Powerful-CB

SDRC 9.1.1:

Development of a Fault limiting Circuit Breaker for Substations

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Contents

1. Executive Summary

Background and Project Motivation

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

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

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

A FLCB is a solid-state circuit breaker that operates 20 times faster than existing vacuum circuit breakers. This high-speed operation can mitigate fault level contributions from distributed generation, allowing us to connect more DG (including CHP) to fault-level constrained networks in dense urban areas. This will help accelerate the decarbonisation of heat, which is a key element of the Government’s Carbon Plan.

We have been working with technology partner, ABB, who will develop a FLCB for use at a primary substation. The project team believe this will be the world’s first demonstration of a FLCB with a fast commutating switch.

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

Fault Limiting Circuit Breaker Development Process

The device developed for the Powerful-CB trial is a hybrid FLCB device. It has a mechanical part, a power electronics part and surge arrester all in parallel as shown in Figure 1. During normal operation the current flows through the mechanical switch, and therefore has low losses. The common problem with mechanical switches is that they are too slow for the speed we need the device to operate. The mechanical switch used for the FLCB is electromagnetically driven and operates in extremely high speeds (0.35ms). When a fault is detected, the mechanical switch opens first, then the arc is transferred to the power electronics. The power electronics then break the current and the energy is released via the surge arrester.[4]

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[1] http://futuresmart.ukpowernetworks.co.uk

[2] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/275163/20140126Community_Energy_Strategy.pdf

[3] https://www.london.gov.uk/what-we-do/planning/london-plan/current-london-plan/london-plan-chapter-five-londons-response/poli-0

[4] https://innovation.ukpowernetworks.co.uk/wp-content/uploads/2019/01/Powerful-CB_paper_CIRED2019_Final.pdf

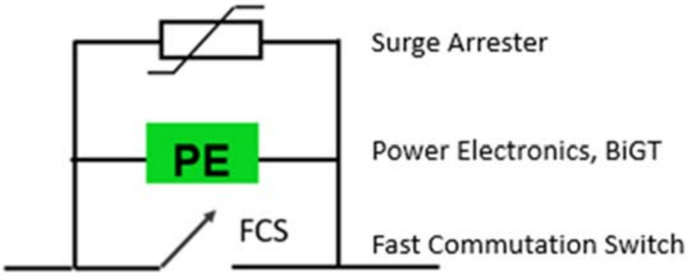

Figure 1 Schematic representation of FLCB key components and basic concept

The development process for the FLCB can be summarised in Figure 2 below.

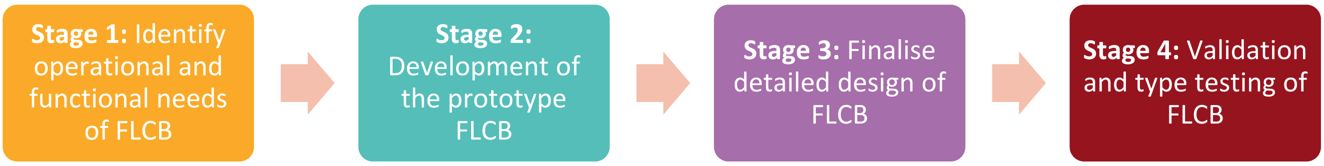

Figure 2 Summary of the FLCB development process

The project team collaboratively produced an Engineering Technical Specification, ETS 03-6511 (an internal UK Power Networks document), which identified the requirements, including performance for the FLCB. The key functional requirements of the FLCB include:

- The device shall use a combination of power electronic switches, typically insulated gate bipolar transistors (IGBTs)/bi-mode insulated gate transistors (BiGTs), surge arrestors and/or snubbers to limit and interrupt the fault current;
- It shall not use any single-use elements such as fuses to interrupt the fault current;
- It shall be capable of reclosing within the rated operating sequence after the fault has been cleared. The device will not be intentionally reclosed onto a fault but it should be designed to safely handle unintentional reclosing onto a fault;
- The device needs to be air-cooled (liquid cooling is not acceptable); and
- The device should be able to carry normal load current either via the interrupters or via a fast bypass/commutating switch.

ABB took these requirements to develop the FLCB from their single-phase proof-of-concept prototype, considered as technology readiness level (TRL) 4, to finalise the design of the three-phase FLCB (TRL7) and complete validation testing of various components with input from UK Power Networks. Throughout this process a number of safety additions were made to ensure safety of personnel working on or in the vicinity of the FLCB. To drive efficiencies and minimise development time in the development process of the FLCB, we used existing key components rather than developing new alternatives such as FLCB proof-of-concept prototype, FC-Protector (an ABB commercial product that limits short circuit current) panel and fault current detection circuitry used in the I_s-limiter and FC-Protector.

The FLCB operates within short timescales, at much faster speeds than existing equipment, bypassing the typical time grading of existing protection systems. This speed of FLCB operation could also cause unintended loss of supply for customers under specific scenarios if appropriate mitigation measures are not applied. As such, during the design process to integrate the FLCB to the existing network, our engineers identified such a scenario at the trial site and applied preventative measures. One of the significant mitigating actions was to implement an autoclose scheme to the pre-existing bus coupler at the trial site.

Currently there are no existing international standards for fault current limiters; instead relevant parts of circuit breaker standards are adapted with certain necessary modifications. Throughout the development of the FLCB, ABB conducted a number of validation tests on individual components and modules prior to commencing type testing. The type tests carried out include:

- 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.

The overall development process was completed successfully with ABB finalising type testing at an accredited high power test laboratory in July 2019. This was following 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.

2. Glossary and Abbreviations

Term	Description
ABB	ABB Group
BAU	Business-As-Usual
BEIS	The Department for Business, Energy and Industrial Strategy
BiGT	Bi-mode Insulated Gate Transistor
CBA	Cost Benefit Analysis
CB	**Circuit Breaker** – protection device that interrupts the flow of current in an electric circuit in the event of a fault.
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
EPN	Eastern Power Networks
FAT	Factory Acceptance Test
Fault Current	A surge of energy that flows through the network in the event of a fault. The energy comes from the momentum of rotating generators and motors connected to the network.
Fault Level	The maximum fault current that could theoretically flow during a fault. **“Make”** fault level is the maximum fault current that could flow during the first current peak of the fault, and that a circuit breaker closing onto a fault would need to safely handle. **“Break”** fault level is the maximum fault current that could be flowing 100ms after the start of the fault, and that a circuit breaker clearing the fault would need to be able to interrupt.
Fault Level Headroom	The difference between fault level and fault rating at a particular substation or part of the network; corresponding to the amount of generation that can be connected to the network without exceeding its fault rating.
FCL	**Fault Current Limiter** – a FLMT that attenuates fault current by increasing its impedance (only) during a fault.
FC-Protector	Commercial product offered by ABB which limits the short-circuit current during the first rise (https://new.abb.com/medium-voltage/apparatus/fault-current-limiters/fc-protector)
FCS	Fast Commutation Switch
FLCB	**Fault Limiting Circuit Breaker** – a FLMT that blocks fault level contributions from a transformer / bus coupler / generator by disconnecting it before the first current peak of the fault.
FLMT	**Fault Level Mitigation Technology** – a technical solution that reduces fault levels on the network.
FMEA	Failure Mode and Effects Analysis

Term	Description
FNC	Fraser Nash Consulting Limited
FSP	Full Submission Pro-forma
GT	Grid Transformer
HSE	Health and Safety Executive
HV	High Voltage
HVDC	High Voltage Direct Current
IGBTs	Insulated Gate Bipolar Transistors
Inhibit / Inter-trip Scheme	A hard-wired protection system that automatically disconnects generators from the network under pre-defined conditions, typically in the event of a transformer outage or other abnormal network configuration that causes elevated fault levels.
I_s-limiter	Commercial product offered by ABB which limits the short-circuit current during the first rise (https://new.abb.com/medium-voltage/apparatus/fault-current-limiters/current-limiter)
KEMA Laboratories	Independent organisation for issuing Testing, Inspections & Certification certificates
LPN	London Power Networks
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
RIIO-ED1	The current electricity distribution regulatory period, running from 2015 to 2023
RMS	Voltage (Vrms) or Current (Arms) Root-Mean-Squared
Rotating DG	A generator that converts mechanical energy to electrical energy using a synchronous AC rotating alternator, e.g. CHP and diesel standby generators. These types of generators have a much larger impact on fault levels than inverter-connected generators e.g. solar PV.
Safety Case	A structured argument, supported by a body of evidence that provides a compelling, comprehensible and valid case that a system is safe for a given application in a given operating environment.
SCADA	Supervisory Control and Data Acquisition
SECRC	ABB Corporate Research Centre in Västerås, Sweden
SDRC	Successful Delivery Reward Criteria

Term	Description
SLD	Single Line Diagram
SPN	South Eastern Power Networks
STC	Short Time Current
TRL	Technology Readiness Level is a measure used to assess the maturity of evolving technologies. It is graded on a scale from 1 to 9 where TRL1-3 is typically defined as research
UKPN	UK Power Networks

3. Background and Project Motivation

In order to accelerate the transition to a low carbon future, a wider spread of renewable and DG will be required. The drive to reduce the carbon footprint of heating was again reiterated this year by both Ofgem's chief executive Dermot Nolan, and in the UK Government Chancellor's Spring Statement 2019[5]. New legislation continues to be introduced to reduce CO_2 emissions and most recently bring all greenhouse gas emissions to net zero by 2050[6].

One characteristic of a number of distributed generators, especially renewables, is that they produce Direct Current (DC) electricity and then use inverters to transform it to Alternating Current (AC) that is distributed in the electricity network. These types of generators do not contribute significantly to the 11 kV fault current when a fault occurs on the network. However, any generator that has rotating parts has the potential to contribute significant fault current contribution. The reason is that the kinetic energy or inertia stored in the rotor of generators gets released as fault current when a fault occurs. An example of rotating generators include CHP units.

Components of the electricity network have limitations in the amount of fault current that they can withstand – known as the fault rating. The amount of current flowing in a network is increased substantially under a fault condition, as the energy aims to supply the fault as a high load source, this extreme current is classed as fault current and can place extreme mechanical stresses on network assets if beyond the rated value or for sustained periods.

In dense urban areas, there is a high demand for electricity which requires multiple power sources. In turn those power sources contribute to increased fault levels in those parts of the network. When the modelled fault levels of an area of the network approaches the fault rating of the equipment, then for safety purposes, no additional generation can be accommodated on the network unless reinforcement work is carried out. This usually means that the equipment, in this part of the network, needs to be replaced with equipment of a higher fault rating capability. Alternatively the power sources can be "split" by adding more equipment, introducing additional normally open points or building new substations on the network.

Such reinforcement requirements subsequently result in higher quotations for customers who wish to connect new generation to fault level constrained parts of the network. However UK Power Networks aims to be a facilitator of the low carbon transition and wants to offer the lowest possible costs to our connecting customers. Therefore we proactively engaged with the industry to find a solution for this problem of keeping the fault levels low while connecting new distributed generation. Consequently we identified that this can be done by using Fault Level Mitigation Technology (FLMTs), and these are generally split in two types: Dynamic impedances and very fast fault interruption.

The first category encompasses dynamic impedance devices. As the term suggests, impedance is the characteristic of components that impedes the flow of current through them. Normally we want to keep this as low as possible because a high impedance also leads to higher losses, typically in the form of heat. A dynamic impedance device has a low impedance under normal operating conditions but during fault conditions the impedance rises to high levels to impede the flow of fault current, or alternatively put, to reduce fault levels. However such devices only limit the current and do not completely interrupt it. An advantage of these devices is that when there is a failure of the device, they fail to a high impedance state, which means the risk of the device short circuiting and catastrophically failing are low. One disadvantage is that they tend to be large and heavy devices, so in densely populated urban areas such as London Power Networks (LPN), where space is a premium and the price of land is high, these devices may not be economically viable. An example of this category was trialled in the past by UK Power Networks at Newhaven for the Pre-saturated Core Fault Current Limiter (PCFCL) project which was funded by the Energy Technologies Institute.

The second category is reliant on very fast fault interruption. Figure 3 presents a waveform of a fault occurrence. The fault occurs in 0.1 seconds and, with the peak fault current coinciding with the first crest of the waveform

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[5] https://www.gov.uk/government/speeches/spring-statement-2019-philip-hammonds-speech

[6] https://www.gov.uk/government/news/uk-becomes-first-major-economy-to-pass-net-zero-emissions-law

after fault initiation. A device with the capability to detect the fault current and interrupt it before it reaches the first peak, would limit the fault current observed by the network; the operating times for conventional circuit breakers is too slow to respond in such a way.

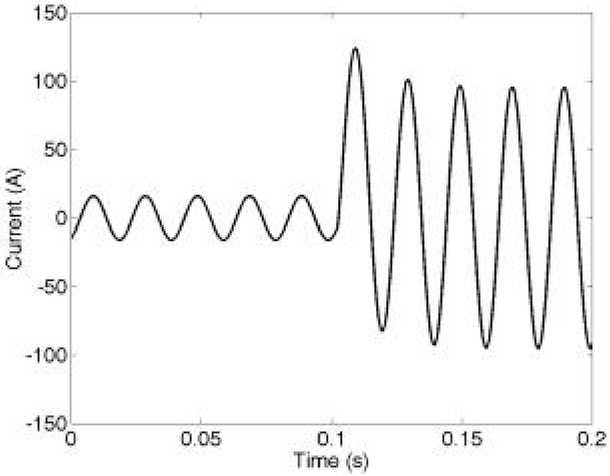

Figure 3 – Generic fault current waveform example

The second category of FLMTs is typically driven by the concept of power electronic based switches or fuses. Using power electronics, such switches are capable of very fast interruptions that can interrupt the current before the first peak of the fault current waveform. However they also have some disadvantages, including the fact that power electronics generate high losses during normal operation through heat dissipation. Losses are wasted electrical energy and typically transform into thermal energy, which means that sufficiently powerful cooling systems are required to maintain the temperature of these devices. These cooling systems consume high energy and also require more space, again, which is premium in dense urban centres.

One other variant under the second category that was trialled in GB by Electricity North West (ENWL) as part of the Respond project is single use fuses designed to operate at the speed needed to break current before the first fault peak. These devices were successful in their application. UK Power Networks identified the value of having such a device however wanted to develop fast current interruption further in order to introduce reusability, so that single use elements were not required. This would reduce the need for stockpiling spare fuses, improve restoration times and not rely resource availability to replace them.

The aforementioned research was considered when setting the functional requirements for the FLCB device to ensure these limitations are overcome and mitigated. The concept we have developed is a hybrid FLCB device; it has a mechanical part, a power electronics part and surge arrester all in parallel. During normal operation the current flows through the mechanical switch, and therefore has low losses and no additional cooling requirements. As the FLCB uses power electronics, consumables such as fuses are not required and the device can be operated multiple times.

We are trialling the FLCB at a primary substation, with the purpose to allow multiple generators, including CHPs, to connect to fault-level constrained 11kV networks.

3.1 Purpose of This Report

The purpose of this report is to describe the process that was undertaken for the development of the FLCB from the point of view of both UK Power Networks and our project partner ABB. Specifically, this report forms SDRC 9.1.1, which is the third Successful Delivery Reward Criteria (SDRC) for Powerful-CB that will be submitted over the course of the project, as described in the Project Direction. The Powerful-CB SDRCs have been designed to demonstrate clear progress towards the project objectives and disseminate valuable learning to interested stakeholders at key milestones of the project. Stakeholders include Ofgem, other DNOs, customers, industry groups and equipment manufacturers.

In this case, SDRC 9.1.1 aims to share knowledge gained during development and any considerations or recommendations for specifying FLCBs in the future. Table 1 summarises the evidence supporting the stated objectives for SDRC 9.1.1.

Table 1 – Summary of SDRC 9.1.1 supporting evidence in accordance with the Project Direction issued by Ofgem

Successful Delivery Reward criterion	Evidence
9.1.1 Prototype and lab test a substation-based solution	**Publish Learning Report – Development of a FLCB for substations**, which will include: recommendations for specifying a substation-based FLCB **[Section 4 of this report]**; results and learning from type tests (including a short circuit test) conducted at an accredited high power laboratory **[Section 7 of this report]**; and requirements for integrating FLCBs into existing networks and ensuring safety **[Section 5 and Section 6 of this report]**.

3.2 Overview of the Report Structure

This report describes the development process for the FLCB which can be summarised in Figure 4 below. The subsequent sections of this report detail these stages.

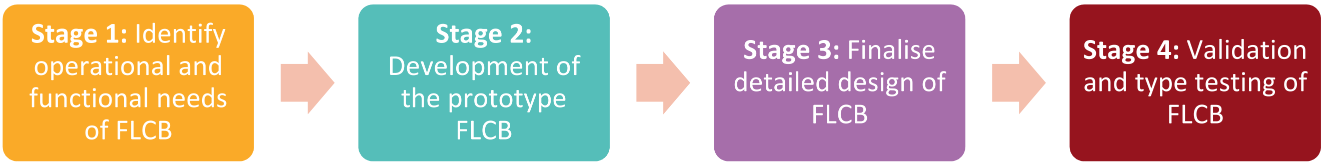

Figure 4 – Summary of the FLCB development process

In Stage 1, we identified the operational and functional requirements for the FLCB. As this is a first of its kind prototype we had to use knowledge from existing equipment standards and apply it to the FLCB. The input of ABB's experts at this stage was invaluable. Details of the operational and functional requirements can be found in Section 4.

Stage 2 saw the development of the prototype device by ABB. Using the newly created Engineering Technical Specification from Stage 1 as a starting basis and frequent input from UK Power Networks, ABB developed the prototype and completed various validation tests on individual components and modules. The development stage of the FLCB is detailed further in Section 5.

Towards the end of Stage 2, Stage 3 commenced in parallel and we began preparation for network demonstration and integration of the FLCB. During this stage a number of considerations were made in order to complete the detailed design of the FLCB and for the substation where the network demonstration will occur. The design process has produced valuable learning regarding the integration of FLCBs to existing substations, with the possible problems and appropriate solutions identified for future applications. Further details of this stage can be found in Section 6.

Finally during Stage 4, the type tests for the FLCB were completed at both the PEHLA Testing Laboratory in Ratingen, Germany and the KEMA laboratory in Arnhem, Netherlands. Following successful completion of all type tests, ABB completed Factory Acceptance Tests (FATs) and the FLCB was delivered to site in October 2019.

4. Fault Limiting Circuit Breaker Requirements

The drivers and requirements of the project were formed following the evaluation of existing FLMTs, identifying any constraints such as limited space in dense urban areas, and consultation with internal UK Power Networks stakeholders. The overall objective of the project is to provide an alternative option to traditional, network reinforcement by overcoming limitations in existing FLMTs and other identified constraints to help facilitate faster, lower cost connections for distributed generation customers.

Developing a new device like the FLCB means there are no precedents on specification and hence a combination of relevant specifications and guidelines from different areas of existing equipment such as conventional circuit breakers were used as a starting basis. We built upon these existing specifications to produce a new standardised approach for the FLCB device; this new specification has been developed as an internal UK Power Networks document, Engineering Technical Specification, ETS 03-6511. The following subsections detail the requirements of the FLCB.

4.1 Physical Requirements

For the physical enclosure of the device, the requirements were formed based on pre-existing specifications for metal-enclosed switchgear. Some of the requirements being that the switchgear is:

- Ground-mounted;
- Cable-connected and allow for either top or bottom cable entry without compromising the internal arc classification of the switchgear;
- Air-insulated; and
- Used for single-busbar applications.

4.2 Functional Requirements

Having defined the physical aspects, the next step was to define the functional requirements. These originate from overcoming the limitations of existing FLMTs outlined in Section 3 and include:

- The device shall use a combination of power electronic switches (typically IGBTs), surge arrestors and/or snubbers to limit and interrupt the fault current;
- It shall not use any single-use elements such as fuses to interrupt the fault current;
- It shall be capable of reclosing within the rated operating sequence after the fault has been cleared. The device will not be intentionally reclosed onto a fault but it should be designed to safely handle unintentional reclosing onto a fault;
- The device needs to be air-cooled (liquid cooling is not acceptable); and
- The device should be able to carry normal load current either via the interrupters or via a fast bypass/commutating switch.

The aforementioned functional requirements are aimed at improving the availability of the FLCB by not using single-use elements, reducing the physical size due to additional cooling and reducing losses due to using only power electronics; all limitations of existing FLMTs.

