified in the retrofit ABB circuit breaker – type VOR-M) which materialised during 2019; changes to the FLCB power supplies; and a number of protection logic changes to address additional issues that were identified in December 2019.

5.3 Summary of Changes During 2021

Following the network faults experienced and the valuable insights they produced, the project team decided to extend the trial end date, and therefore the project completion date, in order to maximise learnings and continue to build confidence in the performance of the FLCB. Due to the high levels of reliability on the network and the fact that network faults occur infrequently, the project team wished to extend the trial to increase the number of faults experienced.

Ofgem were notified of this extension via another non-material change request in July 2021. As a result, delivery of SDRCs 9.2.3 and 9.4.1 were also delayed by seven months.

6. Performance Compared to the Original Project Aims and Objectives

The project satisfied all its original aims and objectives as listed in the FSP, aside from aims related to M2 which were removed .

6.1 Project Aims and Objectives

The details of how the project performed relative to its overall aims and objectives are displayed in Table 3.

Table 3: Aims and Objectives

Aim	Objective	Evidence	Status
Work with industry to advance new Fault Level Mitigation Technology based on FLCB technology.	Deliver one working M1 (ABB) prototype to the M1 trial site. Develop preliminary safety cases for the M1 FLCB.	A working M1 prototype was successfully developed during this project and delivered to the trial site. Its development is recorded within SDRC 9.1.1. Preliminary safety cases were developed – SDRC 9.1.3-4.	Achieved

Aim	Objective	Evidence	Status
Trial the technical suitability of the M1 technology including effectiveness and safety considerations for relieving fault level constraints for 11kV networks.	Install and commission the FLCB at the trial site. Collect adequate data to prove that the FLCB is safe and effective. Update the preliminary safety case to consider data and learning from the field trials	The FLCB was successfully installed and commissioned at the trial site, as recorded within SDRC 9.2.1. The FLCB was trialled under three running arrangements. Data was gathered and FLCB health monitored during each trial. SDRC 9.2.3 contains a record of the FLCB technical performance, results, and learning obtained from the trial. During the January – August 2022 reporting period, the Safety Case report was updated to incorporate learnings from the FLCB trial. The trial indicated that the M1 technology was suitable for the intended purpose.	Achieved
Share the learning throughout the project with the wider utility industry.	Disseminate knowledge to key internal and external stakeholders.	Knowledge dissemination activities were successfully held with internal and external stakeholders. SDRC 9.4.1 was published.	Achieved

Aim	Objective	Evidence	Status
Assess the suitability of the solutions against customers' needs.	Understand our customers' needs. Ensure that we design the solutions to meet our customers' needs.	Customers and other stakeholders were engaged at a number of external events, through social media, mailing lists, online survey, and the launch of a project customer working group. Customers' opinions on the benefits of this project and their concerns were identified. SDRC 9.3.1 was published. The "Learning report – Suitability of FLCBs" SDRC was removed from this project due to its reliance on M2. See section 2.2 for more information on the removal of M2.	Achieved

6.2 Project Successful Delivery Reward Criteria

The project successfully delivered all SDRC commitments outlined in the bid submission to a high quality and on time, as per the final Project Direction. They are shown in Table 4.

Table 4: Timeliness of SDRCs

SDRC Number	SDRC Title	Timeliness
SDRC 9.1.1	Development of a Fault limiting Circuit Breaker for Substations	As per Direction
SDRC 9.1.3-4	Preliminary Safety Case	As per Direction

SDRC Number	SDRC Title	Timeliness
SDRC 9.2.1	Install and Commission Solution at an 11kV Substation	As per revised delivery date
SDRC 9.2.3	Demonstration of Solution at an 11 kV Substation	As per revised delivery date
SDRC 9.3.1	Understanding Customers' Requirements	As per Direction
SDRC 9.4.1	Share Overall Learning from the Project via a Stakeholder Event	As per revised delivery date

7. Significant Variance in Expected Costs

The budget for the project is based on the financial information provided at bid submission in the "Full submission financial spreadsheet". It was used to inform the budget and create the position of all costs as described in the budget section of the amended Project Direction following the removal of Method 2 (M2) and associated budget from the project. The table below presents the view of the actual spend against the amended bid budgeted spend to the end of the project. Commentary is provided to supplement the budget overview table and explain any variances.