To ensure the safe operation of the device during the project trial, the project team considered different running arrangements of the trial site. Following a thorough assessment and analysis, the team has decided to deploy and use conventional circuit breakers on either side of the FLCB so that these can be used to provide isolation and earthing. The adjacent circuit breakers will also act as backup protection during the trial, to mitigate any impact of potential FLCB failure to operate or failure of the device itself. A portion of the single line diagram (SLD) depicting this arrangement can be found in Figure 5.

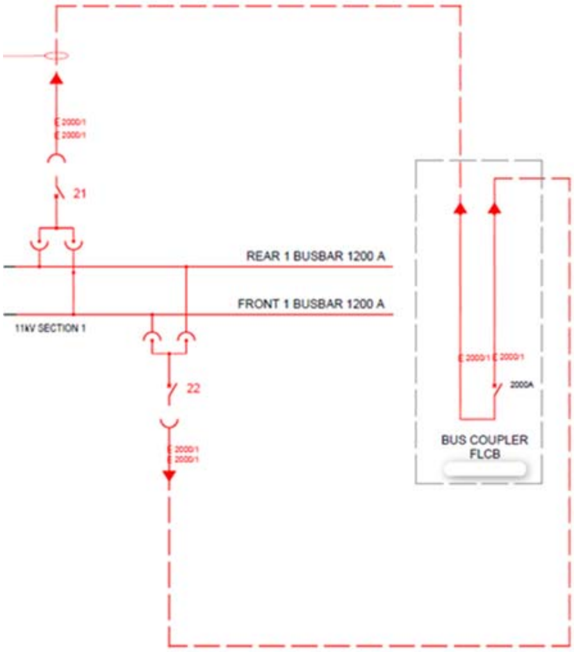

Figure 5 – FLCB installation arrangement for network demonstration – CB 21 and 22 are adjacent circuit breakers to provide isolation and back-up protection for the FLCB during the trial

One of the essential mandatory requirements for business-as-usual (BAU) roll-out of the FLCB is that it must be deployable without any conventional adjacent circuit breakers (CB 21 and CB22 in Figure 5) connected to act as backup protection to the FLCB or in order to isolate the FLCB. The project trial must therefore demonstrate, at least in principle, that the FLCB can operate as a self-contained device and interrupt the fault current with no need for external circuit breakers or disconnectors. For the avoidance of doubt, the integration of isolation/earthing/testing facilities into the FLCB is considered minor and does not need to be demonstrated in the trial as this is established technology.

Excluding the need for adjacent circuit breakers will reduce the total installation cost of the FLCB as well as reducing the overall space required.

4.3 Safety Requirements

FLCBs are not yet proven to be fail-safe, so a number of safety requirements were considered when developing the device. This means that if the FLCB fails to operate as per design in a BAU scenario, there may be a risk that downstream network equipment could be exposed to fault current exceeding its rating. In the worst case, this could result in catastrophic failure of downstream equipment.

As part of the Powerful-CB project, we appointed an independent Safety Consultant, Fraser Nash Consulting (FNC) to prepare a safety case for the trial. FNC led a wider consultation with relevant stakeholders including ABB, internal UK Power Networks stakeholders, other Distribution Network Operators (DNOs), the Energy Networks Association (ENA), and the HSE. The preliminary safety case was published as part of SDRC 9.1.3 and 9.1.4 and is publically available[7].

The trial, including installation, commissioning, operation, maintenance, and decommissioning of the FLCB, shall be conducted strictly in accordance with this approved safety case.

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[7] https://innovation.ukpowernetworks.co.uk/projects/powerful-cb/

4.4 Fault Limiting Requirements

The FLCB developed for the project limits fault levels by interrupting the fault before the first peak of the waveform. During the requirements gathering stage, it was confirmed that the device should not allow the current to reach higher than 13 kA, based on evaluation of existing fault ratings of switchgear and must also achieve interruption within 3 milliseconds. Figure 6 below illustrates the desired fault limiting performance, assuming the fault started at the zero point in time.

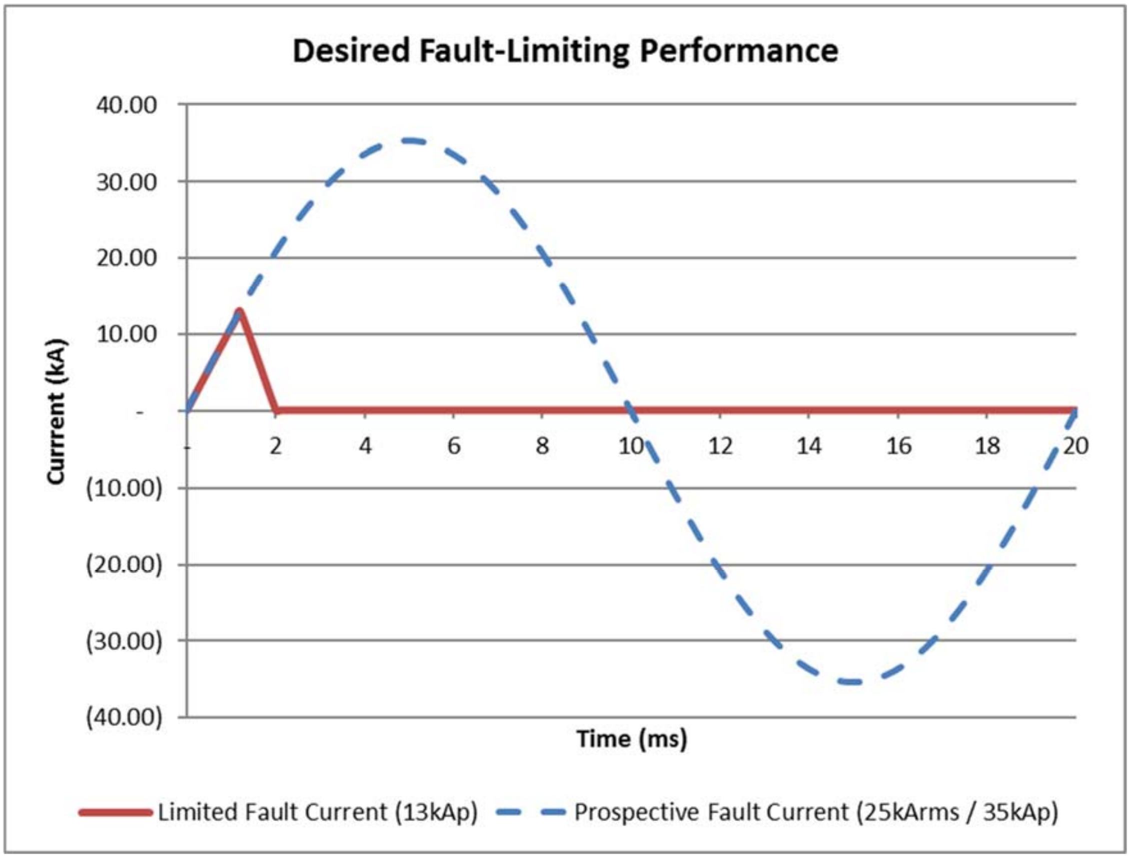

Figure 6 – Desired fault limiting performance of the FLCB

4.5 Auxiliary Equipment

In order for the FLCB to operate as an independent unit, it needs to include protection relays, digital fault recorders, instrument transformers and other sensors needed to mitigate internal fault risk. Having the FLCB operate as an independent unit also reduces the need for additional space and effort needed to install protection relay panels and other auxiliary equipment. This auxiliary equipment will help measure and validate the technical performance of the FLCB during normal operation and fault limiting operation.

4.6 Power System Parameters

The power system parameters specified for the FLCB comply with established GB standards for switchgear for the same voltage level. The ENA has produced the standard “ENA TS 41-36 Distribution switchgear for service up to 36 kV (cable and overhead conductor connected)”, which specifies distribution switchgear up to 36 kV. This standard was followed and **Error! Reference source not found.** below outlines the power system parameters from ENA TS 41-36. By following this standard, we have ensured that the FLCB can be installed across GB with no issues.

Parameter	Nominal	Minimum	Maximum
Voltage	11kV	-6%	+6%
Frequency	50 Hz	49.5 Hz	50.5 Hz
Load Power Factor	0.9 lagging	0.8 lagging	1.0

Table 2 – Power system parameters

Further to these power system parameters, **Error! Reference source not found.** below outlines the withstand ratings that the FLCB and all auxiliary equipment shall be designed for in order to operate satisfactorily. These values align closely with the requirements of existing conventional circuit breakers, which will further facilitate the use of the FLCB across GB. Initially 25 kA/1second was specified for the rated short-time withstand current, however this was later changed to 3 seconds. Changing the withstand time would introduce additional stress on components, as such, following discussions with ABB it was decided to reduce the peak fault current from 25 kArms to 16 kArms for the project. Manufacturers may be able to offer higher fault withstand ratings in future developments of the FLCB.

Parameter	Rating
Rated short duration power-frequency withstand voltage	28 kVrms/1 min
Rated lightning impulse withstand voltage	75 kVp
Rated normal current	1250 A or 2000 A
Rated short-time withstand current	16kA/3s
Rated short-circuit breaking current	16 kA rms
Rated short-circuit breaking current time constant	45 ms
Let-through current at rated short-circuit breaking current	13 kA peak

Table 3 – Withstand rating requirements

4.7 Equipment Cooling

As highlighted in Section 4.2, cooling systems of the FLCB shall be either natural or forced ventilation and shall be designed such that no special equipment or skills are required for routine maintenance. As the FLCB is to be installed into existing substations where space is limited, especially in dense urban areas, we made it a requirement that liquid cooling systems should not be used as this will increase the overall size of the device. Liquid cooling would have also increased the upfront cost of the FLCB along with increasing routine maintenance costs, both of which are undesirable.

4.8 Operation and Control Requirements

The operating and control requirements of the FLCB shall be designed to allow:

- Automatic reclosing (only after the fault has been cleared);
- Remote closing/opening via SCADA; and

- Local closing/opening via controls on the equipment.

These operation and control requirements are standard for switchgear across DNOs in GB and hence was logical to ensure these were reflected in the FLCB design.

4.9 Testing

As part of the development process, it was agreed that a number of type tests were to be completed before the FLCB can be deployed. This was to ensure that the FLCB complies with the ratings found in ETS 03-6511 and for further assurance that the device will function as expected on the network abiding by our safety requirements. The type tests shall comprise of the following:

- The type tests defined in clause 2.6 of ENA TS 41-36;
- Measurement of losses; and
- If the equipment includes any active cooling systems:
    - Measurement of acoustic sound level;
    - Measurement of power consumption of cooling and other systems; and
    - Measurement of vibration.

The following tests, as a minimum, shall be witnessed by UK Power Networks or an agreed independent third party:

- Voltage withstand;
- Internal arc test;
- Temperature rise;
- Short-time withstand current and peak withstand current tests; and
- Short-circuit making and breaking tests.

We chose to follow ENA TS 41-36 where applicable, such that the FLCB is subject to similar testing regimes as applicable to other switchgear, namely circuit breakers, and to ensure higher adoption across GB.

5. Development of the Fault Limiting Circuit Breaker

This section details the development of the FLCB and focuses on our project partner and supplier, ABB's research team.

As introduced in Section 3, several technical concepts exist for limiting short circuit currents, such as, variable impedances through magnetic saturation or super conduction. The FLCB, developed for this project, limits the current by interrupting the current extremely fast, typically 20-50 times faster than a conventional circuit breaker. Such fast operating times ensure that the fault current never exceeds the fault level rating of the network equipment, as illustrated in Figure 7.

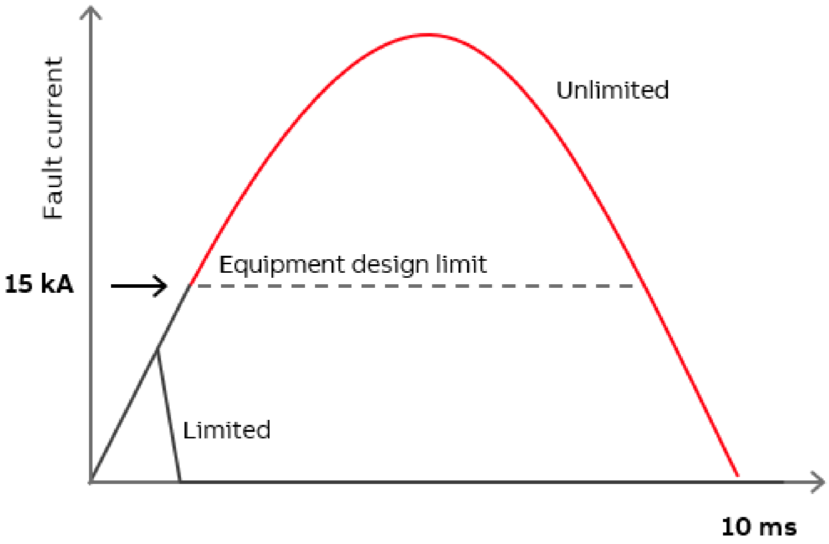

Figure 7 – Fault Current Limiting Circuit Breaker performance concept

To meet the gathered requirements and specification for the device, as outlined in Section 4, the key strengths of different technical principles were consolidated into the hybrid FLCB as there is no single existing solution to meet all the requirements. For instance, the operating times of a conventional breaker would be too slow to respond to interrupt fault currents, and a power electronics based circuit breaker alone would incur high losses and require forced cooling. The already available, fuse based, I_s-limiter[8] from ABB would comply with the interruption performance requirements but is not capable of multiple operations due to the use of single-use components, namely fuses. These require personnel to travel to site and replace the fuses after interruption and hence means the availability of the I_s-limiter is lower than that of the FLCB.

In an earlier independent research and development project, ABB demonstrated the principles of combining power electronics with a mechanical switch to meet all the requirements for the device being developed for this project. This was a single-phase proof-of-concept prototype of TRL4 and the Powerful-CB project took this device and developed a three-phase design of TRL7 based on the same principles and logic.

The single-phase proof-of-concept was tested[9] with a very similar network data and topology to the Powerful-CB project. Figure 8 and Figure 9 depict the device from this previous project.

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[8] I_s-limiter https://new.abb.com/medium-voltage/apparatus/fault-current-limiters/current-limiter as tested by ENWL Respond project

[9] L. Liljestrand, L. Jonsson, M. Backman, M. Riva, 2016, “A new hybrid medium voltage breaker for DC interruption or AC fault current limitation”, 18th European Conference on Power Electronics and Applications (EPE'16 ECCE Europe), 1-10

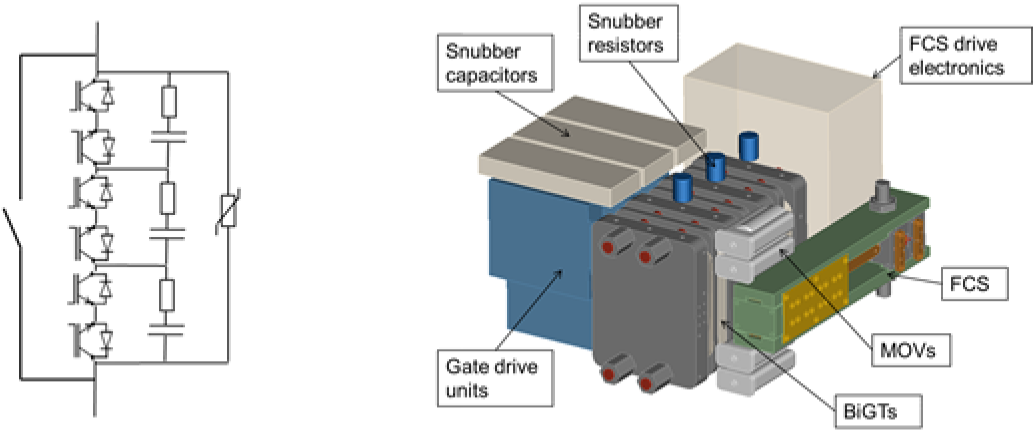


Figure 8 – Hybrid breaker schematics and early design used in ABB's R&D project (note this is not the device developed for the Powerful-CB project)

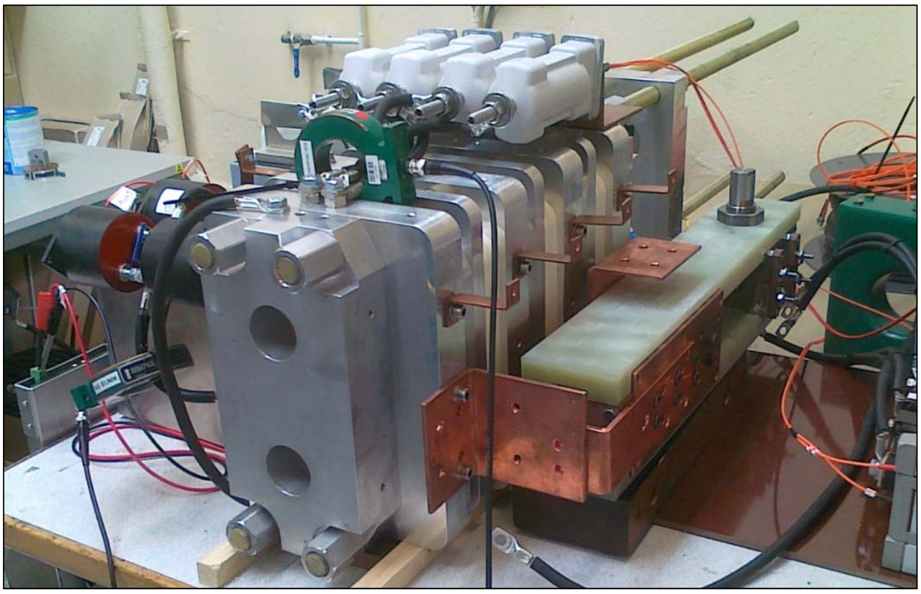


Figure 9 – FLCB single-phase proof-of-concept prototype (TRL4) from ABB's R&D project that the Powerful-CB project has developed further)

The device developed for the project has a mechanical part, a power electronics part and a surge arrester – all in parallel. During normal operation, the current flows through the mechanical switch and therefore has low losses. Figure 10 below is a representation of FLCB key components and basic concept and Figure 11 shows how the FCS and power electronics fit together (note the surge arrester has been omitted for clarity). However a common problem with mechanical switches is that they are too slow for the operating time required for this device. Therefore, the mechanical switch used in this case is electromagnetically driven and operates at extremely high speeds (0.35ms to current commutation). When a fault is detected, the mechanical switch opens and the arc is then transferred to the power electronics module. The power electronics breaks the current, and the transferred energy is then released via the surge arrester.

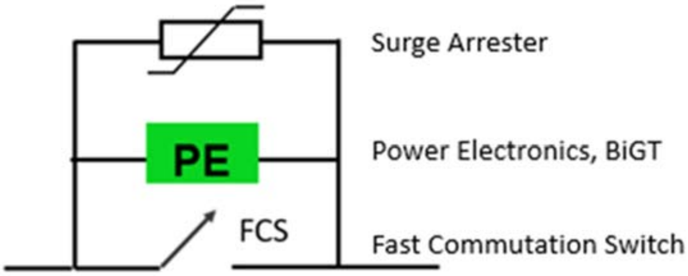


Figure 10 – Schematic representation of FLCB key components and basic concept

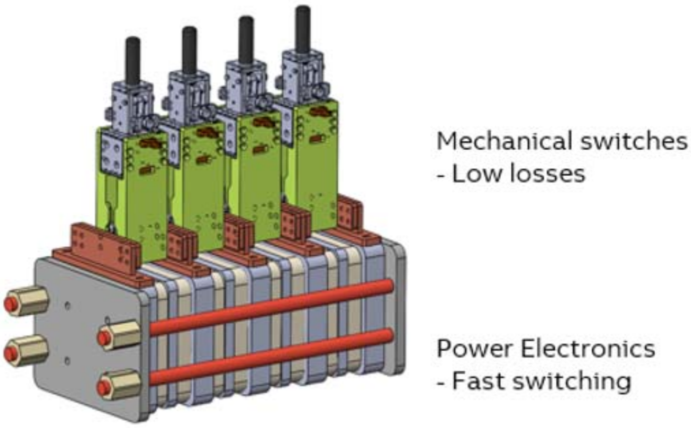


Figure 11 – Modular concept of the FLCB

5.1 Designing the FLCB for the Project

When designing a novel device in preparation for demonstration on a live network, numerous factors need to be considered. These include:

- Ensuring all components or parts of the device integrate to deliver the required functionality;
- Ascertaining that the device and its components comply with all appropriate technical and safety standards; and
- Improving the performance of the device to meet the testing success criteria.

As previously stated, in the absence of any dedicated international standards for fault current limiters, where applicable, the conventional circuit breaker standard requirements were used in the development of the device.

Furthermore to ensure the device is designed to operate safely under different operating conditions and site locations, a safety case and a Failure Mode and Effects Analysis (FMEA) activity were conducted. The safety case, led by an independent and a well-known technical consultancy – Fraser Nash Consulting (FNC), focused on possible issues and risks related to the installation in the substation, while the FMEA focused on the performance and reliability of the FLCB.

It was clear from the safety case that the reliability and availability of the device is absolutely critical for the installation and that this needs to be verified through extensive development, validation and type testing. The reliability was critical because for the BAU application, we would allow the fault level on parts of the network to rise above the rating of the switchgear; if the FLCB were to fail to interrupt the current, catastrophic failure of substation equipment could occur. As highlighted in Section 4.3, the preliminary safety case that documented these findings was released in the public domain via SDRC 9.1.3 and 9.1.4.

From the FMEA, a number of focus areas were identified for the design and verification to comply with the functional requirements, including:

- Mechanical performance of the Fast Commutation Switch (FCS);
- Interruption performance/limit of the power electronics;
- Control system development; and
- Panel integration.

Each of the above focus areas are discussed further in the following subsections.

Where possible to reduce the time and effort in the overall development process of the FLCB we used existing components rather than developing new ones. These components included the FC-Protector panel and fault current detection circuitry, QR6, that is used in the I_S-limiter and FC-Protector.

5.1.1 FCS Design Considerations

The FCS design and testing was one of the most time-consuming activities and was a key focus area in in the early stages of FLCB development. The FCS design had several constraints that warranted further consideration, such as:

- Extremely fast operation – needs to open in less than 1 millisecond otherwise the fault current will become too high;
- Have low contact resistance – if this is too high, there will be a thermal rise and cause over-heating of the component; and
- High mechanical durability – needs to operate reliably for the life of the FLCB (minimum number of operations).

It was clear from the FMEA that the concept of the FLCB would benefit from a modular design which provides higher flexibility and creates redundancy, which greatly improves the reliability. A decision was made by ABB to choose one smaller switch for each semiconductor position rather than the larger switch used in the early concept demonstrator and can be seen in Figure 12 (the multiple number of switches has also be seen previously in Figure 11). This resulted in a specially designed FCS for the Powerful-CB project.

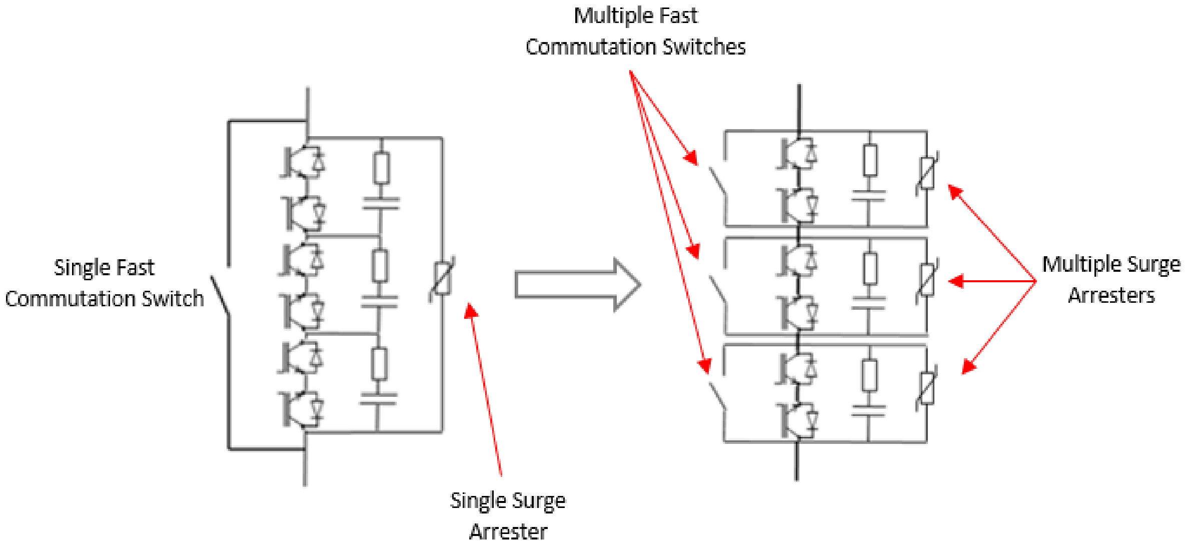


Figure 12 – Completely modular concept introduced to enhance flexibility and redundancy

To limit the current in <1 ms, the FCS needs to open in approximately 0.5 ms. Therefore an electromagnetic repulsion drive was used, which creates an acceleration of the contacts in the 5000 g (5000 times the acceleration of gravity) range, imposing extremely high forces on the mechanical structure. It was therefore essential for the device to have the ability to withstand such mechanical stress. As such, one of the key activities in the design phase was to ascertain the mechanical endurance of the FCS. To pass a mechanical endurance test, the repeat operation of the equipment under test must complete a defined number of operations without failure, and in this case the requirement was 2000 operations. Several test series were performed to identify any potential the weak spots of the device design. Initial tests encountered problems such as broken pull-rods, contact deformation and increased resistance. These experiences instigated investigations, simulations, re-design and re-testing of the FCS, leading to successful operation of the required 2000 operations with only minor maintenance. 2000 operations of the FCS are far more than expected for the project or even in a business-as-usual case. Figure 13 shows the FCS along with the test set-up used for endurance testing.

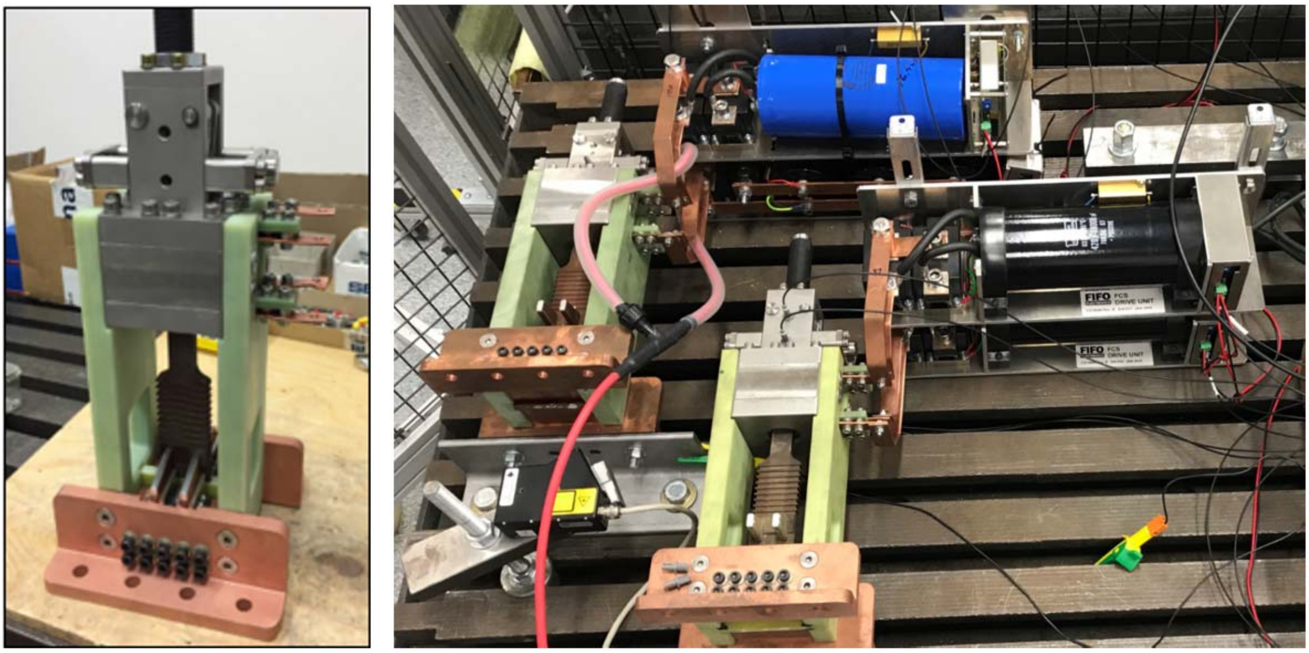


Figure 13 – FCS for the FLCB (left image) and set-up for endurance testing (right image)

Another requirement for the project is that the FLCB needs to withstand full short circuit current in the closed position which means the FCS is in the closed position. This creates a challenge for the drive system of the mechanical switch, especially on the spring-loaded cam solution that maintains the switch in either closed or open position. The forces during the short circuit test create a repelling force between the fixed and moving contacts and since the peak current may exceed 50 kA, this force becomes significant. This is a design contradiction with the fast opening of the contacts. However, through design considerations and simulations a good balance between these factors was found and the FCS has passed several short circuit tests.

5.1.2 Semiconductor Performance

The type of power semiconductors used, insulated gate bipolar transistors (IGBTs)/ bi-mode insulated gate transistors (BiGTs), are conventionally used in applications like High Voltage Direct Current (HVDC) transmission, converters and drives. Typically in the design and specification of such components, the focus is therefore on continuous switching of a certain nominal current rather than infrequent switching of high fault currents such as is the case with the FLCB. The power semiconductors have excellent performance for switching including at much higher currents than required for the project, however this is dependent on keeping the duration short and managing the energy during switch-off of the IGBTs/BiGTs. In the case of the FLCB, energy is released by the surge arresters.

To ensure correct operation for this new application of the IGBTs/BiGTs and operating mode of the FLCB, several steps were considered. The most critical ones included: gate-unit design, snubber selection, circuit simulations and performance verification testing.

A key aspect in the overall performance of the FLCB is to secure the interruption capability and the electrical endurance of the IGBTs/BiGTs. Therefore, a series of tests were conducted to secure these parameters; a diagram illustrating the test circuit for verifying the performance of the power semiconductors is shown in Figure 14. It is also important to understand not only the basic requirements but also the design margins in order to understand the effect of operating under various conditions and covering the statistical spread in component values and performance.

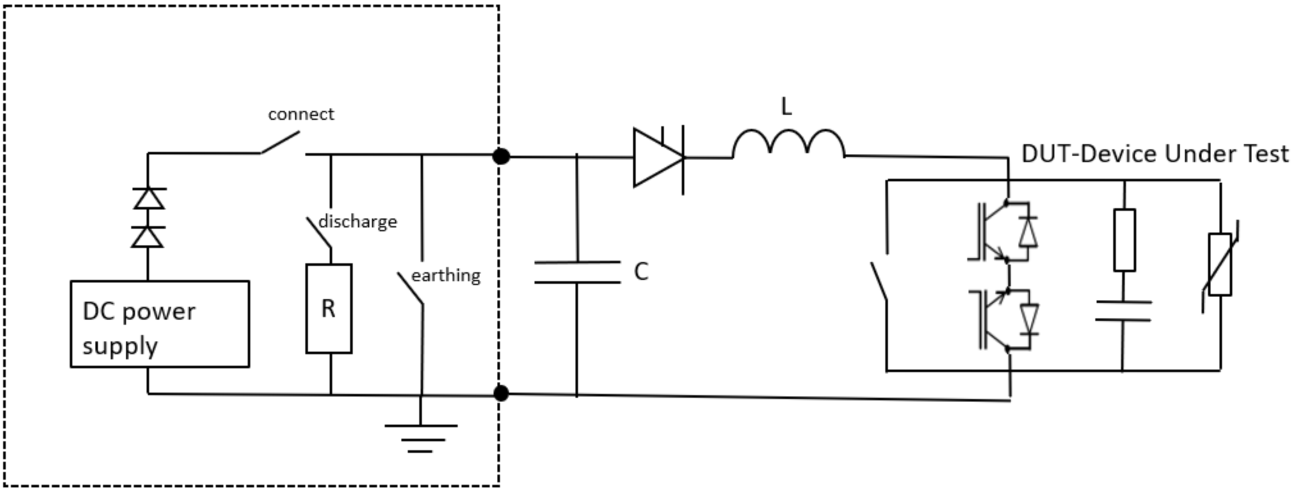


Figure 14 – Test circuit for verifying performance of the power semiconductors

The most important findings during the design and testing of the power semiconductors were:

- Interruption capability and endurance are sufficient for the application of the FLCB;
- Power semiconductor limit is well above design limit creating a healthy margin; and
- Interruption capability is strongly influenced by circuit design, such as, snubber and surge arrester values.

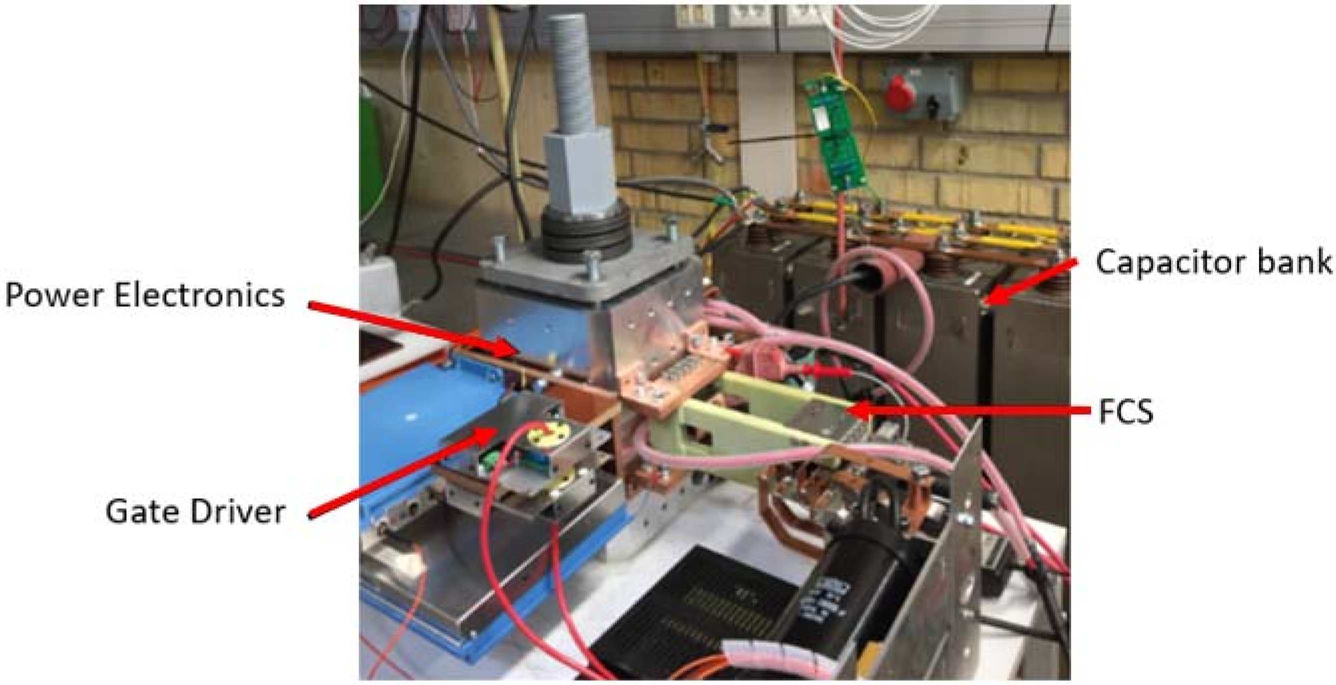


Figure 15 – Test circuit for Power Electronics and commutation performance of the FCS

5.1.3 Control System Design

In parallel with the mechanical switch (the FCS), semiconductor design and verification, a new control system was also developed for the FLCB. Conventional circuit breakers have a limited need for controllability – typically open, close and earth status are used and communicated directly to the substation controls. For the FLCB, consisting of several active components, which needs to be operated in a very short time with a high accuracy, a completely different control unit is required. The control system controls both the FCS and power electronics, ensuring that they: operate; and operate in a synchronised manner. The control system also communicates with the protection relay providing watchdog supervision and receiving trip commands from the relay.

Within the FLCB, most of the major components are operated at elevated potential and placed in the High Voltage (HV) compartment of the panel. Due to this, a purely optical interface was chosen because using an electrical interface would mean signals would be subject to interference and have the risk of flashover.

In order to reduce the time and effort in the development of the FLCB, a commercially available platform for the control system was used. Using an established platform, both hardware and software, would also allow for greater contingency and support should problems arise with the control system. After investigating some possible solutions, the National Instruments Compact-RIO platform was selected. It has a flexible Field Programmable Gate Array (FPGA) solution, optical I/O modules and is tested in an industrial environment. For a potential future product, it may be more effective to develop a dedicated solution for the control system of the FLCB.

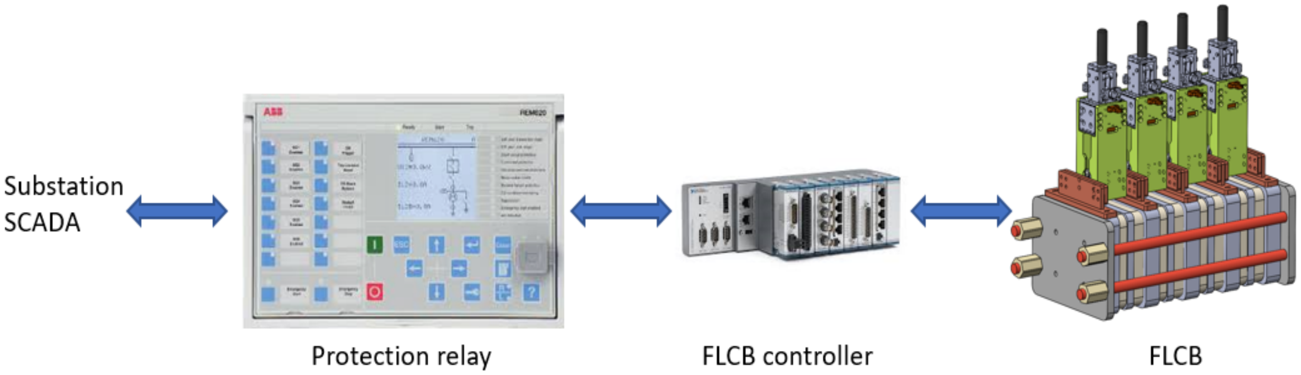


Figure 16 – Control system and communication set-up of the FLCB

Conventional network components are connected and operated using a standardised protocol; which could be hard wired or via a data bus. For the project, to enable substation communication, the FLCB panels have been equipped with a standard protection relay, ABB REF 620 in the Low Voltage (LV) compartment. This is a well-known relay and has the necessary functionalities to interact with UK Power Networks' SCADA network. The protection relay then communicates with the individual fast controllers for each phase of the FLCB. A high level diagram showing the overall control and communication system is shown in Figure 16 above.

5.1.4 Panel Integration

As previously mentioned in Section 5.1, the FC-Protector panel and fault current detection circuitry, QR6, used in the I_S-limiter and FC-Protector were used for development of the FLCB.

Another key requirement for the project is that the FLCB should fit into standard HV panels, so that it is small enough to retrofit them into existing substations as necessary. ABB identified at an early stage that the single-phase proof-of-concept would not fit it in less than three separate panels, one for each phase as seen in Figure 17 and Figure 18 respectively. To drive efficiencies in the development process we used the panel for the FC-Protector and redesigned this to contain the FLCB, which significantly simplified the integration.

Figure 17 – FLCB (single phase) integrated into a standard MV panel including tripping unit

Figure 18 – Powerful-CB installation using three MV panels to house the FLCB

Again rather than developing a new short circuit fault current detector, the QR6 from the I_S-limiter and FC-Protector was used as it was already available in the panel. The QR6 detects faults and issues a trip signal to the FLCB much faster than existing protection relays. Having the tripping unit available as an approved component allowed ABB to reduce the development time of the overall FLCB.

The main challenge when integrating the FLCB into the panel was to maintain the dielectric performance of the device. Since most of the FLCB, except the drives for the FCS, will be at high potential, the structure needs to have sufficient clearance between these components and the earthed panel at all positions. If the correct clearance is not maintained, this poses a safety risk to people as the structure of the panel could become live. In a small compartment this is always a challenge.

Another concern was the gate drive units for the power semiconductors. These are placed at elevated potential and the supply voltage therefore also needs to comply with the insulation requirements. For this purpose, a commercially available insulation transformer solution was selected. The concept is based on an electrically isolated current loop running through current transformers in the gate units and is a well proven solution for similar applications.