Table 5 Budget Overview

Cost Category	Total Project Budget (£)	Actual Expenditure (£)	Variance (£)	Variance (%)
Labour	469,500	469,500	0	73%*
Equipment	973,787	866,514	-107,272	-11%
Contractors	1,902,834	1,653,258	-249,576	-13%
Travel & Expenses	65,200	28,287	-36,913	-57%
Payments to Users	0	0	0	0%
Contingency	370,759	341,146	-29,612	-8%
Decommissioning	77,419	61,911	-15,509	-20%
Total	**3,859,499**	**3,420,616**	**-438,883**	**-11%**

*The actual spend to August 2022 on labour was £810,646 (£469,500 from labour line and £341,146 from contingency line) giving a variance of 73% compared to budget

- The project overspent on Labour costs by 73% when compared to the project plan and is attributed to:
  - Increased effort to complete the design for integration of the FLCB into the trial substation;
  - Additional effort following the need to carry out a second internal arc type test;
  - The busbar extension of the existing switchgear taking longer than estimated due to the highly skilled expertise required that was labour intensive and needed much hand crafted work;
  - Additional time needed to complete commissioning, including multiple visits from ABB to rectify issues highlighted in the main report for the previous reporting periods; and
  - Additional project management and project support not originally budgeted for in the FSP due to the second internal type test, delay in site works completion, managing COVID-19 delays which delayed energisation and the decision to extend the project trial to gather additional performance data.
- The project underspent on Equipment by 11% due to efficiencies in the installation works and development of the unit
- The project underspent on Contractors by 13% due to the savings from project efficiencies made for trial site preparation including civil works, steelworks, small power and lighting
- The project underspent on Travel & Expenses by 57%, mainly due to savings highlighted in the project progress reports such as:
  - Holding customer sessions as part of BAU events;
  - The external event we hosted being cheaper than budgeted;
  - Lower spend for Low Carbon and Network Innovation (LCNI) events;
  - Lower spends for Energy Networks Innovation Conference (ENIC) being held virtually due to COVID-19;
  - The ABB presentation with internal stakeholders being hosted as a webinar than in person;
  - The external presentations being held as two webinars rather than in person; and
  - Minimising travel where possible.
- The Payments to Users costs were no longer included in the amended Project Direction following the removal of M2 from the project.
- The project underspent by 20% on Decommissioning costs due to efficiencies in the decommissioning process
- This project utilised additional costs of £341,146 related to labour overspends as noted in Table 5 and the labour costs spend justification expenditure

Overall, the project has delivered all of the key objectives and outputs whilst underspending by 11%. This underspend can be attributed to reduced Equipment, Contractor costs, Travel & Expenses and decommissioning costs.

8. Updated Business Case and Lessons Learnt for the Method

8.1 Business Case Update

Multiple learnings were generated during the trial of the FLCB device in UK Power Networks' Glaucus Street site. At the same time a number of assumptions that were included in the initial Business Case have been updated due to the shifts in the decarbonisation path in both local and national level. All the updates in the assumptions, financial benefits and increase in the DG connections are presented in the subsequent sections.

8.1.1 Updated Assumptions

All the assumptions and data utilised for the Business Case update are shared below:

- Data from the Future Energy Scenarios (FES) published by National Grid in 2022 have been used to identify the number of synchronous generation technologies (Biomass, Biomass CHP, hydro, marine, waste, waste CHP, CCGT, Gas CHP, Gas Reciprocating Engines, OCGT, Hydrogen, Hydrogen CHP, Diesel, Fuel Oil) expected in the GB network for the next decades up to 2050. There are four different scenarios related to the speed of decarbonisation:
    - Consumer Transformation
    - Leading the Way
    - System Transformation
    - Falling Short (referred to as Steady Progression by UK Power Networks).

  It was noticed that the number of synchronous generators especially CHPs decreased compared to the figures available at the time and included in the FSP.
- The Network Development Plans were acquired from all the DNOs' websites in order to get the number of constrained sites in each licence area for up to 2050.
- The Long Term Development Statements were acquired from all the DNOs' websites in order to obtain the most up to date fault level constrained sites in each area for the next five years. Any sites with planned solutions were excluded from the Business Case calculations.
- The initial Business Case generated a fault level forecast up to 2050 based on each DNOs' LTDS and the 2016 FES data. As the 2016 scenarios included increasing volumes of synchronous generation (much more than what is included in 2022 forecasts), the resulting fault level forecast showed a very large number of fault constrained substations across GB. The 2022 FES data includes a higher amount of synchronous generation being disconnected and lower added volumes than before. Thus, the overall number of fault level substations included in the CBA update (Table 6) is lower than the initial assumption.

Table 6 Percentage of fault level substations compared to the overall number of substations in GB

Consumer Transformation				Leading the Way				System Transformation				Steady Progression			
2028	**2030**	**2040**	**2050**	**2028**	**2030**	**2040**	**2050**	**2028**	**2030**	**2040**	**2050**	**2028**	**2030**	**2040**	**2050**
2.2%	2.8%	4.0%	4.4%	2.5%	3.0%	4.3%	4.7%	2.4%	2.9%	4.1%	4.4%	2.3%	2.9%	3.9%	4.3%

- Initially it was assumed that the FLCB could be applicable to any 11 kV site with fault level issues. However, the trial highlighted that the FLCB is best applied to sites with:
    - A two transformer layout;

    - A three transformer layout; and
    - A four transformer layout that operate with a closed bus coupler.