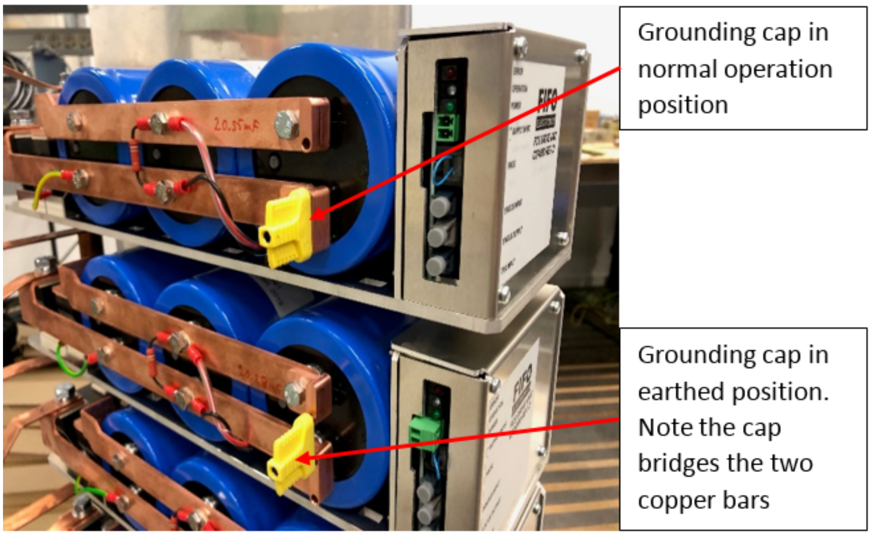
5.1.5 Safety Additions During Development

In the latter stages of development, during discussions with the Technical Standards team at UK Power Networks, the project team identified further practical requirements to improve safety. Although an interlocking system to prevent accidental opening of the cabinet doors was already included in the design, we aspired to apply UK Power Networks' standard approach for switchgear cabinets to support the BAU roll-out upon the successful completion of the project.

This approach is used for all switchgear cabinets, enforcing a requirement to use tools to open the cabinet, adding an additional layer of protection to prevent accidents. Subsequently, ABB integrated a solution for this and the door handle was modified to include a bolt, which needs to be unscrewed in order to open the doors as shown in Figure 19.

Figure 19 – Door handle with safety bolt to restrict access

Another safety addition to the FLCB was a grounding cap. The prototype includes capacitors which hold charge for the FCS which can potentially hurt people working on the device. Although the device shall be earthed before any work is carried out, the project team requested an additional visible item to ensure the capacitors are earthed prior to work being carried out. The yellow grounding cap was introduced by ABB as seen in Figure 20 below. The top half of the figure shows the cap during normal operation, and the bottom half shows the position of the cap prior to any work being carried out. It can be seen in the figure that the cap links two copper bars connecting to the capacitors. The bottom metallic bar is earthed and the top has potential voltage. Hence when the yellow cap bridges the two copper bars, the capacitors are earthed and safe to work on.



Grounding cap in normal operation position

Grounding cap in earthed position. Note the cap bridges the two copper bars

Figure 20 – Grounding cap shown in normal position and maintenance position

5.2 Efforts and Experience

Throughout the development of the FLCB, approximately 10 ABB employees were continuously involved, with the level of effort varying depending on the stage of the project. Typically this fluctuated between 20-100%, both at the research centre and the business unit. When considering the various design and testing focus areas to develop the FLCB, the split in effort to develop the FLCB is divided as illustrated in Figure 21 below.

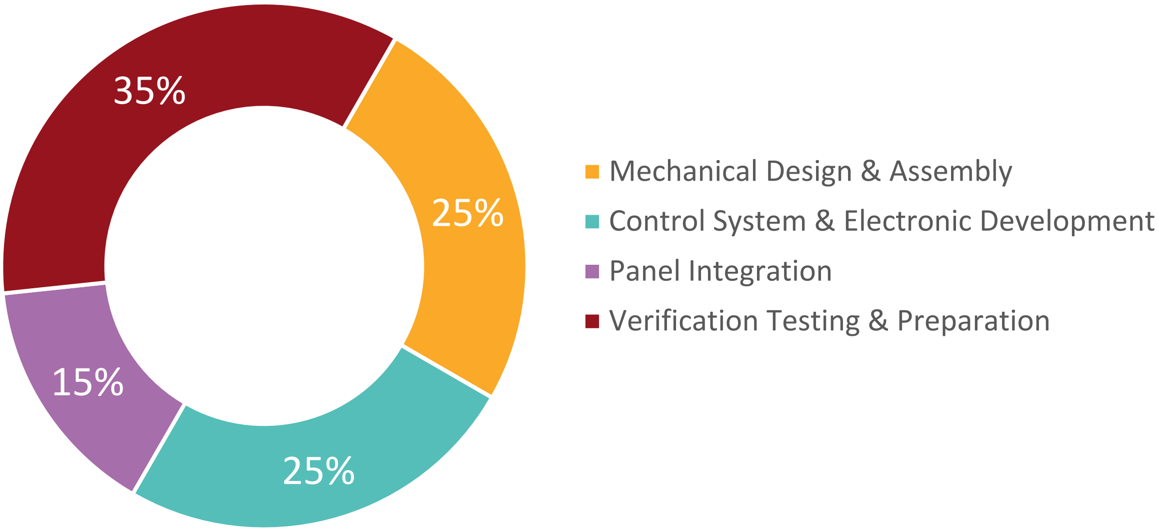


Figure 21 – Percentage of total effort per development area

One key learning from project execution, was that the time frame for completing the FLCB would have been much longer if a number of key components had not already been available, such as, FLCB single-phase proof-of-concept, FC-Protector panel and QR6 fault current detection circuitry.

The project team also learnt that the general knowledge of the performance and limitations of the various components is critical for successful development of the device. It is not sufficient to know only whether components pass or fail a certain requirement to meet the functional requirements, but rather what additional margins exist in the design to ensure correct and safe operation of the FLCB. This is also underlined by the fact that there is not yet any existing international standard for fault current limiters. Instead relevant parts of circuit breaker standards are adapted with certain necessary modifications.

Another key element for the progress of the project is the very close cooperation between the ABB R&D team based in Sweden and the ABB business line, Distribution Solutions as part of ABB's Electrification business in Germany who assembled the FLCB. Since there is a major difference between a technology demonstrator and prototype installed onto the network, close cooperation between research and implementation is essential along with input and feedback from UK Power Networks.

6. Integration into Existing Network

The process of finding a suitable site for the network demonstration and the design process has produced a number of learnings about design considerations and requirements for the installation of FLCB into an existing substation. Some of these considerations are discussed in the following subsections.

6.1 Space Requirements

The use of the FCS reduces the need for larger cooling arrangements that other FLMT require, however, the current design of the FLCB still requires a greater footprint than a conventional circuit breaker. As we used the panel for the FC-Protector and redesigned this to contain the FLCB, one typical HV switchgear panel is required per phase of the FLCB. This made it approximately three times the size of a conventional circuit breaker as can be seen in Figure 22 and knowing this from the outset formed part of our site selection criteria.

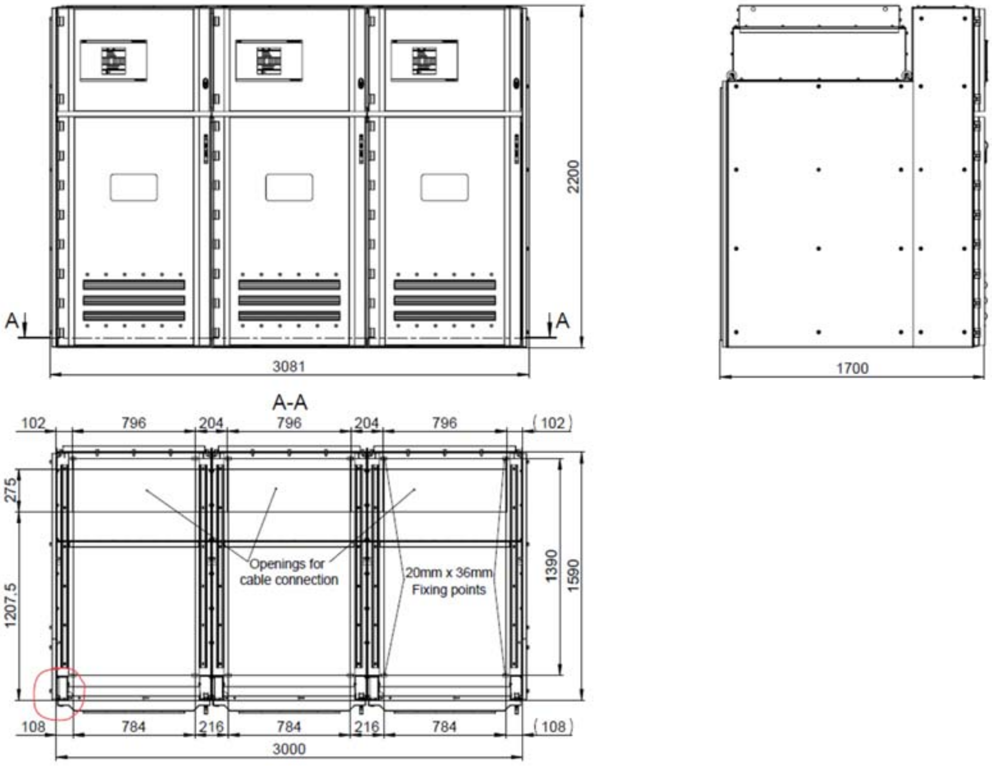


Figure 22 – General arrangement and dimensions of the FLCB

When installing at an existing substation, the designer must ensure there is adequate space to accommodate the FLCB including any additional space that may be required to extend the existing busbar as is the case for the Powerful-CB project. The busbar extension is to allow for installation of adjacent circuit breakers for isolation and backup of the FLCB, as indicated in Section 4.2. The physical busbar extension can be seen in Figure 23 and the electrical schematic of this extension in Figure 24.

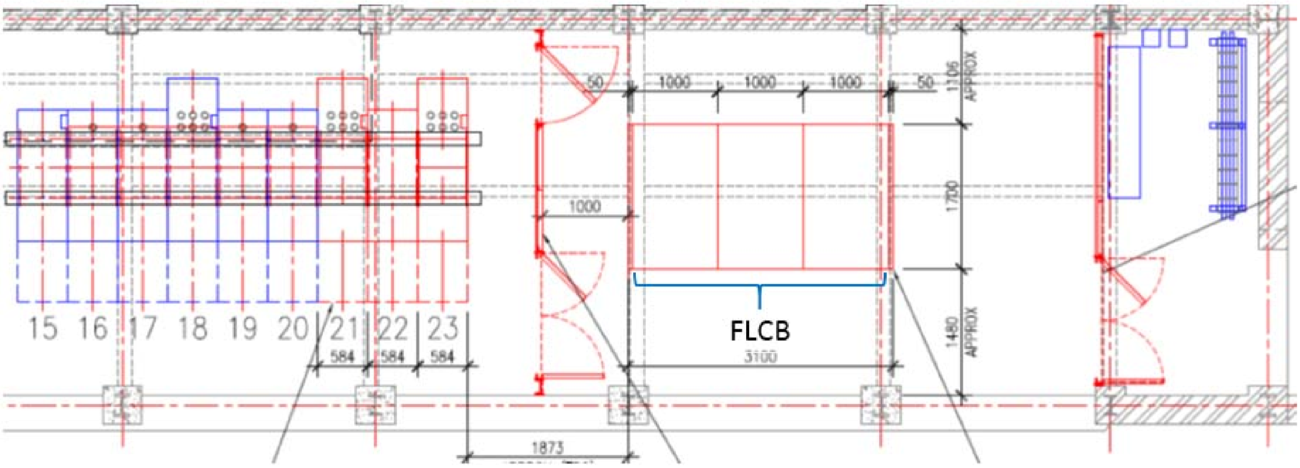


Figure 23 – Layout plan for works at the demonstration site – busbar extension and adjacent circuit breakers located in position 21, 22 and 23. The FLCB is in the adjacent room to the right

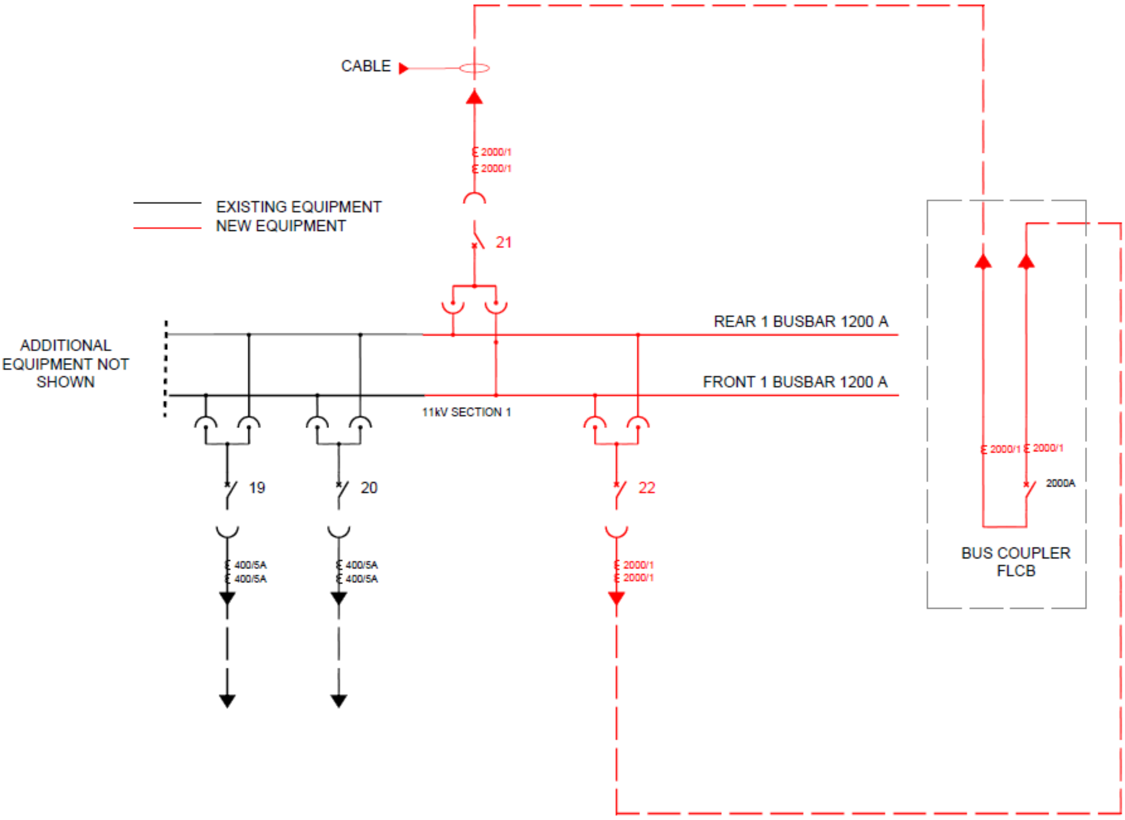


Figure 24 – Electrical schematic showing FLCB installation including busbar extension

6.2 Communication Equipment Requirements

During the development of the device, a list of suggested indicator signals were identified. For the purposes of the trial, the team has produced a list of information and signals that will need to be transmitted to the control centre via SCADA. During the trial we will further validate the data and information requirements for BAU.

For installation in existing substations, it needs to be verified whether the existing communications systems have the capacity to deliver additional signals or there is a need to upgrade or replace the remote terminal unit (RTU). The FLCB has more signals when compared to conventional circuit breakers because of the more complex control system required and increased number of health indications.

The FLCB is best utilised using modern communications standards such as via Ethernet as this allows for increased information to be transmitted. However depending on the age of the substation, as is the case for the trial substation, communications were reliant on hard wired signals. Due to the limited capacity of both the protection relay, ABB REF620, and the RTU on site, a number of signals had to be grouped together to be sent back to the control centre.

6.3 Protection Considerations

The protection design of a substation needs to be considered before installation and this must be on a case by case basis. For the purpose of the trial, the systems are simple, we are only using overcurrent protection schemes with intertripping.

The challenge for the trial is to select an appropriate protection setting so that we ensure the FLCB will trip and gather as much operational performance of the FLCB while also avoiding nuisance tripping. Protection studies have been carried out to select the protection settings, i.e. at what fault current will trip the FLCB. To generate the most performance data from the project, the protection settings may be modified during the trial as necessary.

If however, the FLCB is installed at a substation with more complicated protection, such as blocking or rough balance protection, the impact of using the FLCB would need to be assessed.

The impact of the FLCB on protection and the best way to integrate into existing protection schemes will be part of the Engineering Design Standard, an internal UK Power Networks document that will be produced towards the end of the project, when more performance information is available. There are a number of items to be considered at that stage, such as protection design philosophy and tripping settings prior to BAU handover.

6.4 Safety Considerations

The main work done on the safety case for the device use is presented in SDRC 9.1.3 and 9.1.4, which was published earlier as part of this project. Based on the guidance provided in the preliminary safety case and the learning during design, we have identified some further consideration for future installations which include:

- Interlocking with existing substation switchgear;
- Isolation and earthing of the FLCB; and
- Protection of existing switchgear during BAU when fault levels exceed their rating.

One part of the device design for safe operation is an interlocking mechanism for the doors of the cabinet containing the FLCB. Inside the cabinet there is equipment at high potential, so if someone opens the cabinet when energised there is a significant safety risk if contact is made with the equipment. As previously mentioned, for the project trial the device has two adjacent conventional circuit breakers to achieve galvanic separation after the FLCB interrupts the current. In order to make it safe for operational personnel to open the cabinet doors and work on the device, we need to check that the adjacent circuit breakers are open and earthed. The interlocking mechanism achieves this purpose as it allows the cabinet doors to open only if both the adjacent circuit breakers are open and earthed. Modern switchgear have signalling capabilities to provide this information to the FLCB control drivers.

For the trial, our existing equipment cannot provide an earth status signal as the circuit breakers must have manual earths applied. It can only provide a status signal of the circuit breakers. Therefore we will use the circuit breaker open status with the addition of a strict operating procedure/instruction explaining that unless visible earths have been applied to the adjacent circuit breakers, the cabinet doors shall remain closed and no work shall be done to the FLCB. It is therefore important for future installation in existing substations to consider whether the switchgear has the ability to provide an “earth applied” signal to the FLCB for interlocking purposes and to prevent from operational errors from personnel. However as previously mentioned in Section 4.2, for the BAU application of the FLCB, the device must be able to be isolated and earthed without the need for adjacent equipment.

For the purposes of the trial, we will keep the fault levels within the operational limit of the existing switchgear. Therefore a FLCB failure will not have an impact greater than the existing arrangement of the substation. However, the risk is greater when fault levels are allowed to increase beyond the limits of existing equipment as would be the case for BAU. The impact of a device failure must be mitigated and safety measures applied in future integration to existing substations for BAU. The potential impact of a failure on the network will determine the level of mitigation measures needed. One example of mitigation is the use of an ultra-fast earthing switch (UFES)[10] that could be installed both sides of the FLCB and will earth the network on both sides of the FLCB, if it were to fail.

6.5 Operational Considerations

The operational impact of installing a FLCB must be considered not only at the trial substation, but also on the wider network. To implement this device successfully UK Power Networks will be required to establish new protection methodologies in our network that are currently not in use on the network. In general protection systems are designed to operate in a sequence. With existing protections schemes the device closest to the fault location to operate first. If that fails, we want the device directly upstream of the first to operate second. If the second one fails then, the one upstream from the second one to operate third and so forth. See Figure 25 below for a basic illustration of the above where F is the location of the fault and D is the device closest to the fault.

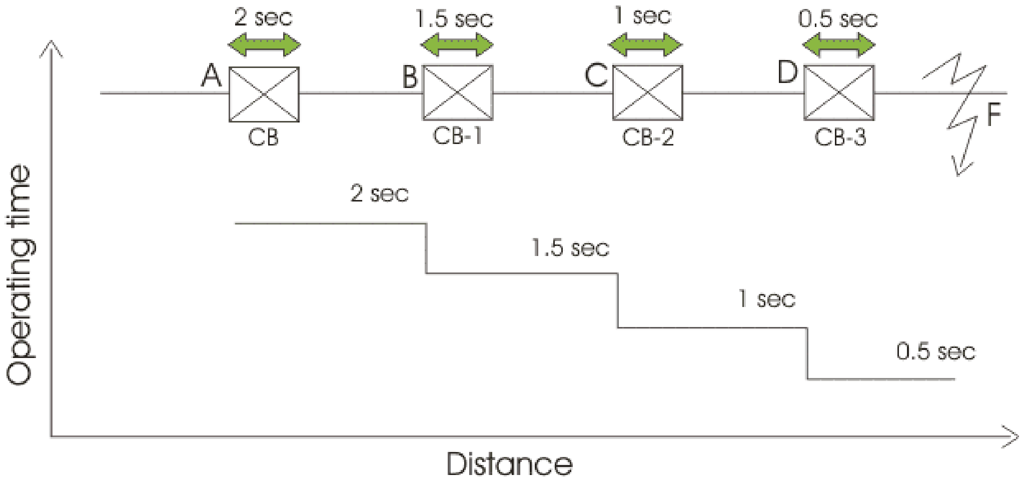


Figure 25 – Basic protection discrimination principles

This principle is called protection discrimination or selectivity, and it ensures that the disruption to the network due to a fault is kept to minimum by protecting all network assets, i.e. protection should only disconnect the faulted part of the network and keep the rest of the healthy network in operation. This is typically achieved through current and time grading, which is the selection of initiating value and speed of operation for the various protection devices in the network.

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[10] https://new.abb.com/medium-voltage/apparatus/arc-fault-protection/ultra-fast-earthing-switch-ufes

The FLCB operates so quickly that it does not grade with existing protection, along with most other traditional protection standards. We aim to produce guidelines on how to approach this in the Engineering Design Standard that will be produced later in the project.

During the design process to integrate the FLCB to the existing network, our engineers identified a scenario where there may be a dead section of bus due to the fast operation of the FLCB and applied preventative measures. The mitigation was to implement an autoclose scheme to the pre-existing bus coupler at the trial site. For further details see Appendix C for an explanation.

7. Testing of the Fault Limiting Circuit Breaker

To verify the performance and safe operation of the FLCB a series of validation tests, type tests and FATs were conducted throughout the development of the FLCB. The main development tests performed are summarised in **Error! Reference source not found.** and summary of each test is presented in Appendix A.

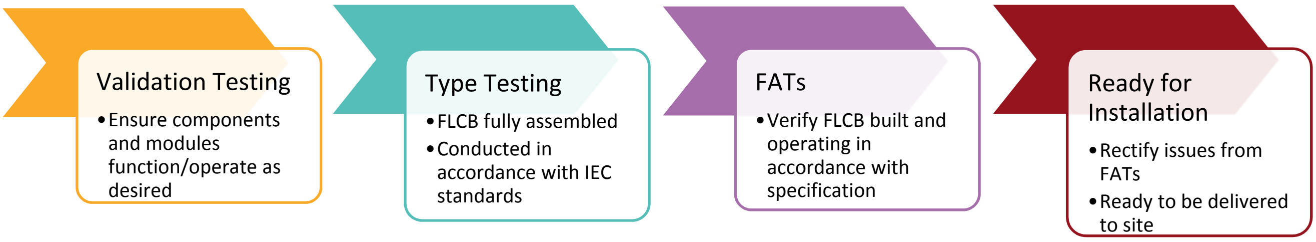


Figure 26 – Testing process carried out by ABB to produce the FLCB

A number of validation and verification tests were completed on a component level and on separate modules prior to assembly. This was undertaken to ensure the components operate/function as desired. Once the success criteria for validation testing was met, full assembly of the FLCB was completed prior to the commencement of type testing. These type tests were carried out in accordance with the relevant IEC standards which include the following:

- 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

Following successful completion of type testing, the FLCB was prepared for FATs which ensures the FLCB has been built, assembled and operates in accordance with the specification, ETS 03-6511. Once FATs were successfully completed, this signified that the FLCB was delivered to site for installation.

Appendix A Reference	Description	Date	Comments
VALIDATION TESTS			
A.1	Internal arc of panel ZS-P, 40 kArms	September 2017	Same panel similar application
A.2	BiGT interruption performance	December 2017	Endurance >13 kA, >100 operations and limit testing
A.3	Functional test first assembly	March 2018	Milestone delivery with UK Power Networks present
A.4	FLCB one module electrical endurance	May 2018	>100 operations completed

Appendix A Reference	Description	Date	Comments
A.5	1 sec short time current test (STC), one FCS	June 2018	25 kArms, 63 kApeak
A.5	High power interruption test one phase, 25 kA prospective, limited voltage	June 2018	Milestone delivery with UKPN present SECRC High Power Lab
A.6	Preliminary temperature rise test at SECRC	October 2018	Performed on an early assembly
A.7	High power interruption test, one phase	November 2018	12 kVrms, 25 kArms, Official report
A.7	High power C-O test, one phase,	November 2018	12 kVrms, 25 kArms, Official report
A.7	1sec short time current test (STC), one phase	November 2018	25 kArms, 62.5 kApeak, Official report
A.8	Preliminary dielectric withstand test at SECRC	November 2018	AC 28 kVrms, BIL 75 kV
N/A	3 sec short time current test (STC), one FCS	December 2018	16 kArms, SECRC High Power Lab
A.9	Energy/redundancy capability at multiple operations		Multiple operations at nominal voltage and prospective fault current, validation of FLCB energy behaviour
A.10	EMC test on one phase panel	March 2019	Complete panel and selected components tested
A.11	Mechanical endurance of FCS	March 2019	2000 operations verified with minor service
TYPE TESTS			
A.12	Dielectric test	April 2019	AC 28 kVrms, BIL 75 kV, Ratingen, PEHLA observed
A.13	Temperature rise	May 2019	Ratingen, PEHLA observed
A.14	Breaking and making	May 2019	12 kVrms, 16 kArms, KEMA Netherlands
A.15	Short time current / peak current test	May 2019	16 kArms, 40 kApeak, KEMA Netherlands

Appendix A Reference	Description	Date	Comments
A.16	Internal arc (test no. 1)	May 2019	KEMA. This test failed with the panel sustaining damage to the panel rear wall
A.16	Internal arc (test no. 2)	July 2019	KEMA. Panel modifications were made and successful retesting occurred
FACTORY ACCEPTANCE TESTS			
N/A	FLCB tripping equipment	August 2019	Demonstration of tripping level calibration and tripping of FLCB
N/A	FLCB switching element	August 2019	Demonstration of FLCB as well as operation of the device, open and close, trip see above
N/A	FLCB current transformer	August 2019	Routine CT test
N/A	FLCB voltage transformer	August 2019	Routine VT test
N/A	FLCB cubicle	August 2019	Demonstration of integration, interlocks, safety features and wiring
N/A	QR6-B test set	August 2019	Check/demonstration of the test device and settings

Table 4 – List of validation tests, type tests and FATs carried out in the development of the FLCB

Based on some of the validation and verification results, ABB made design changes such as those highlighted in Section 5.1.1 to the FCS to ensure long-term operation.

All type tests and FATs passed with the exception of the internal arc test (IAC test) carried out at KEMA laboratories in Arnhem, the Netherlands in May 2019. During validation testing of the FC-protector, the design successfully passed an IAC test of 40 kA for 1second and as a result it was expected the FLCB designed for this project would have no issues at 25 kA for 1 second. However during the type test at KEMA, the rear wall of the panel was burnt through (see left image of Figure 27) as it was not designed to withstand an arc flash on it for one second. This unexpected failure was due to the difference in behaviour of an internal arc in a three-phase application compared to a single-phase one. It is worth noting that the front of the FLCB was unaffected due to the failed internal arc test as can be seen in the image on the right of Figure 27.

Figure 27 – Rear of FLCB panel (left) and front of panel (right) after failed internal arc test

After the failed first IAC test, the ABB team analysed and understood the direction the arc is forced and as a result redesigned the rear part of the panel. With reference to Figure 28 below, one earthing bar (1) and a C-shaped sheet (2) was added to attract the arc, “catch it” and prevent the arc from jumping to the rear wall. Additionally the rear wall was reinforced with an isolating sheet (3) and a metal sheet (4). As intended during the second IAC test, the arc could be controlled in the area of (1) and (2) and did not damage the rear wall; hence a successful pass of the IAC retest occurred in July 2019.

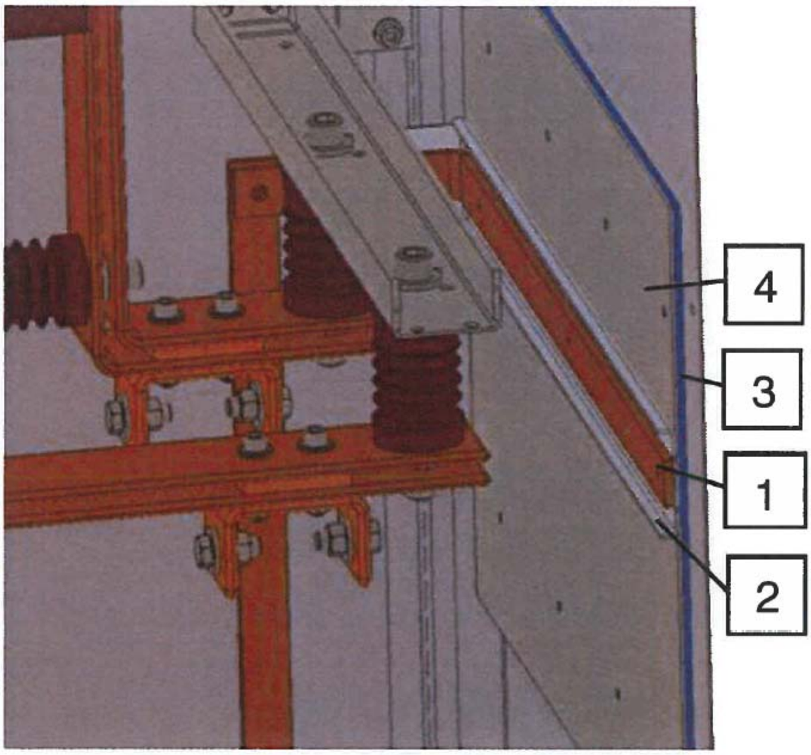


Figure 28 – Design modifications made to the rear of the FLCB panel following failure of internal arc test

In August 2019, FATs for the FLCB were carried out at ABB in Ratingen, Germany with UK Power Networks present. The FLCB passed all tests in the test plan with only minor issues for ABB to rectify before the device could be prepared for shipping. The issues to be rectified included:

- Addition of various warning labels and documentation;
- Time relay to be installed to allow opening of MV compartment door only after certain time has passed since capacitor charging voltage has been switched off;
- Covering the manual door release with a lockable cover and labelling it ‘Interlock override’; and
- Replacing CT-terminals with spring-loaded, screwed terminals.

8. Lessons Learned

The below subsections outline some of the key learning points from the development process of the FLCB for the Powerful-CB project.

8.1 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 was continuous discussion 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.

8.2 Losses Reduction

One of the requirements for the Powerful-CB project is that it should not have significant losses, both to limit waste of energy and eliminating the need for external cooling, which requires additional space and in most cases maintenance.

One of the most straight forward solution for realising a very fast fault current limiting circuit breaker is to use power semiconductors. However, a pure semiconductor based FLCB will not fulfil the requirements regarding cooling. The Powerful-CB addresses this by introducing an innovative hybrid concept introducing a very fast mechanical switch in parallel with the semiconductors. This will create low loss nominal operation, as well as, fast interruption.

8.3 Changes in Short Time Current Withstand Rating

It was initially stated in the requirement specification for the Powerful-CB project that the FLCB should be tested for a short time withstand current (STC) of 25 kArms for 1 second. This capability was verified at an early stage for the mechanical switch (FCS). However, at a later stage it was identified that to comply with the network standards for the selected trial substation the STC should be performed for 3 seconds instead. This introduces additional stress on the device since time is an important factor when considering the overall stress on the components.

Possible solutions were discussed, and it was agreed that the 3 second demand was definite, but the peak fault current could be reduced from 25 kArms to 16 kArms. This agreement would then limit the increase in stress on the FCS. Extended development testing was conducted, and the FCS was able to pass the new requirements, which was also verified in the type test.

8.4 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 will allow the doors to open only if the adjacent circuit breakers are set to earthed position, which is defined by transmitting a "status: earthed" signal. For the Powerful-CB trial, the existing switchgear does not have the ability to send this signal. Additionally, earthing for the cable part needs to be applied manually. For the trial we will need to use the "status: open" signal and apply manual earth before opening the cabinet doors. For future applications we need to check the ability of switchgear to provide "earthed" signal and decide on the required actions if this capability is absent. However as mentioned in Section 4.2, if a commercial FLCB is produced, the requirement is that the device must have integral isolating/earthing facilities.

8.5 Redundancy of Modules

Throughout the project reliability and availability of the device has remained a key focus area. Introducing a concept consisting of several individual components could therefore be considered a risk factor if a single component failure would lead to device failure.

It was therefore decided that the modular concept used would consist of four instead of three independent modules. The idea being that if a sub-component fails during interruption, the remaining three modules would still interrupt the current. The FLCB is then blocked from further operation until the problem is resolved.

8.6 Use of Off the Shelf Components

To implement the FLCB within the project timeframes one of the key enablers was the use of already existing concepts and components, such as, FLCB technical demonstrator, existing panel for similar application and fault detection/tripping device. This made it possible to design, verify and type test the FLCB within the given time frame. If new components were to be designed for this application, additional time in excess of the project duration would have been required.

8.7 Selection of Control Systems

The Powerful-CB project introduces a new concept of fault current limitation and interruption that requires a more sophisticated controller than what is conventionally used. Several sub-components need to operate, not only very fast, but also very accurately regarding time difference, typically in the micro second range. It was also decided that the use of existing hardware and software would deliver the most flexible solution and reduce the development requirement. Therefore, a commercial FPGA platform with optical modules was selected running a commonly used programming platform. Again, similar to Section 8.6, additional time would have been required to design the control system.

8.8 Need for an Autoclose Scheme

When we studied all the possible fault scenarios at the trial substation, we identified a specific situation where we could end with a "dead" busbar. This is caused by the high speed of the FLCB which introduces complications with the conventional protection grading of the equipment. The issue can be resolved by a control engineer, but in order to have an automated and quick resolution of such a scenario we decided to install an autoclose scheme which will re-energise the busbar in the case of that specific fault occurs. This lesson will be useful in the development of the engineering design standards and is dependent on the configuration of the substation.

8.9 Signal List Decisions

The exact number and type of signals that the FLCB device will need to provide, as information back to the control centre, was not defined at the start of the project. We wanted a larger number of signals transmitted through copper cables in accordance with UK Power Networks' standards instead of Ethernet. This posed issues with the limited number of relay contacts available so for the trial we have grouped a number of signals into one. The lesson here is that we need to consider the 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 explored further within UK Power Networks.

9. Summary

The project has successfully delivered on the requirements of SDRC 9.1.1, and this report provides an overview of the functional requirements, design considerations, validation and testing carried out to develop the FLCB ready for network demonstration.

The report captures the development process for the FLCB undertaken by the Powerful-CB project including the following:

- Identifying operational and functional needs of the FLCB;
- Design and development of the prototype FLCB by ABB;
- Completion of detailed design to integrate the FLCB into the existing network: and
- Validation, type testing and FATs of the FLCB

The project produced an Engineering Technical Specification and provided this to project partner, ABB, which identified our requirements as outlined in Section 4. ABB then began to finalise the design of the FLCB and complete validation testing of various components with input from UK Power Networks. Throughout this process a number of safety additions were made to ensure safety of personnel working on or in the vicinity of the FLCB. Given the time frames of the project, ABB used existing key components rather than developing new ones such as FLCB demonstrator, FC-Protector panel and fault current detection circuitry.

The FLCB operates with so quickly, bypassing the typical time grading of existing protection systems. We aim to produce guideline on how to approach this in the Engineering Design Standard that will be produced later in the project.

During the design process to integrate the FLCB to the existing network, the project identified a scenario where there may be a dead section of bus due to the fast operation of the FLCB and applied preventative measures. The mitigation was to implement an autoclose scheme to the pre-existing bus coupler at the trial site.

Currently, there are no existing standards for fault current limiters; instead relevant parts of circuit breaker standards are adapted with certain necessary modifications. Throughout the development of the FLCB, ABB conducted a number of validation tests on components and modules prior to commencing type testing. These type tests include:

- 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 on the first attempt. Investigations by ABB showed that only minor modifications were needed to the FLCB panel to resolve the issue and detailed in Section 7.

In August 2019, FATs for the FLCB were carried by ABB with UK Power Networks present. The FLCB passed all tests in the test plan with only minor issues for ABB to rectify before the device could be prepared for shipping.

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

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

9.1 Next Steps

Following the successful development of the FLCB – passing all type tests and completing FATs, the project will transition to installation, commissioning and commencement of the network trial. As highlighted in the June 2019 Project Progress Report, site works have already commenced to extend the existing busbar and to ready the space the FLCB will be installed.

The key outputs over the next phase of the project include:

- Commencement of network demonstration period;
- Delivery of SDRC 9.2.1 – Install and commission solution at an 11 kV substation (Method 1); and
- Updating the safety case that formed part of SDRC 9.1.3 and 9.1.4.

Appendix A – Explanation of Testing Activities

The following appendix details the validation tests, type tests and FATs carried out to ready the FLCB for network demonstration.

A.1 Internal Arc Test (Validation Testing)

The internal arc test is intended to verify the effectiveness of the design in protecting people in the vicinity of electrical equipment in case of an internal arc. The internal arc class makes allowance for protection against internal overpressure, thermal effects, ejected hot gases and glowing particles.

The panel used for the Powerful-CB project is an existing MV panel which is, for instance, used for the existing ABB FC-protector. The FC-protector has previously passed internal arc testing at 40 kA and it was thought that even though it is not identical to the Powerful CB device being developed, it was likely that the FLCB would also comply with this test, especially since the project requirement is significantly lower, 16 kA (25 kA).

A.2 BiGT Verification Testing

The type of power semiconductors used, IGBTs/BiGTs, are conventionally used in applications like transmission, converters and drives. In the design and specification of such components the focus is therefore on continuous switching of a certain nominal current. Specified data is therefore focusing on these applications. However this does not mean that they could not be used for other applications, such as the FLCB. The devices have an excellent performance in switching, also at much higher currents, provided that the duration is short and the energy during turn-off can be managed.

To secure operation in this new type of application and operation mode, several steps are considered. Some of the most critical ones are; gate-unit design, snubber selection, circuit simulations and performance verification testing.

A.2.1 BiGT Endurance Testing at Room Temperature and Elevated Temperature

The FLCB being developed is using BiGTs in a new application, it is therefore important to investigate their performance and limitations. According to the Powerful-CB requirement specification, the FLCB should be able to perform a minimum of 100 electrical interruptions. The BiGTs were therefore tested 100 times at >13.5 kA interruption current, both at room temperature and elevated ambient temperature of 70°C. Figure 29 below shows the test circuit and Figure 30 shows the recorded test data displayed.

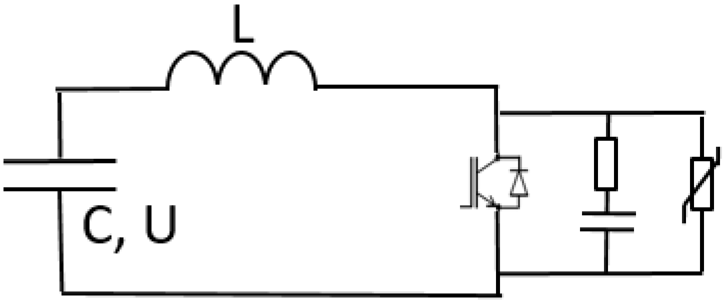


Figure 29 – Test circuit used for BiGT interruption test

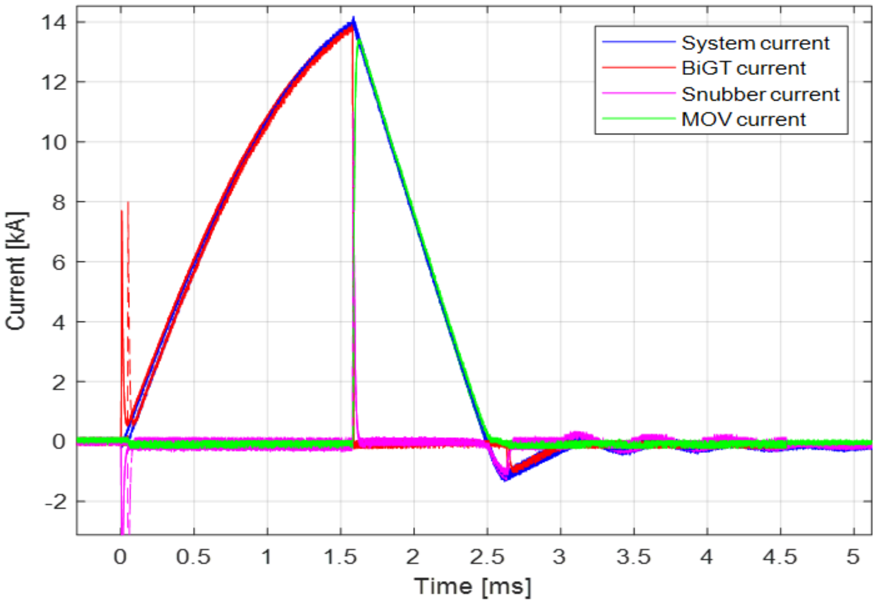


Figure 30 – Interruption testing with BiGT and MOV surge arrester

The BiGTs passed the 100-operations endurance test, both at room temperature and elevated temperature successfully, interrupting >13.5 kA in each test. During the Powerful-CB pilot the interrupted current is expected to be <12 kA, based on the tripping level and the operation time of the FLCB.