  In these sites, the addition of the FLCB reduces the fault current that the whole system is likely to experience and can support the connection of more generation without having to reinforce the network. UK Power Networks operate their four transformer sites open, thus these sites are excluded from the calculation. For the sites of other DNOs, there is no information on their site operational strategies, thus the total number of fault level constrained sites were included in the CBA.
- Fault level constrained sites from all UK Power Networks licence areas (LPN, EPN & SPN) were included in the CBA update compared to the initial assumption which was based only on LPN sites. The reason for the change is that the major deployment of generation is expected to take place in the EPN and SPN areas. Also, initially the main driver for the project was to support the deployment of CHPs in the network especially in the LPN licence area. However, the CHP installation rate has decreased significantly due to the shift in the national decarbonisation strategies and the LPN area is projected to see less FLCB installations compared to the other licence areas.

8.1.2 Financial benefits

The financial benefits expected in the UK Power Networks licence areas as well as in GB are presented in the table below. The average benefits across the four FES scenarios in UK Power Networks by 2050 is £24.21m while the respective figure for GB is £224.17m. As illustrated below, the overall benefits have decreased compared to the FSP figures due to the reduced number of fault level constrained substations (see section 8.1.1) in UK Power Networks and GB as well as the changes in the FES scenarios compared to the FSP in 2016.

Table 7 Cumulative discounted net benefits for UK Power Networks and GB

DNO	FES Scenario	Benefit			
		2028	2030	2040	2050
UK Power Networks	Customer Transformation	£ 9.70m	£ 11.87m	£ 19.26m	£ 23.61m
	Leading the Way	£ 10.35m	£ 12.18m	£ 19.54m	£ 24.25m
	System Transformation	£ 10.35m	£ 12.63m	£ 20.45m	£ 25.05m
	Steady Progression	£ 9.70m	£ 12.32m	£ 19.62m	£ 23.94m
GB	Customer Transformation	£ 67.67m	£ 91.83m	£ 179.54m	£ 218.32m
	Leading the Way	£ 75.15m	£ 99.46m	£ 194.45m	£ 235.26m
	System Transformation	£ 72.79m	£ 97.03m	£ 187.63m	£ 226.03m
	Steady Progression	£ 71.49m	£ 95.40m	£ 180.30m	£ 217.06m

8.1.3 DG Capacity Released

The average cumulative enabled capacity across GB distribution networks by 2050 is 10.73MW (Table 8). This takes into consideration an average of the best and worst case of each of the four FES scenarios.

Table 8 Cumulative enabled capacity across GB distribution networks by 2050

	Consumer Transformation	Leading the Way	System Transformation	Steady Progression

Best Case	-2.65MW	29.27MW	3.19MW	4.27MW
Worst Case	-4.03MW	44.46MW	4.86MW	6.50MW

The overall capacity released is lower than the initial CBA due to updates in the FES scenarios where high carbon intensity synchronous generation technologies are expected to be removed in the next years whilst low carbon synchronous generations are expected to be added.

In the best-case scenario, it is assumed that the additional generation to be connected to the 11 kV network is spread equally across all GB substations.

The worst-case scenario is defined as the scenario in which future generation connection requests occur at those substations that have the least headroom available. A UK Power Networks analysis of the distributed generation database found that substations constrained due to fault levels were 1.6 times more likely to receive a connection request when compared to unconstrained substations. This likelihood has been assumed to be true for all DNOs. The released capacity in this scenario follows this likelihood. Note that in the Consumer Transformation scenario, more synchronous generation will be removed than added, leading to a negative enabled capacity. Overall, the capacity benefits are the highest in the Leading the Way scenario because this sees the highest uptake of renewables.

8.2 Lessons Learnt from Method

The project has produced an extensive set of learnings which are discussed in the below subsections.

8.2.1 Safety Case Processes and Principles

Two key lessons were learnt whilst producing this document:

- **Ensure the terminology and risk thresholds align with those in the DNOs' safety management system** – safety cases in other industries use terminology and risk thresholds that may be unfamiliar to DNOs.
- **Ensure sufficient focus on lower-impact, higher-probability risks**, such as unplanned power cuts, which can have indirect safety consequences – safety cases in other industries tend to focus on high impact, low probability risks such as fatalities.

8.2.2 Safety Considerations for Operation and Maintenance

During the FLCB development stage, additional safety considerations for operation and maintenance were made which resulted in further design requirements. The solutions to the problems were relatively simple however it was important these were identified during the development phase of the FLCB rather than once the device was on site.

The observation and incorporation of these additional considerations was enabled by regular internal technical stakeholder engagement undertaken by the project team and regular meetings between ABB and the project team. Further information on the safety considerations observed can be found in the January – June 2019 PPR.

8.2.3 Delivery Planning

On 15 October 2019 an attempt was made to deliver the FLCB on site. This was unsuccessful as the road to access the substation was narrow, and parked vehicles prevented the lorry entering the site. The parking suspension requirements were not communicated from ABB UK to the delivery company and as such the delivery had to be rescheduled for 5 November 2019. This communication problem occurred due to the number of parties involved in the delivery and assumptions made on who was responsible for organising parking suspensions. Even though ABB UK had visited and surveyed the site, parking suspension was not requested when communicating specific needs to the delivery company.