A.2.2 BiGT Limit Testing

Even though the BiGTs passed the interruption and endurance testing in Appendix A.2.1, it is important to, as well as for the FCS, understand the full performance and margins in the design. In addition to the interruption testing at the design level limit testing is performed. After the finalisation of the electrical endurance, the fault current in the test circuit is increased in steps until the interruption capability of the device is exceeded. This was done both at room temperature and at elevated ambient temperature 70°C. This resulted in breakdown at a level significantly higher than the design value, approximately 0.14kA, creating a good margin and reducing the risk of failure to an acceptable level.

A.3 Functional Test – First Assembly

One of the first delivery milestones of the project was the assembly and functional verification of a complete single phase FLCB. 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 1 kA range and very limited voltage.

Figure 31 – First test assembly of the FLCB

A.4 FLCB Endurance Testing

Equally important as showing the endurance of only the BiGTs is to verify the endurance of the commutation of the current from the mechanical switch to the BiGTs.

This is verified by performing multiple operations/interruptions with a complete FLCB module. To comply with the requirement specification produced by UK Power Networks, a series of 100 interruptions at full current was performed. All 100 tests, commutations and interruptions, were performed successfully.

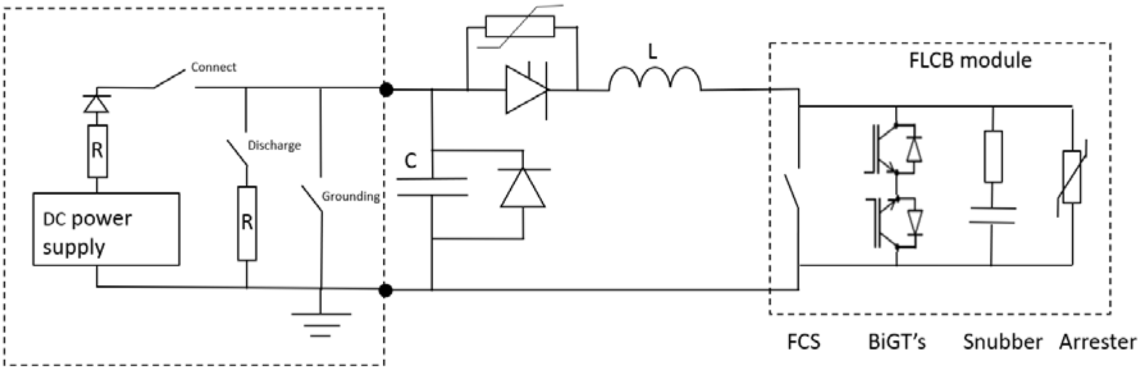


Figure 32 – Test circuit for interruption testing of FLCB module

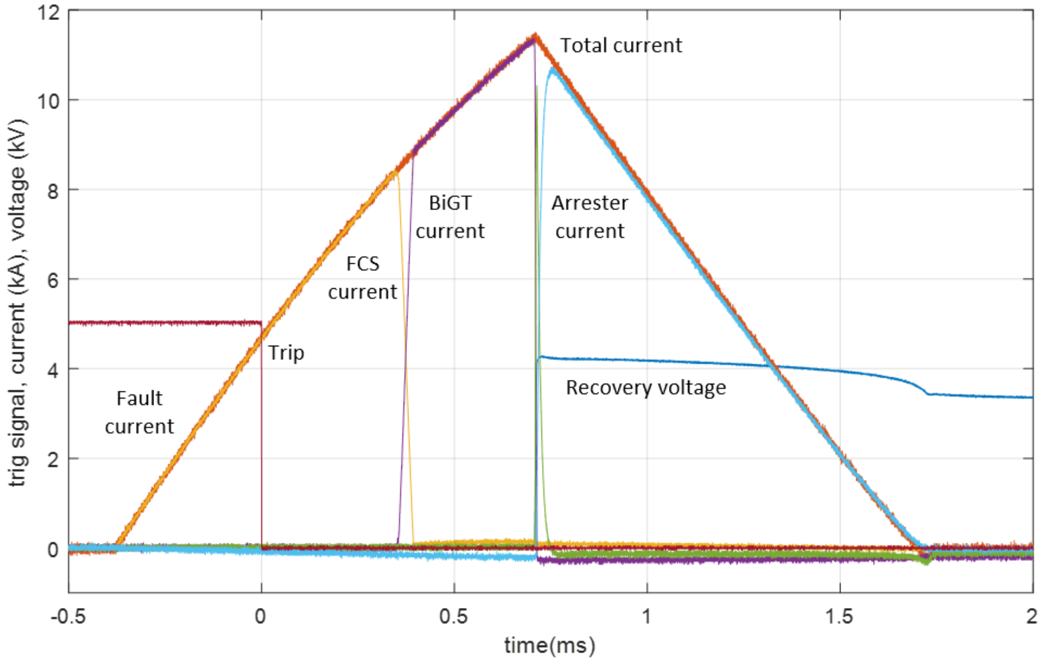


Figure 33 – Description of the test sequence for the FLCB module for endurance testing

A.5 Short Time Current (STC) Test, 25kA 1 sec Single FCS

For the short time current (STC) withstand requirements the critical component is 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 are remaining in closed position, i.e. resisting the current forces, and avoiding damage to the contact system. Therefore, it is important to verify the STC capability of the FCS. In initial stages this was tested on a single FCS.

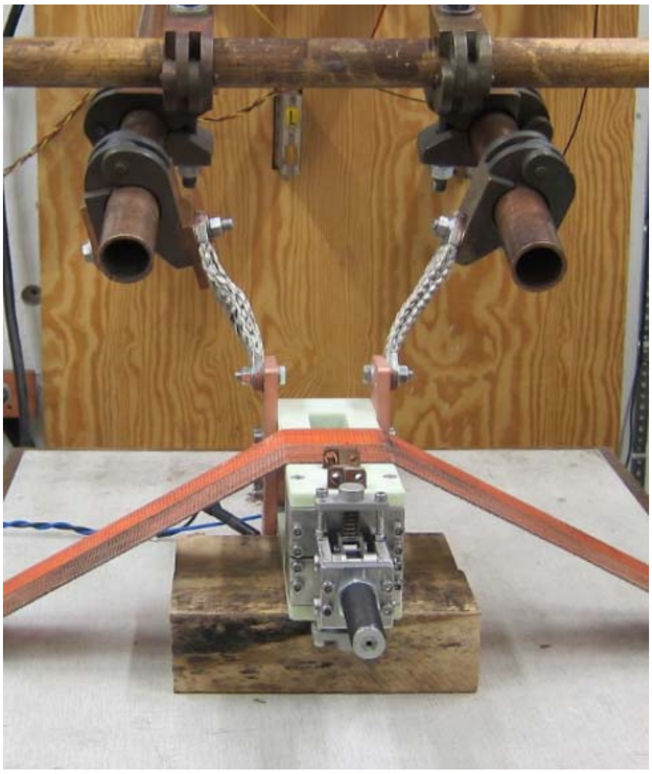
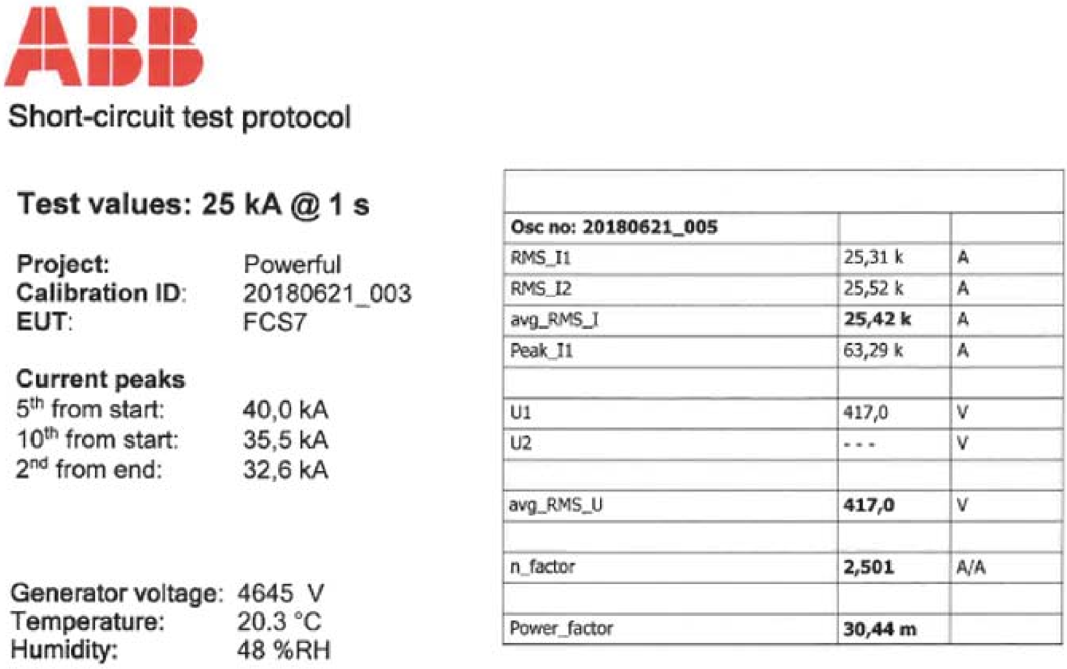


Figure 34 – Set-up for one of the 25kA 1sec short time currentt tests of the FCS

The FCS passed the STC test successfully at 1 s 25 kArms, 63 kApeak and an extract from the testing documentation can be found below in Figure 35.



ABB

Short-circuit test protocol

Test values: 25 kA @ 1 s

Project: Powerful
Calibration ID: 20180621_003
EUT: FCS7

Current peaks
5th from start: 40,0 kA
10th from start: 35,5 kA
2nd from end: 32,6 kA

Generator voltage: 4645 V
Temperature: 20.3 °C
Humidity: 48 %RH

Osc no: 20180621_005		
RMS_I1	25,31 k	A
RMS_I2	25,52 k	A
avg_RMS_I	**25,42 k**	A
Peak_I1	63,29 k	A
U1	417,0	V
U2	- - -	V
avg_RMS_U	**417,0**	V
n_factor	**2,501**	A/A
Power_factor	**30,44 m**	

Figure 35 – STC test results for a single FCS

A.6 Temperature Rise Test (Validation Testing)

A preliminary temperature rise test was performed with an early version of the FLCB. The test indicates that there is a good margin between the measured and the values given in the standards as can be seen in Figure 36. The criteria for passing the test is delta-T < 65°C and the absolute temperature should not exceed 105°C.

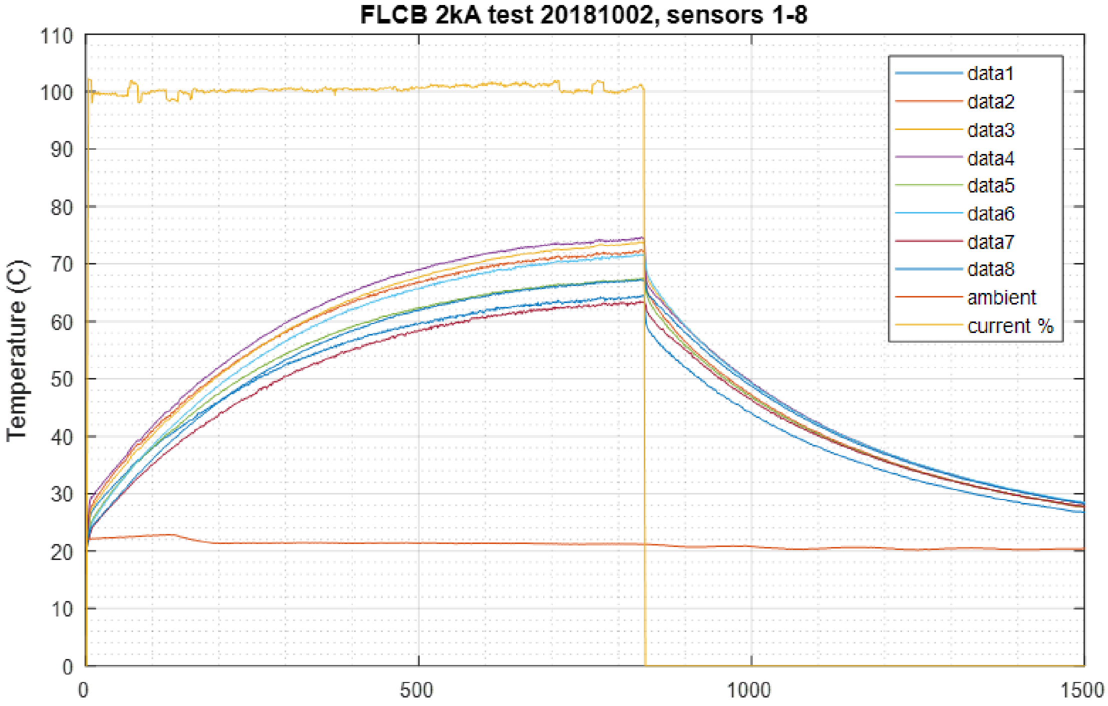


Figure 36 – Preliminary temperature rise test on an early assembly performed at SECRC in Västerås, Sweden. The various results are measurements from different sensors situated in within the panel

A.7 Interruption, Close-Open (C-O) and Short Time(STC) Test on FLCB Integrated in Panel

After having verified the necessary performance and acceptable endurance on a module level, as a next step the complete four module FLCB, integrated into the panel was tested PEHLA Testing Laboratory in Ratingen, Germany. This test was performed at the full rating according to the requirement specification on a single phase unit. However, since the installation is in a neutral grounded configuration the single-phase test will very well represent the actual performance. Also, the first pole to clear factor[11] is emulated by increasing the applied voltage during the single-phase test. The first-pole-to-clear-factor is used for calculating the transient recovery voltage for three-phase faults.

During this test shift at the laboratory, three different tests were performed:

- STC 1 s, 25 kArms, 63 kApeak;
- Interruption test up to 25 kA prospective fault current; and
- CO-3 min-CO at 25 kA prospective fault current.

All tests were performed successfully and are documented in the test report.

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[11] Explanation of first-pole-to-clear-factor http://www.ewh.ieee.org/soc/pes/switchgear/presentations/tp_files/2013-1_Thu_Dufournet.pdf

Figure 37 – FLCB after final interruption test

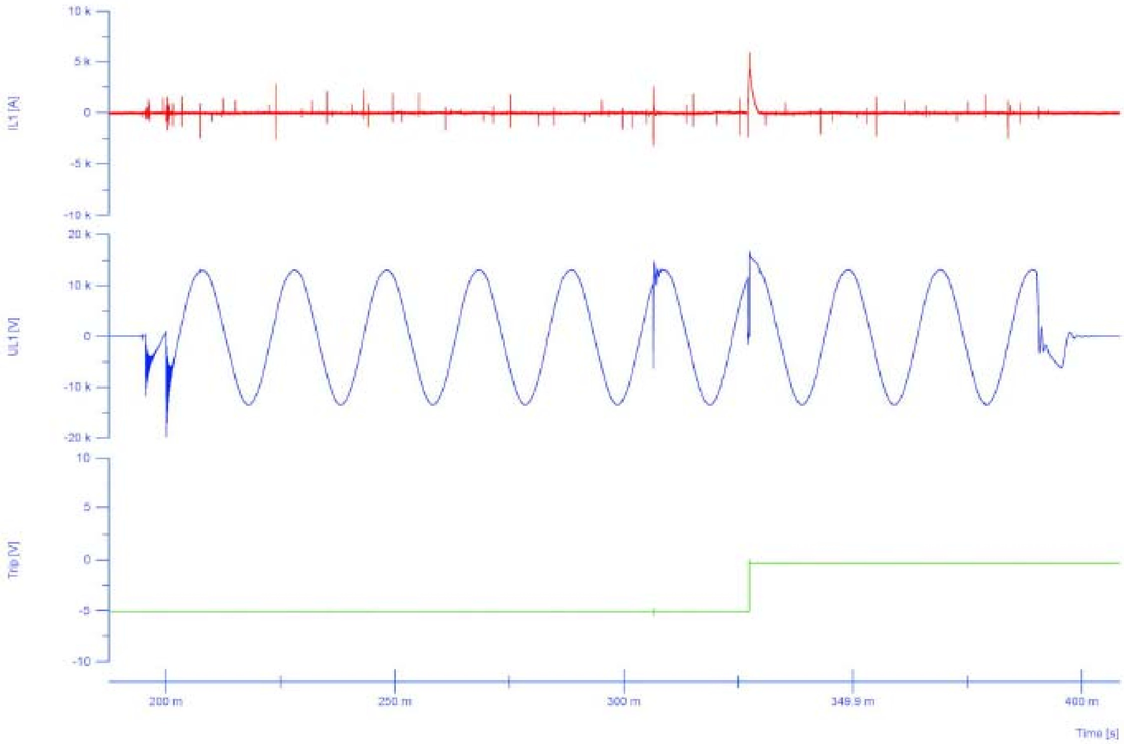


Figure 38 – Example of a C-O operation at full prospective fault current (25 kArms).

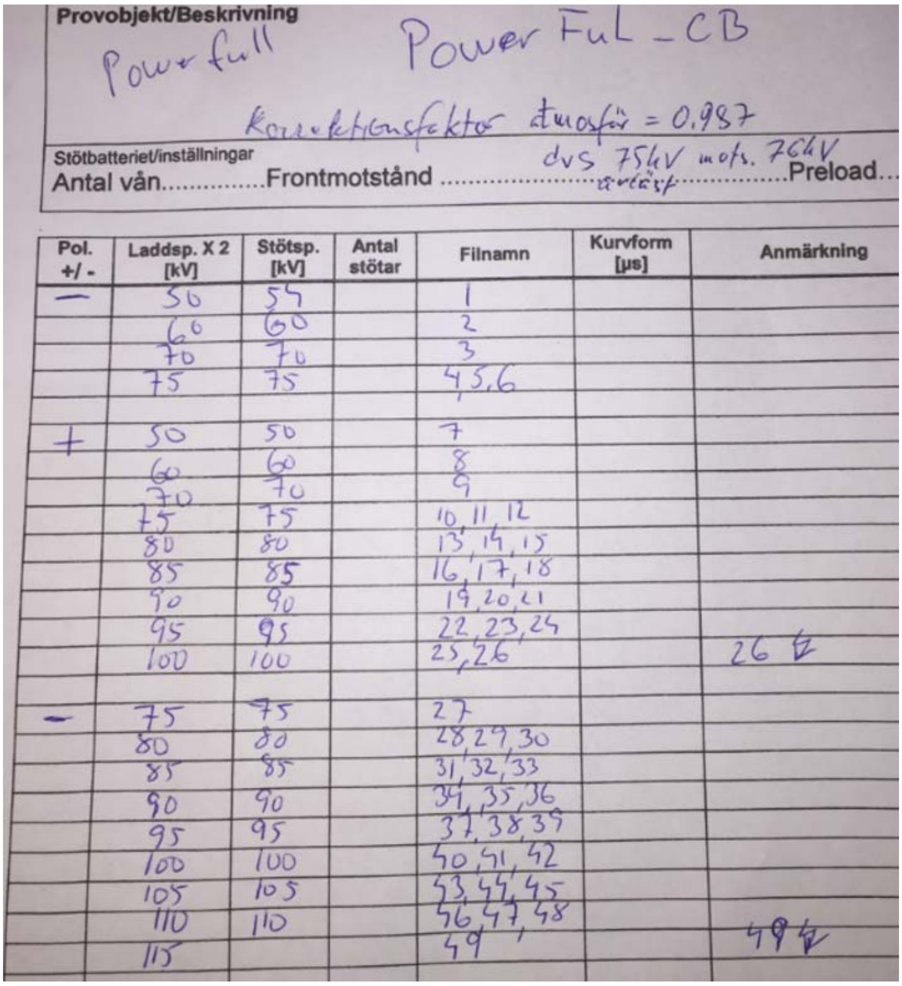
Legend: Blue line (voltage), Red line (current), Green line (close command)

A.8 Insulation Testing

Insulation testing of the new components affecting the insulation performance and the complete FLCB, mounted in the panel, was performed during the design and will also be repeated as a type test before the installation.

Most of the components used, such as, cables and insulators are certified for this voltage level. However, the newly developed mechanical switch, FCS, will during operation be exposed to the full voltage and potentially over-voltages. A dedicated investigation of this component was therefore conducted.

In a preliminary test using an early version of the FCS it passed the required 75 kV basic insulation level (BIL) with results shown in Figure 39 below.



Provobjekt/Beskrivning
Powerfull
Power FuL _CB
Korrektionsfaktor atmosfär = 0,987
dvs 75kV mots. 76kV
avläst

Stötbatteriet/inställningar
Antal vån…………….Frontmotstånd ……………………………………….Preload…

Pol. +/-	Laddsp. X 2 [kV]	Stötsp. [kV]	Antal stötar	Filnamn	Kurvform [µs]	Anmärkning
–	50	54		1		
	60	60		2		
	70	70		3		
	75	75		4,5,6		
+	50	50		7		
	60	60		8		
	70	70		9		
	75	75		10,11,12		
	80	80		13,14,15		
	85	85		16,17,18		
	90	90		19,20,21		
	95	95		22,23,24		
	100	100		25,26		26 ↯
–	75	75		27		
	80	80		28,29,30		
	85	85		31,32,33		
	90	90		34,35,36		
	95	95		37,38,39		
	100	100		40,41,42		
	105	105		43,44,45		
	110	110		46,47,48		
	115			49		49 ↯

Figure 39 – Protocol from insulation testing of FCS; required 75 kV lightning impulse (LI)

After performing the first high power test series in Ratingen, November 2018, the FLCB was returned to SECRC and a dielectric test was performed. The FLCB passed both the 28 kV AC test and the 75 kV BIL test according to the standards including IEC 62271-200 clause 6.2.

A.9 Energy/Redundancy Capability at Multiple Operations

In addition to demonstrating the functional performance of the FLCB it is also valuable to understand the influence on the components at multiple operations. Multiple operations do not directly influence the interruption capability but could indirectly be affected by the temperature rise, due to energy dissipation, in the arresters and Power Semiconductors. A test series was therefore conducted in the high power laboratory at SECRC where several C-O and interruptions at full prospective fault current were performed with a minimum time delay of 3 minutes, which is defined in the requirement specification. Since the test laboratory at SECRC was not able to produce the correct test voltage for the three phase FLCB, the test was performed on a single module. This will give the correct verification results for the single module and may then be scaled to the full FLCB.

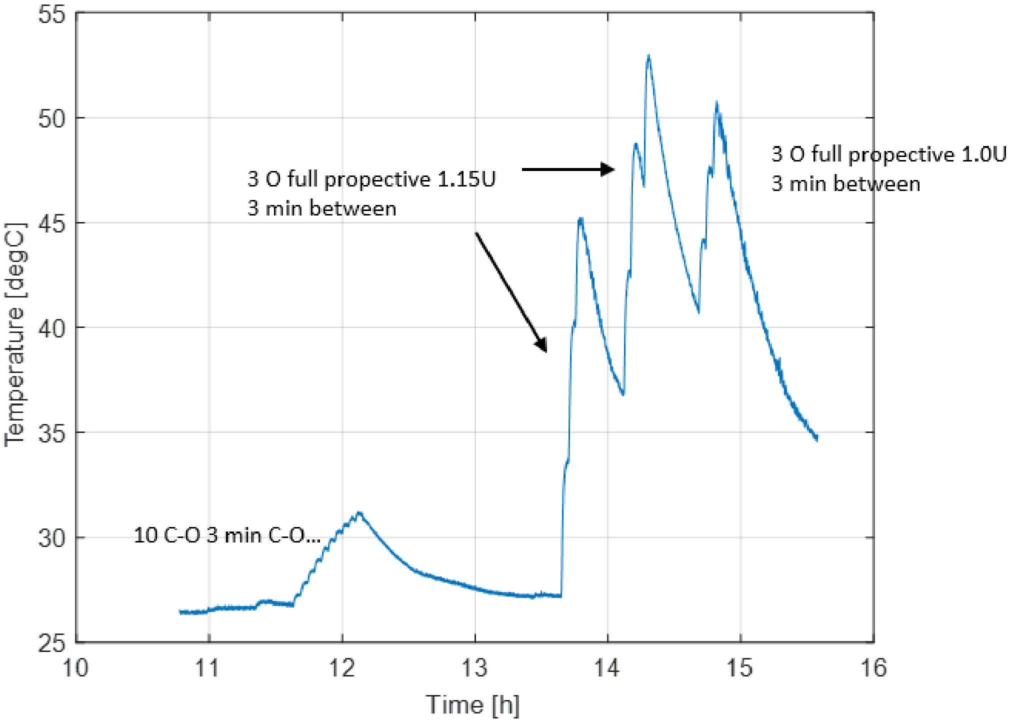
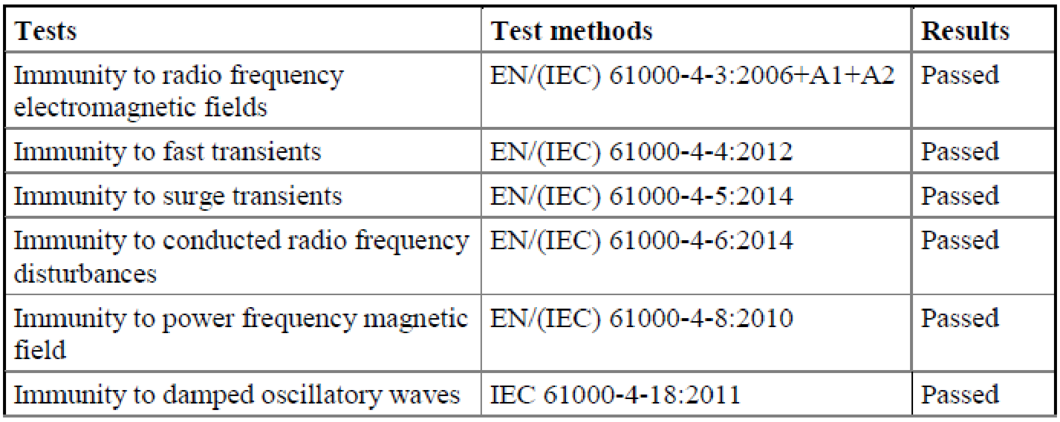


Figure 40 – Temperature increase on the surge arresters during multiple operations

The conclusion was that multiple operations, at least according to the requirement specification, should not affect the performance of the FLCB due to energy dissipation or elevated temperature.

A.10EMC Testing

Since the FLCB consists of several new controllers and sensors, which are new for this application, an EMC test was performed on the complete panel (single phase) and selected critical components. Tests performed and the methods used are summarised in Figure 41 below.



Tests	Test methods	Results
Immunity to radio frequency electromagnetic fields	EN/(IEC) 61000-4-3:2006+A1+A2	Passed
Immunity to fast transients	EN/(IEC) 61000-4-4:2012	Passed
Immunity to surge transients	EN/(IEC) 61000-4-5:2014	Passed
Immunity to conducted radio frequency disturbances	EN/(IEC) 61000-4-6:2014	Passed
Immunity to power frequency magnetic field	EN/(IEC) 61000-4-8:2010	Passed
Immunity to damped oscillatory waves	IEC 61000-4-18:2011	Passed

Figure 41 – EMC tests performed on the FLCB, complete panel and selected components

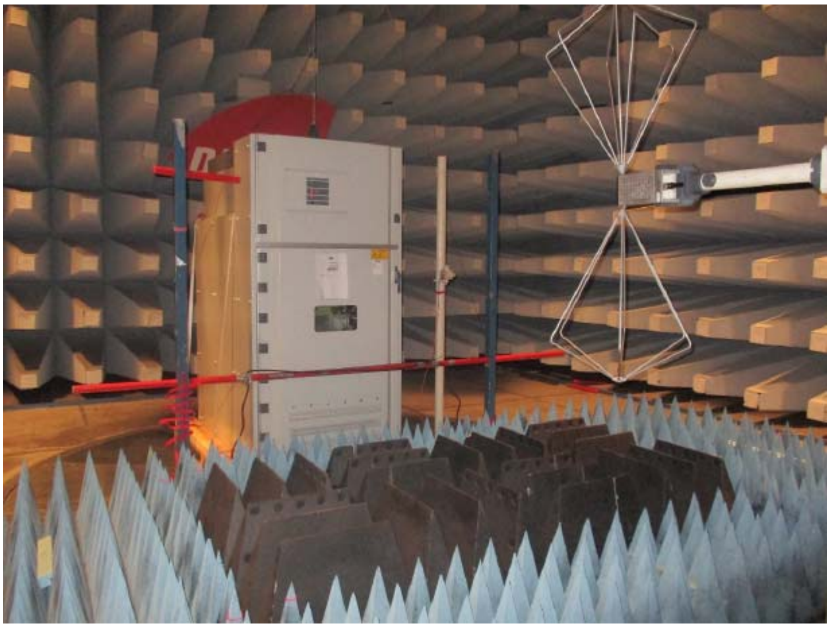


Figure 42 – FLCB panel (single phase) during EMC testing

A.11FCS Endurance Testing

One of the most critical parts of the design is the long-term stability of the mechanical switches, since these are new components designed for the FLCB device. Although there is past experience from using similar design switches for several applications, this is a new design and it needs to be thoroughly validated.

The key features of the switch are speed and contact resistance. It needs to operate within <1 ms and it should have a resistance low enough to meet the thermal requirements of the FLCB. These features, especially in combination, put a high demand on contact force, low weight and high mechanical strength.

To meet these challenges several actions are identified, such as, selection and evaluation of materials, simulations on operation and mechanical stress, as well as, extensive endurance testing.

In the initial testing some critical design limitations were identified and the first couple of FCS's did not pass the targeted number of operations. After a re-design, mainly of the pull-rod and attachment to the moving contact, an updated version passed the 2000 mechanical operations required.

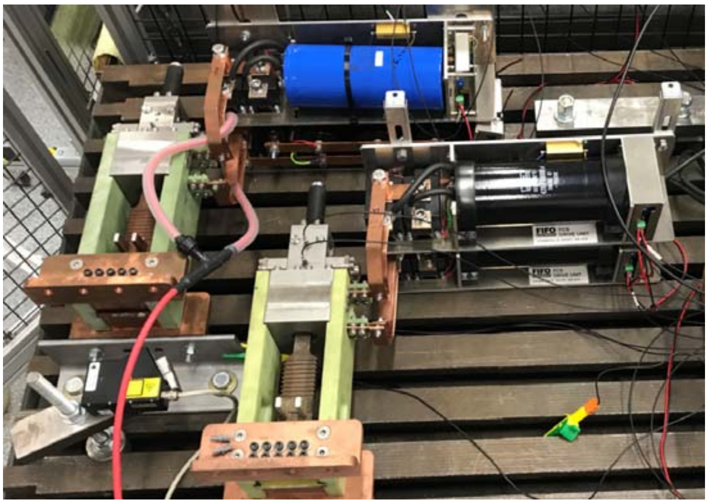
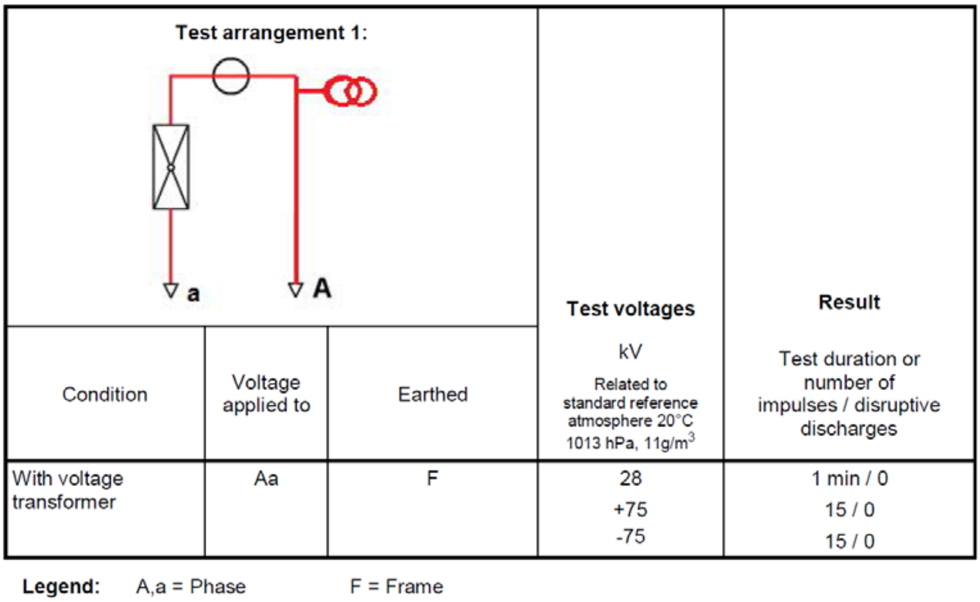


Figure 43 – Mechanical endurance test set-up

Even though the FCS passed the 2000 operations with only minor service attention, the design received a last update with minor changes before the installation. Endurance testing is still on-going, in parallel with type testing and installation preparation, to gain as much knowledge and confidence as possible prior to the installation.

A.12 Dielectric Withstand

The dielectric withstand test for this type of equipment, rated 12 kV, is 28 kV power frequency for 1 minute and lightning impulse, pos. and neg., 75 kV. All dielectric tests were performed successfully in accordance with IEC 62271-200 clause 6.2.



Condition	Voltage applied to	Earthed	**Test voltages** kV Related to standard reference atmosphere 20°C 1013 hPa, 11g/m^3	**Result** Test duration or number of impulses / disruptive discharges
With voltage transformer	Aa	F	28 +75 -75	1 min / 0 15 / 0 15 / 0

Legend: A,a = Phase F = Frame

Figure 44 – Test arrangement including VTs for dielectric testing

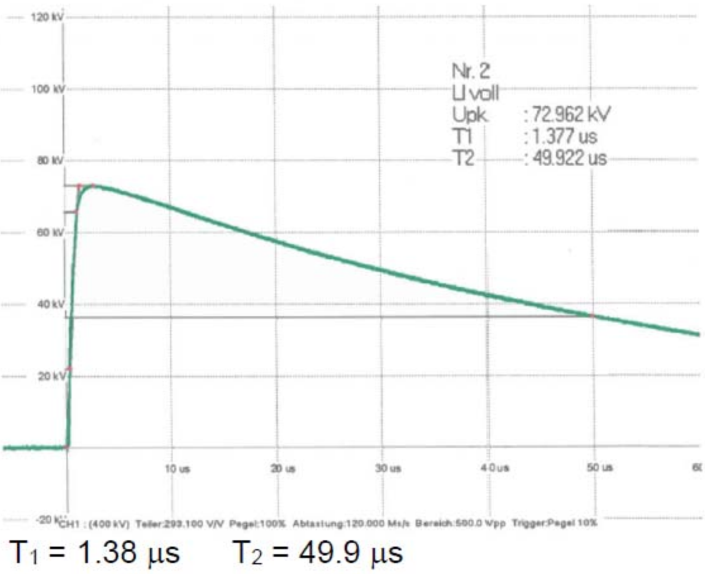


Figure 45 – Lightning impulse test voltage 75 kV

A.13 Temperature Rise Test (Type Test)

The temperature rise test was undertaken to ensure that the maximum temperature of the switchgear does not exceed during operation under nominal current. For the project trials, 1250 A is expected to be the maximum current. However, to extend the possible scope of the device, it was tested for both 1250 A and 2000 A. The test was carried out in accordance with IEC 62271-200 clause 6.4 and 6.5.

Both tests were passed with a healthy margin. Since completion of the type test, further improvements have been made, especially in terms of nominal losses so that an even larger margin is expected.

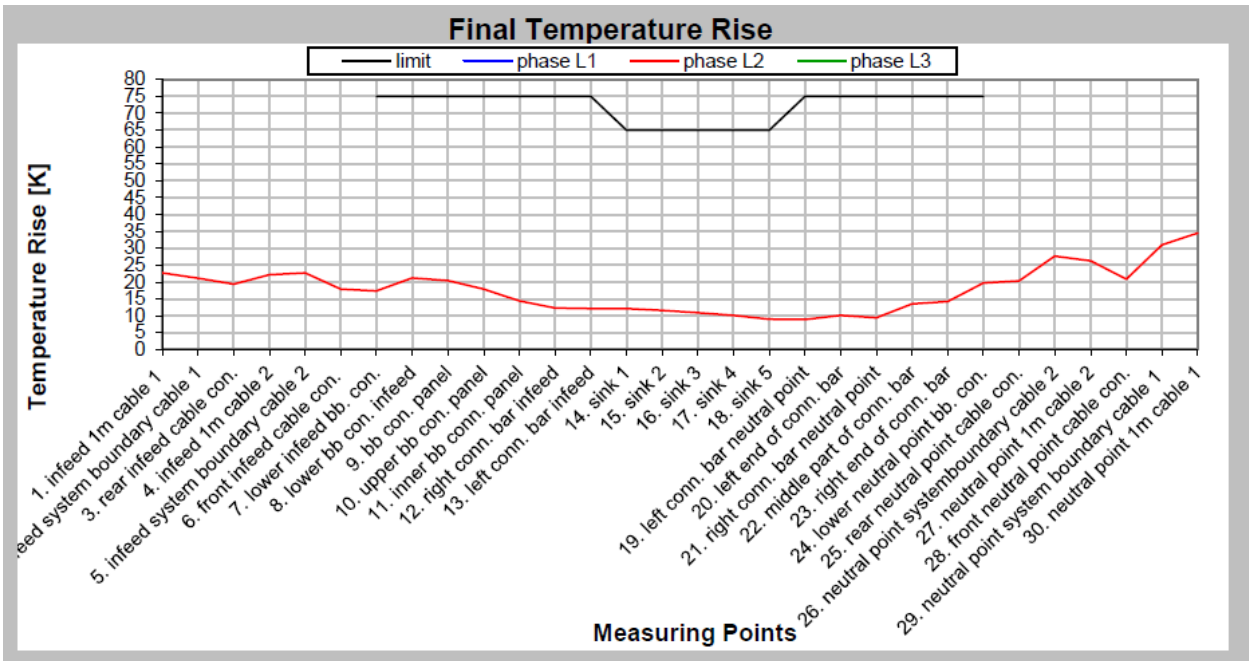


Figure 46 – Temperature rise test results for phase L2

A.14 Making and Breaking Test

Make-break testing is performed to confirm the breaking performance of the FLCB. It is agreed by the project team that for the trial, the making current, in other words, closing onto live equipment, will not be done with the FLCB but with the adjacent breakers. It was, however, requested for the project that it should still be verified through testing that the close-open (C-O) sequence in the requirement could be performed with the FLCB stand alone.

The make-break was performed according to the agreed sequence O-(3 min)-CO-(3 min)-CO. This test was repeated at T30, T60 and T100, which means at 30, 60 and 100 percent of the full prospective fault current 16 kArms. The FLCB closed and cleared during all tests performed.

Below is the test circuit and an example of a CO operation at 100% prospective fault current.