To address this risk in the future, early engagement with the supplier to discuss any delivery and logistics requirements should be undertaken.

8.2.4 Consider rare switching scenarios

The switching steps required for energisation were not explicitly considered while defining the committed behaviour of the FLCB relay, which was resolved via an ad-hoc solution on site. The lesson learnt is to consider rare switching scenarios, such as those required for commissioning, in the requirements so that the manufacturer can provide this functionality in a well-controlled manner.

8.2.5 Interlock Issues with Existing Equipment

One of the safety features of the FLCB is an interlock mechanism to allow or block the opening of the cabinet doors. The mechanism allows the doors to open only if the adjacent circuit breakers in the earthed position, which is defined by transmitting a “status: earthed” signal. For the Powerful-CB trial, the existing switchgear did not have the ability to send this signal. Additionally, earthing for the cable part needed to be applied manually. For the trial the project team used the “status: open” signal and applied manual earth before opening the cabinet doors.

For future applications the ability of switchgear to provide “earthed” signal should be confirmed and an agreed approach if this capability is absent. However, as mentioned in SDRC 9.1.1, if a commercial FLCB is produced, the requirement is that the device must have integral isolating/earthing facilities.

8.2.6 Need for an Auto-close Scheme

During development, when studying all possible fault scenarios at the trial substation, a specific scenario was identified which would result in a “dead” busbar. This was caused by the high speed of the FLCB which introduced complications with the conventional protection grading of the equipment. The issue could be resolved by a control engineer, but in order to have an automated and quick resolution of such a scenario, an auto-close scheme was installed which re-energised the busbar in the case of the specific fault.

This lesson will be useful in the development of the engineering design standards and is dependent on the configuration of the substation.

8.2.7 Signal List Decisions

The number and type of interface signals between the FLCB and the control centre, was not defined at the start of the project. The project requested a larger number of signals transmitted through copper cables in accordance with UK Power Networks’ standards instead of Ethernet. This was not possible due to the limited number of relay contacts available on the device and so a number of indications were grouped onto one signal for the trial.

For future projects, signal outputs and channels of transmission should be considered during the initial production of device specifications in order to avoid late design changes. Alternatively, the standard use of optical fibre communication channels could be explored further within UK Power Networks.

8.2.8 Increased FCS Switching Speed

During the first half of 2021, a deviating trend was observed for switch three in the L3 phase: the opening time became faster whereas the closing time for the same switch became slower. The switch was consequently replaced during ABB's maintenance visit in September 2021 and shipped back to ABB facilities for testing.

This event highlighted the importance of supervising the various components of the FLCB to provide an early indication of possible deterioration. This way, an inspection could be initiated in advance of any serious malfunction of the device.

8.2.9 Alarm duration for Remote Terminal Unit

When testing the tripping of the FLCB, the SCADA system could not detect 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 operated; 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, GE, the manufacturer of the Remote Terminal Unit (RTU), developed an update for the SCADA to enable short duration fleeting alarms to be displayed. The update allowed the HMI to display alarms greater than 30ms and this was deployed to the RTU during the commissioning visit in February 2020.

The valuable lesson learnt for wider rollout of the FLCB is the requirement to check the RTU is capable of displaying short duration fleeting alarms.

8.2.10 Incorrect Power-Down Procedure

Whilst UK Power Networks staff were carrying out routine maintenance in September 2021, it was noted that the FLCB had been incorrectly powered down. Incorrect powering down could result in electrical shock to operators due to the UPS configuration that was retrofitted to the design.

Figure 21: Control System Power Supply MCB Locked in the 'On' Position, with Cover and Labelling Applied

There are identified mitigations to this risk i.e. the nominal current arc would be contained and dissipated within the high voltage FLCB panel mitigating risk to personnel. Also, the device had been tested to IEC 62271-200 for internal arc rating 25 kA for 1 s and 16 kA for 3 s.

To prevent future reoccurrence, the Miniature Circuit Breaker (MCB) on the control systems 24 V power supply was locked into the 'on' position, as this configuration was analysed with no safety concerns raised. Additionally, a label was placed next to the MCB detailing the correct shutdown procedure, and lockable handles were fitted to the LV doors. The label and lock are shown in Figure 21.

8.2.11 FLCB Control Software Design

A hardware issue was discovered in the optical modules used in the FLCB control system. During power-up, the optical transmitters sent a short pulse of light. For the FLCB, this is a severe problem as an uncontrolled restart of the control system would cause these unintended light pulses. If the FCS drives are still powered, these pulses may cause unintended opening of the mechanical switches. This issue was detected too late in the development to be rectified by the manufacturer; however a mitigation plan was put in place with the use of a UPS.

For future projects an updated version of the optical modules should be used.

8.2.12 Physical Distance & COVID-19

The physical distance between ABB (Västerås, Sweden, and Ratingen, Germany) and the installation site (London, UK) proved a barrier, as it made site visits for update and inspection of the equipment more difficult. This put high demand on thorough testing prior to implementation. Although this was known in advance, and managed accordingly, the COVID-19 pandemic resulted in additional restrictions which made it impossible to visit the site.

If there had been a possibility to visit the site earlier during the trial (after energisation), some minor updates would have been performed on the supervision unit to maximise the data collection at site and future projects should plan for these early installation issue resolution trips.

8.2.13 Fault Recorder Data

In the trial installation the following fault recorders were available: the supervision unit within the FLCB, two external fault recorders, and the FLCB REF relay. Several challenges were observed regarding the retrieval of data from these devices. The FLCB REF relay was mainly installed to simplify the communication between the control system of the substation and the dedicated controls of the FLCB. The data was stored in the REF at each event and similarly for the external fault recorders but needed to be downloaded manually on site by UK Power Networks' staff. In addition, the standard UK Power Networks' fault recorders installed for the adjacent breakers were from another manufacturer. There was no software easily available to interpret the downloaded data. This was solved during the trials but created additional difficulties that could, most likely, have been avoided.

If the functionality and selection of fault recorders had been more closely considered during the planning phase of the project, the retrieval and interpretation of the data would likely have been more efficient.

8.2.14 UPS Fault Issue

An alarm incident on the REF620 relay took place near the end of June 2022 when there was an indication of 'CB Supply Faulty'. Figure 22 shows the UPS fault alarm. Although the FLCB was still operating, an investigation was initiated which identified that the UPS acting as back-up power for the control system in the phase L2 reported an error. This error was only reported to the REF620 relay and did not affect the control system or supervision unit.

Figure 22: UPS Fault Alarm Indication in Phase L2

It was concluded that the issue was related to the battery status of the UPS, which would subsequently be unable to provide the requested back-up power in the event of any problem with the primary supply. As the faulty UPS would have required repair before the FLCB trial could continue and the start of decommissioning was imminent (July 2022), the FLCB was taken out of service.

9. Lessons Learnt for Future Innovation Projects

In addition to the lessons learnt relating to the method presented in section 8, the following project learnings could be used as guidelines for future innovation projects.

9.1.1 Finalise Contractual Agreements Prior to Starting the Project

The M2 method was removed because AMAT, the M2 project partner, was unable to sign the contract that aligned with the NIC Governance. This affected the production of two deliverables, and prevented the creation of three other deliverables.

Therefore, it is important to finalise any contractual arrangements with contract partners before the start of the project, to reduce the risk of major changes.

9.1.2 Fully Define Requirements Early in the Project

There were various technical requirements on the FLCB device which emerged during the installation and trial phases, these are outlined in section 8.2. Although the team successfully adapted the FLCB to accommodate these requirements, it is advised to define requirements, including those for spatial, interface, monitoring and commissioning as early as possible.

9.1.3 Critical Resource – Early Engagement

An important lesson learnt during the design phase was the type of resource required for innovation projects. Due to the nature of innovation projects, the site designers need to be flexible, creative, and capable of developing solutions out with existing standards and guidelines, as well as the ability to break down problems in a systematic manner. Such engineers are critical resources and are generally earmarked for high priority BAU projects. It is vital for any innovation team to engage early with the relevant teams and secure the necessary skilled resources for these complex, non-standard projects.

Similarly, a valuable lesson learnt was to secure critical, scarce resources for construction. This was especially relevant when working in old substations where there are limited skilled internal and external resources to carry out the work. These internal resources are also used in many network reinforcement projects which can at times take precedence over innovation projects. The project team worked closely with internal capital delivery teams to explore options and mitigate the associated risk of delay in installation works due to resource availability.

9.1.4 Standards to Design and Test Against

When developing a new concept/product, it is usually a challenge to define the relevant verification tests required. This is especially clear when introducing new functionalities. The FLCB is, in many aspects, a circuit breaker but since it also introduces the possibility of fault current limitation, parts of the standard for circuit breakers do not apply.

To mitigate this, there were continuous discussions throughout the project to define what type of testing that would be applicable, both to demonstrate the new functionality and secure safe operation in the network. These discussions required participation from the following teams: Project Team, Network Operations (Control, Outage Planning), Asset Management (Standards), and Health Safety and Sustainability.

These broad stakeholder discussions and engagement are recommended for projects where a new concept/product is being developed.

9.1.5 Connection to aged Switchgear

The project identified trial arrangement RA3 which saw the FLCB operated as a bus coupler 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 failed to operate. The busbar at Glaucus St was of considerable age and meant it was challenging to find materials for the expansion. There were 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.

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

10. Project Replication

This project aimed to develop and trial a new FLCB that was significantly smaller and more efficient than any similar device currently in use. Successful demonstration of this FLCB would facilitate quicker and cheaper connection of DG, including CHP units. High-speed protection could allow hundreds of megawatts of low-carbon electricity sources to connect to the electricity network safely and cheaply.

The methodology followed during this project is available within the PPRs (see Table 11) and is summarised within section 3 of this document.

A list of the key lessons learnt over the course of the project have been included in sections 8.2 and 9 of this report. More information on lessons learnt can be found within each SDRC.

10.1 Project Teams

In order for any other licensed network to replicate this project, a similar undertaking would require engagement with the equivalent of the following teams:

- UK Power Networks' project team to manage the project as detailed in section 3.1.2
- UK Power Networks' internal teams to form detailed requirements, support project development and any required works on site:
    - Networking planning
    - Technical Sourcing and Standards
    - Network Operations and Maintenance
    - Health and Safety
    - Procurement
    - Legal

- External technical partner that can develop the electrical device and technically support the project throughout its lifecycle

10.2 Physical Considerations

In order to develop a similar FLCB, use of the following would be required: a test laboratory for verification tests, validation tests, type tests, and FAT, equipment and resource for installation and commissioning activities and data logging and processing. If the FLCB from this project was to be reused, further laboratory testing may not be necessary.

A similar project would also require commissioning checklists and test reports. SDRC 9.2.1 provides the commissioning checklists used for this project, and could be used as a basis for future projects. The UK Power Networks Component Checklist can be found within Appendix B, and the ABB Commissioning Report within Appendix A of this SDRC.

The FLCB is a switchgear made up of three panels, it has a particularly large footprint therefore consideration must be made for its space requirement within the customer substation. For this project, additional footprint was required for the UPS, data recording equipment and an expansion to the substation control and monitoring system in order to incorporate new equipment related to this project. For this project, on-site data logging was used.

10.3 Intellectual Property Rights

Information regarding the Intellectual Property (IP) generated during this project can be found within the PPRs (Table 11) and is detailed within Appendix A of this report. The project conformed to the default intellectual property rights (IPR) arrangements set out in Chapter 9 of the Electricity NIC Governance Document. The project conformed to LCNF IPR requirements, and this has been formalised via the collaboration agreement between all partners that reflects acceptance of these arrangements in full.

IP generated during this project can be found on the UK Power Networks website, or can be requested via email.

11. Planned Implementation

The Powerful-CB project developed a FLCB device which was eventually trialled in UK Power Networks site in Glaucus Street. The successful trial generated a large amount of learnings and gained confidence in its operation as a BAU unit. These learnings were shared with the network planning teams within UK Power Networks as well as stakeholders inside and outside the business who were interested through the project dissemination activities.

As per the project scope, the pilot was decommissioned, and the project team engaged with the UK Power Networks network planning teams to identify any sites with fault level issues where the FLCB could be relocated. A feasibility study was undertaken against substations listed as fault level constrained sites. It was concluded that out of all the sites only one is an appropriate candidate for the installation of the pilot. However, there is currently no customer connection request for the site in order to trigger any works to resolve any fault level issues. However, the pilot will be considered as one of the potential solutions when a connection request is received. With regards to the remainder of the constrained substations, they were not considered for the relocation of the pilot for the following reasons:

- There was not enough space within the substations to accommodate the installation of the unit. The pilot unit is large and also requires two conventional circuit breakers, one on each side of the FLCB, in order to offer isolation, earthing and testing facilities.
- The FLCB device is suitable for sites that operate with the bus coupler closed. Most of UK Power Networks' sites with four transformer arrangement operate open which means that the bus coupler is open during normal operation and closes when there is an outage and the remaining transformed need to share the load evenly. Due to this operational strategy only sites with two and three transformer layout were considered.

As part of the future deployment of the FLCB in UK Power Networks' network, the FLCB unit will be considered as a one of the solutions available to customers for fault level constrained sites. That means that when there is a need to resolve fault level issues in constrained sites, the FLCB will be one of the options that will be considered.

To disseminate the knowledge with the rest of the industry, two events took place as part of the project closedown activities:

- A webinar on 18 August 2022 to share the project learnings and findings with anyone interested in the project (more information can be found on SDRC 9.4.1); and
- An online session with DNOs on 20 October 2022 to discuss the benefits that the unit can offer in fault level constrained substations and support its future deployment in Great Britain.

As mentioned above, two of the main barriers for implementation are the spatial requirements of the units as well as the need for the adjacent circuit breakers. This information has been fed back to ABB, the supplier that designed and manufactured the device. The aspiration for any business-as-usual commercial units is to be smaller and deployable without any conventional circuit breakers. ABB's plan for major deployment of the unit is currently under consideration and depends on the interest that will be shown by network operators over the next period. In the case that an updated commercial model is provided by ABB, then UK Power Networks would have to review the internal standards of the device as well as revisit the Safety Case developed as part of Powerful-CB project.

12. Learning Dissemination

Learning dissemination was performed throughout the project. This section outlines the methods which were used.

12.1 Learning Dissemination Mechanisms

The PPRs and SDRCs produced during this project are available publicly on UK Power Networks website, in addition to material from presentations and briefings which can be seen on the table below.

Table 9: Learning Dissemination Mechanisms

Mechanism	Number
Project website	1
PPRs	11
SDRC reports	7
FLCB Technical Standards	2
Press Release	1
Closedown Event	1
Partner dissemination events	2
Conferences, forum, industry briefings and presentations	13
Total	38

12.2 Industry Recognition and Awards

We received two awards over the course of this project:

- "Energy Tech – Innovation" award at the 2021 Better Society Energy Awards
- "Electrify our world Award – first in innovation" internal ABB award made quarterly by the ELDS (Electrification – Distribution Solutions) Business Division. These awards aim to highlight exceptional examples of projects that embody “First for Customers”; “First for Innovation” and “First in Digital”.

We were also shortlisted for the “Energy Tech – Innovation” award at the 2022 Better Society Energy Awards

12.3 Learning events

A closedown event was held in August 2022 via webinar, to present learning from this project to customers, regulators, other DNOs, other manufacturers, and academia. Key materials from this webinar can be found in

SDRC 9.4.1 and the presentation slides can be found here. Other presentations were held throughout the project, such as our presentation during the LCNI 'Transition to a Low Carbon Future' session in 2019. These learning events are covered in more detail within section 3.6.

13. Key Project Learning Documents

The main documents produced during this project can be found on the project website. This section provides links to the project SDRCs and PPRs.

13.1 SDRCs

Table 10 contains a list of the SDRCs produced during this project, along with their publication dates and a description of their contents.

Table 10: List of SDRCs

Title	Publication Date	Content
SDRC 9.1.1 Prototype and lab test a substation-based solution (Method 1)	31 May 2019	Learning Report – Development of an FLCB for substations, including: recommendations for specifying a substation-based FLCB; results and learning from type tests (including a short circuit test) conducted at an accredited high power laboratory; and requirements for integrating FLCBs into existing networks and ensuring safety.
SDRC 9.1.3 Independent review of safety case	31 May 2018	Preliminary safety case to relevant ENA panel(s) for independent review, including: definition and justification of acceptable levels of risk; analysis of failure modes and effects; details of proposed mitigations; and claims, arguments, and evidence to demonstrate that the proposed mitigations reduce the overall level of risk to an acceptably low level.

Title	Publication Date	Content
SDRC 9.1.4 Safety case for FLCB installation without back-up	31 May 2018	Preliminary safety case including the technological and operational safety case for when the trial equipment could be deployed as BAU without the FLCBs being installed in series with a back-up circuit breaker.
SDRC 9.2.1 Install and commission solution at an 11kV substation (Method 1)	30 November 2020	Interim Learning Report – Demonstration of an FLCB for substations, including results and learning from installation, commissioning, and operation to date of an FLCB at a substation.
SDRC 9.2.3 Demonstration of solution at an 11kV substation (Method 1)	30 June 2022	Final Learning Report – Demonstration of an FLCB for substations, including, results and learning from operating and maintaining a substation containing an FLCB, and technical performance of the FLCB and overall solution under real network conditions.
SDRC 9.3.1 Review the customer needs for these two FLCBs technologies on behalf of DNOs and DG stakeholders	31 October 2017	Learning report – Understanding customers' requirements, including description of the findings from customer dialogue sessions, i.e. understanding their requirements and concerns about FLCBs, and customer feedback.
SDRC 9.4.1 Share overall learning from the project with customers, regulators, other DNOs, other manufacturers, and academia via a stakeholder event	31 August 2022	Key materials from the stakeholder event (e.g. slides), and a list of invitees and attendees.

13.2 Project Progress Reports

Table 11 lists the PPRs submitted to Ofgem. During the project, PPRs were submitted twice per year. These reports tracked the overall project progress as well as project progress for individual Workstreams, discussed deliverables and learning & dissemination activities performed, as well as, identifying risks, issues, and mitigation measures.

Table 11: List of PPRs

Project Progress Report Hyperlinks			
June 2017	**December 2017**	**June 2018**	**December 2018**
June 2019	**December 2019**	**June 2020**	**December 2020**
June 2021	**December 2021**	**August 2022**	

14. Data Access Details

Information on how network or consumption data gathered during the course of this project can be requested, please see the UK Power Networks Data Sharing Policy available on our website.

15. Contact Details

Details of the project and its learnings can be found on the Powerful-CB website.

For further questions on this report or more general questions about the project, please contact the Powerful-CB team or Innovation Team via email on the following addresses:

Email Address: powerful-cb@ukpowernetworks.co.uk; innovationteam@ukpowernetworks.co.uk

Postal Address: Newington House, 237 Southwark Bridge Road, London, SE1 6NP.

Appendix A Intellectual Property Rights

The following table is a summary of the project IPR listed within each Progress Report.

Table 12: Project IPR generated

IPR Description	Owner(s)	Type	Royalties	Year
Safety case process & principles document	UK Power Networks / Frazer-Nash Consultancy	Relevant Foreground IPR	Nil	2017
FLCB technical specification document	UK Power Networks	Relevant Foreground IPR	Nil	2017
SDRC Learning Report 9.3.1	UK Power Networks	Relevant Foreground IPR	Nil	2017
Safety Case related documents: Mitigations, Hazard assessment, Cost benefit analysis	Frazer-Nash Consultancy	Relevant Foreground IPR	Nil	2017
SDRC Learning Reports 9.1.3 and 9.1.4	UK Power Networks	Relevant Foreground IPR	Nil	2018
Testing methodology of the FLCB	ABB UK Power Networks	Relevant Foreground IPR	Nil	2019
Running arrangements for network demonstration	UK Power Networks	Relevant Foreground IPR	Nil	2019
SDRC 9.1.1 including test reports	UK Power Networks	Relevant Foreground IPR	Nil	2019
FLCB installation manual	ABB	Relevant Foreground IPR	Nil	2019
FLCB commissioning plan	ABB UK Power Networks	Relevant Foreground IPR	Nil	2019

IPR Description	Owner(s)	Type	Royalties	Year
Panel modifications to correct internal arc performance	ABB	Relevant Foreground IPR	Nil	2019
Commissioning reports	UK Power Networks	Relevant Foreground IPR	Nil	2020
FLCB and control system status snapshots (as necessary)	ABB	Relevant Foreground IPR	Nil	2020
Commissioning reports	UK Power Networks	Relevant Foreground IPR	Nil	2020
FLCB and control system status snapshots (as necessary)	ABB	Relevant Foreground IPR	Nil	2020
Data and performance of FLCB during network demonstration	ABB UK Power Networks	Relevant Foreground IPR	Nil	2020
SDRC 9.2.1 – Install and commission solution at an 11kV substation	UK Power Networks	Relevant Foreground IPR	Nil	2020
FLCB and control system status snapshots (as necessary)	ABB	Relevant Foreground IPR	Nil	2021
Data and performance of FLCB during network demonstration	ABB UK Power Networks	Relevant Foreground IPR	Nil	2021
Data and performance of FLCB during network demonstration	ABB UK Power Networks	Relevant Foreground IPR	Nil	2021
Webinar content	ABB UK Power Networks	Relevant Foreground IPR	Nil	2021

IPR Description	Owner(s)	Type	Royalties	Year
Safety case documentation	ABB UK Power Networks	Relevant Foreground IPR	Nil	2021
SDRC 9.2.3 Final Learning Report – Demonstration of a FLCB for substations	ABB UK Power Networks	Relevant Foreground IPR	Nil	2021
Data and performance of FLCB during network demonstration	ABB UK Power Networks	Relevant Foreground IPR	Nil	2022
Webinar content	ABB UK Power Networks	Relevant Foreground IPR	Nil	2022
Safety case documentation	ABB UK Power Networks Frazer-Nash Consultancy	Relevant Foreground IPR	Nil	2022
SDRC 9.2.3 Final Learning Report – Demonstration of a FLCB for substations	ABB UK Power Networks Frazer-Nash Consultancy	Relevant Foreground IPR	Nil	2022
SDRC 9.4.1 Share overall learning from the project with customers, regulators, other DNOs, other manufacturers, and academia via a stakeholder event	ABB UK Power Networks	Relevant Foreground IPR	Nil	2022
Closedown report	ABB UK Power Networks Frazer-Nash Consultancy	Relevant Foreground IPR	Nil	2022

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Appendix B Peer Review

Process and Technology/Future Networks | SP ENERGY NETWORKS

FOA: PETER PAPASOTIRIOU
Programme Manager
Newington House
237 Southwark Bridge Road,
London
SE1 6NP

Andrew Moon
Senior Innovation Engineer
SP Energy Networks
3 Prenton Way
Wirral
CH43 3ET

November 2022

Dear Peter,

Powerful CB Closedown Report - DNO Peer Review

In relation to your request for SP Energy Networks to review the Close-Down Report, produced in respect of UK Power Networks PowerFul-CB NIC funded project, I can confirm that SP Energy Networks have undertaken this review and consider that the objectives and deliverables, as agreed in the December 2019 amended Project Direction, have been satisfied by UK Power Networks.

SP Energy Networks can confirm that it considers the Close-Down Report, SDRC and progress reports to be clearly written and their contents are understandable, containing sufficient detail to enable another DNO to make use of the learning generated to implement their own network solution, as part of a Business as Usual.

Please don't hesitate, should you wish to discuss anything further or have any additional requirements that you need to address in respect of the PowerFul-CB project.

Yours faithfully,

Andrew Moon
Digitally signed by Andrew Moon
DN: cn=Andrew Moon, c=GB, o=SP Energy Networks, ou=Future Networks, email=a.moon@scottishpower.com
Date: 2022.11.09 12:28:15

Andrew Moon

Senior Innovation Engineer
SP Energy Networks