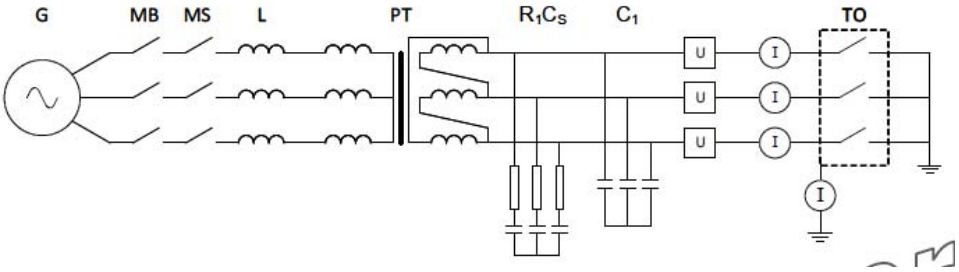


Figure 47 – Test circuit for the make-break (CO) testing

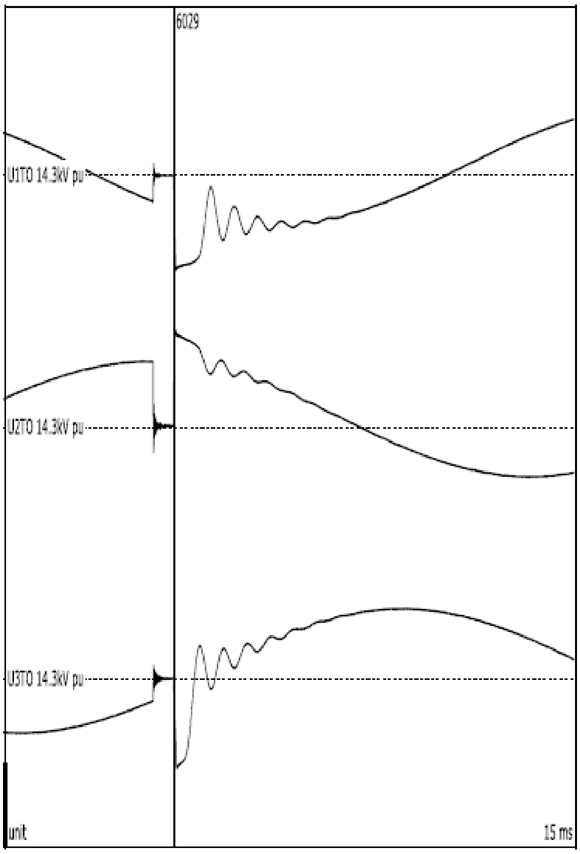
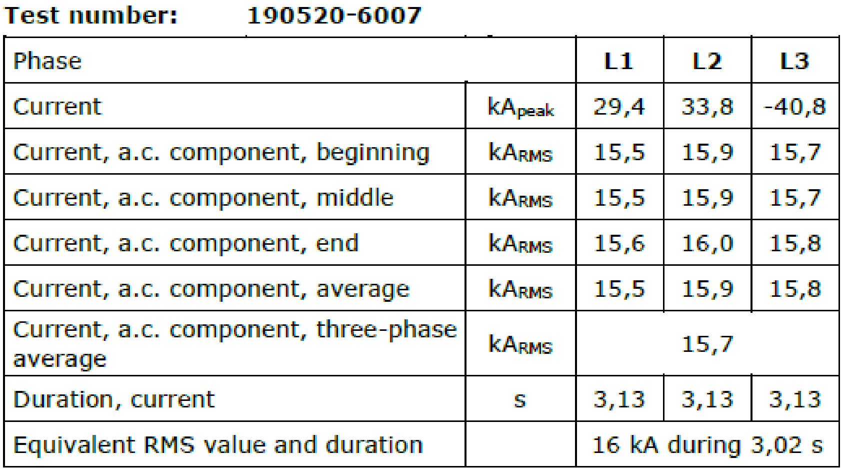


Figure 48 – Voltage graph from the CO operation at full prospective fault current

A.15 Short Time Current Withstand

In the short time current (STC) test, the FLCB's ability to withstand the full prospective fault current in closed position for 3 second was tested. No load operations and resistance measurements before and after the test is performed to ensure that the device has not been damaged during the short circuit. The FLCB passed the STC without any remarks.

Figure 49 – FLCB panels after short time current withstand testing



Test number: **190520-6007**

Phase		**L1**	**L2**	**L3**
Current	kA$_{peak}$	29,4	33,8	-40,8
Current, a.c. component, beginning	kA$_{RMS}$	15,5	15,9	15,7
Current, a.c. component, middle	kA$_{RMS}$	15,5	15,9	15,7
Current, a.c. component, end	kA$_{RMS}$	15,6	16,0	15,8
Current, a.c. component, average	kA$_{RMS}$	15,5	15,9	15,8
Current, a.c. component, three-phase average	kA$_{RMS}$	15,7		
Duration, current	s	3,13	3,13	3,13
Equivalent RMS value and duration		16 kA during 3,02 s		

Figure 50 – Values from the STC testing

A.16 Internal Arc Test

As previously mentioned in Appendix A.1, internal arc testing is performed in order to secure personal safety incase of an arcing fault in the panel during operation. The test is performed with an ignited arc in the panel at full prospective fault current for 1 s. The test object is surrounded by indicators as shown in Figure 51 that should not be compromised during the test.

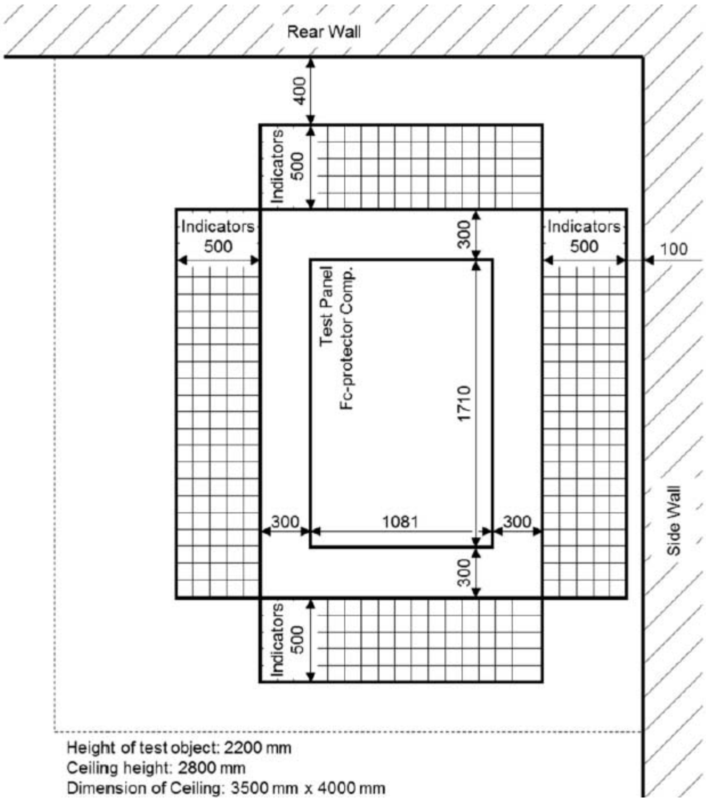
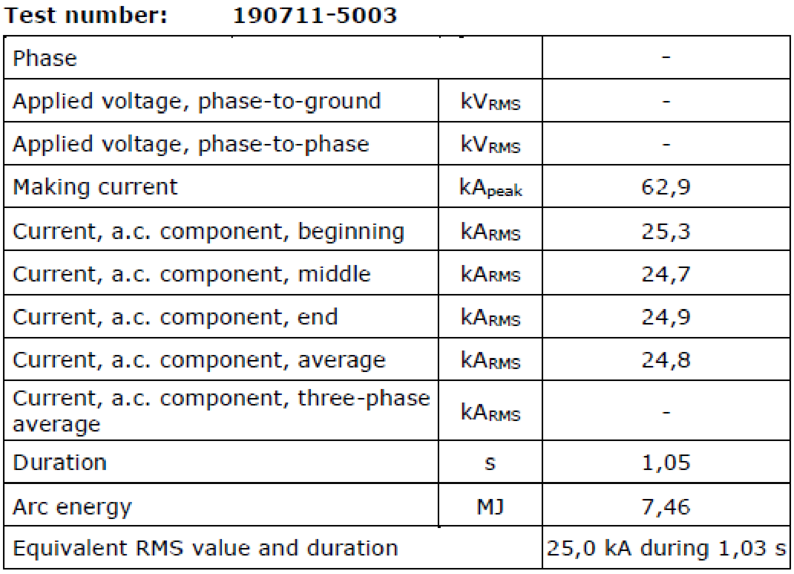


Figure 51 – Set-up for internal arc testing of the FLCB

The internal arc tests were conducted according to IEC 62271-200 clause 6.106. However as mentioned in Section 7, when conducting the initial internal arc test at KEMA for the completed FLCB, the test failed at the rear of the panel. ABB carried out an investigation into the cause of the failure and then made modifications to the panel design. Following these changes the FLCB passed the second internal arc test at 25 kArms test current for 1 s.



Test number: 190711-5003

Phase		-
Applied voltage, phase-to-ground	kV_{RMS}	-
Applied voltage, phase-to-phase	kV_{RMS}	-
Making current	kA_{peak}	62,9
Current, a.c. component, beginning	kA_{RMS}	25,3
Current, a.c. component, middle	kA_{RMS}	24,7
Current, a.c. component, end	kA_{RMS}	24,9
Current, a.c. component, average	kA_{RMS}	24,8
Current, a.c. component, three-phase average	kA_{RMS}	-
Duration	s	1,05
Arc energy	MJ	7,46
Equivalent RMS value and duration		25,0 kA during 1,03 s

Figure 52 – Values from the successful internal arc test of the FLCB

Appendix B – Reports Produced During Development

The following documents and test reports were produced during the development of the FLCB and are available upon request:

[1] ETS 03-6511, Specification for Indoor 12 kV Power-Electronic Fault-Limiting Circuit Breakers

[2] PEHLA test report, 17062Ra, “Internal arc testing of metal-enclosed, air insulated switchgear with fault current limiter, ZS-P with FC-Protector”

[3] 2018/SECRC/P/LR/410, “Interruption testing of a one phase FLCB at 25 kA prospective fault current”

[4] 2019/SECRC/P/TN/284, “FCS electrical endurance”

[5] 2019/SECRC/P/TN/286, “FLCB temperature rise test, 2 kA”

[6] HQ 136 F 001, “STC C-O and interruption testing 12 kV 25 kA” Official report High Power lab in Ratingen

[7] 2019/SECRC/P/TN/283, “Test protocol FCS14 16 kA 3 sec”

[8] 619-20000-10-R0, “EMC immunity test of FLCB panel 1 and breaker module”, DELTA Development Technology AB”

[9] 2019/SECRC/P/TN/327, “FCS mechanical endurance test”

[10] PEHLA test report, 19016Ra, “Metal-enclosed, air-insulated switchgear with short-circuit protection device – Dielectric test”

[11] PEHLA test report, 19018Ra, “Metal-enclosed, air-insulated switchgear with short-circuit protection device – Temperature rise test 1250 A”

[12] PEHLA test report, 19019Ra, “Metal-enclosed, air-insulated switchgear with short-circuit protection device – Temperature rise test 2000 A”

[13] KEMA preliminary test report 72117788_1-02, “Internal Arc testing of “FLCB”” (First internal arc test attempt)

[14] KEMA test report 2207-19, “STC testing of “FLCB”.

[15] KEMA test report 2206-19, Making and breaking testing of “FLCB””

[16] KEMA test report 2352-19, “Internal Arc testing of “FLCB”” (Second internal arc test attempt)

[17] 244445087, “FAT – Shop Inspection and Test Plan”

[18] TYPE TEST CONFORMANCE DECLARATION TO ENATS 41-36

Appendix C – Memo For the Philosophy of Autoclose Scheme at Network Demonstration Site

For the trial of the FLCB there will be three different running arrangements demonstrated. In a discussion between the project team and Network Operations (Control, Outage Planning & Head of London Network Operations) it was identified that the third running arrangement will require an auto-close scheme to remove the risk of a busbar outage for a transformer fault of Grid Transformer (GT2). The third running arrangement is shown below in Figure 53.

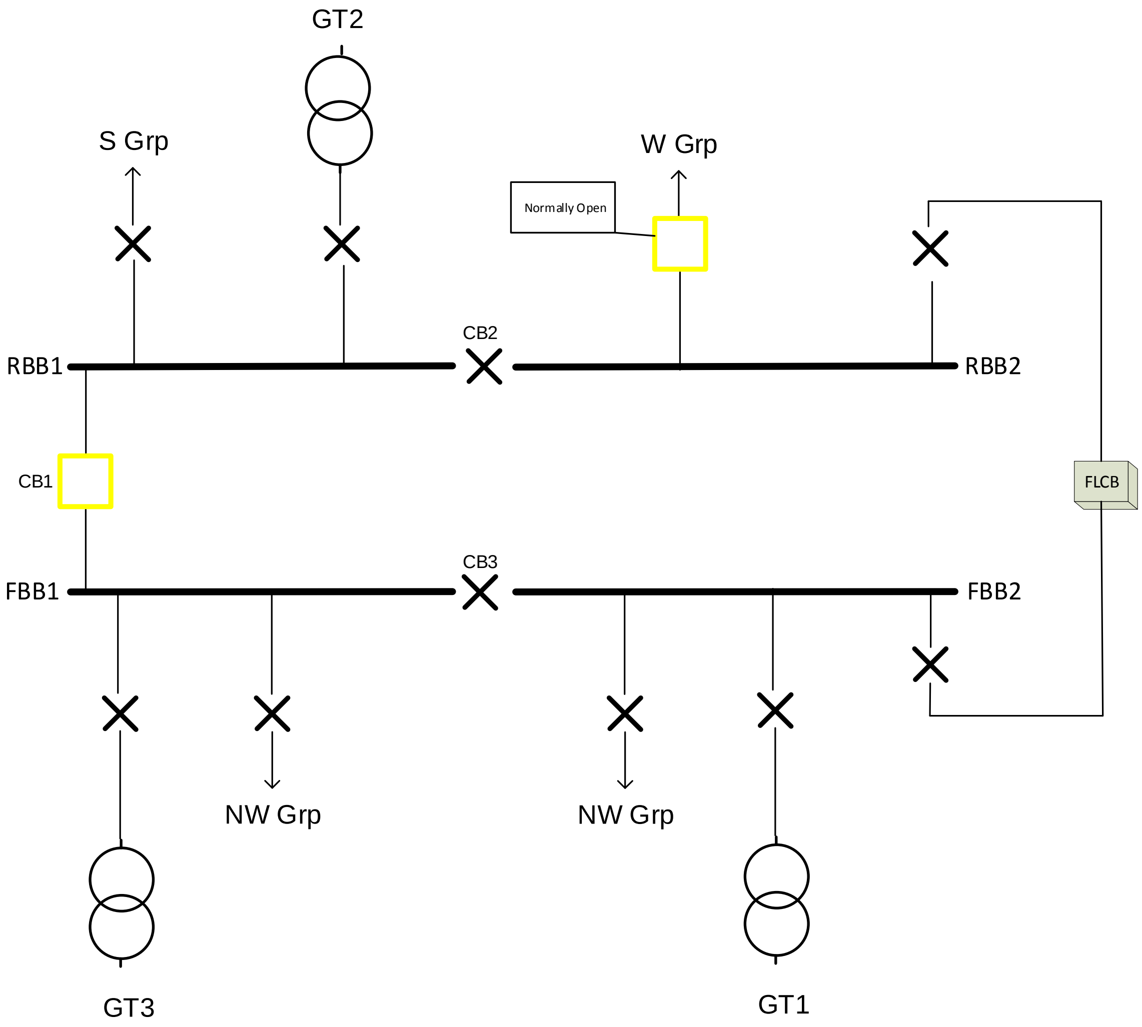


Figure 53 – Electrical schematic for running Arrangement 3 at trial substation (yellow denotes normally open)

For a fault anywhere upstream of the LV CB (shown) for GT2, the transformer protection will operate to open the CB or remote upstream protection could send an inter-trip. Additionally, as the FLCB is designed to operate faster than all protection and CBs currently installed in the network, it will open before GT2 CB to remove the fault contribution from FBB1-2. This would lead to RBB1-2 becoming dead as per the below diagram:

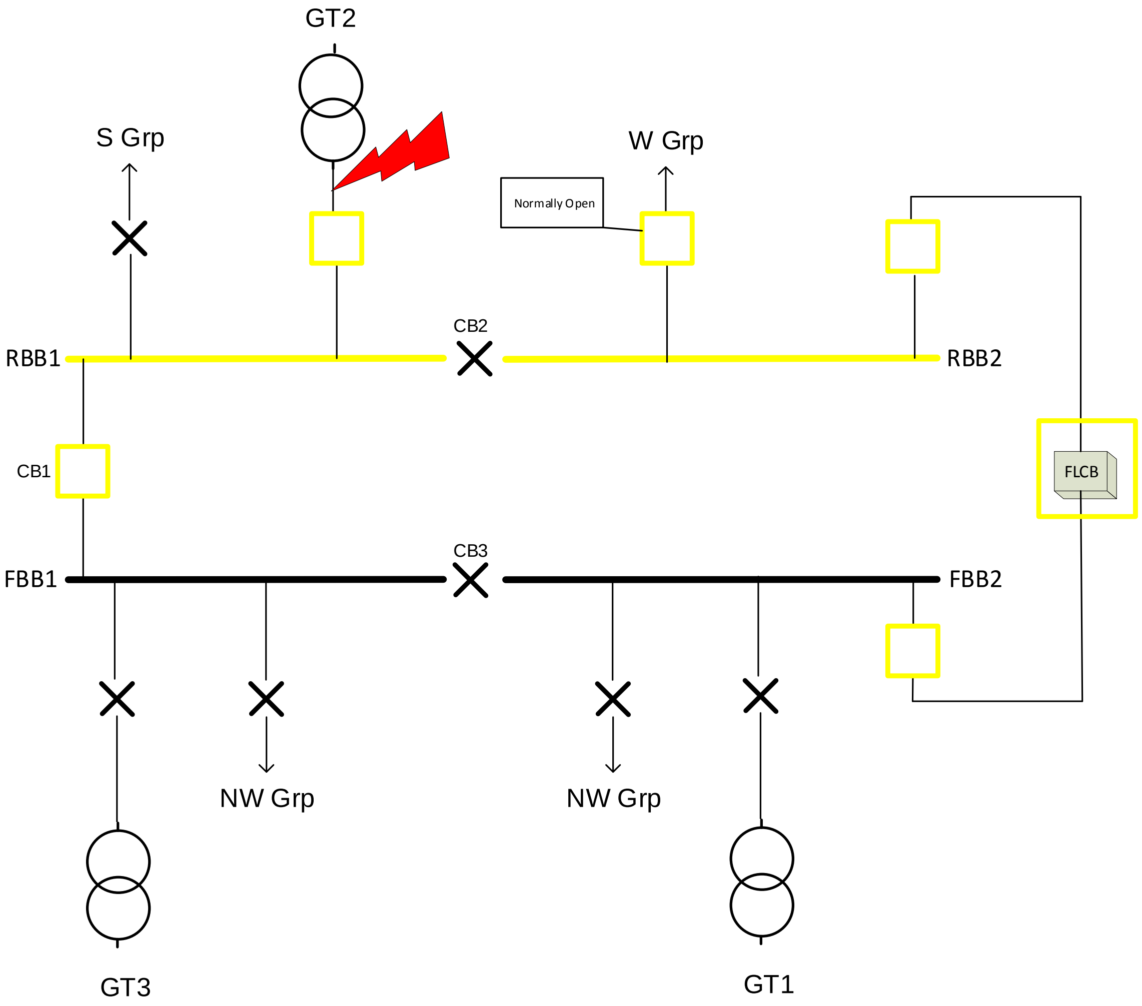


Figure 54 – Example of when a fault leaves the S group with a dead busbar (yellow denotes open or de-energised)

The FLCB requires a time of 3 minutes to reclose so in order to avoid this situation we need to install an auto-close scheme that will resolve the issue by reclosing bus coupler CB1.

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

1. GT2 transformer protection trip or received intertrip from remote protection;
2. Check if CB1 is open;
3. Check if GT2 CB is open; and
4. Send close command to CB1.

A logic diagram of the decision making of the above process which is completed by the auto-close scheme is shown below:

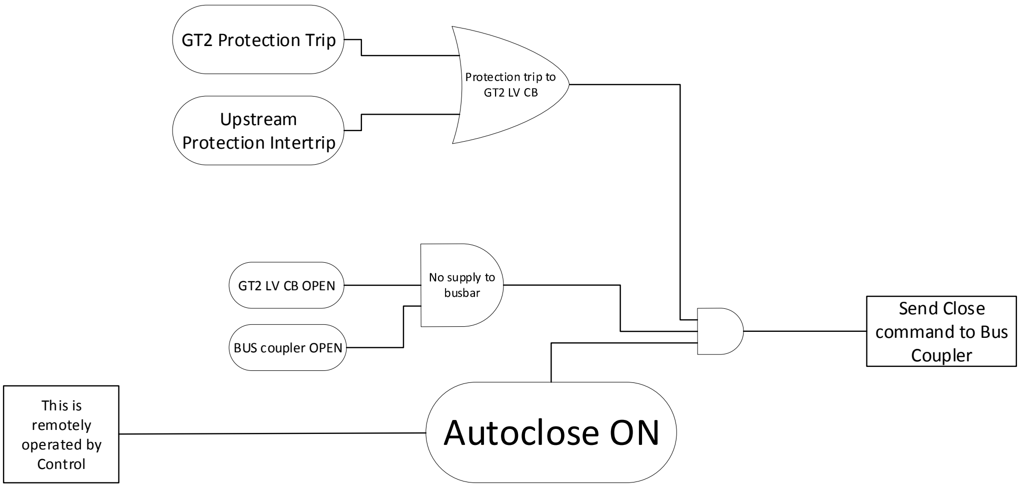


Figure 55 – Block logic diagram of the autoclose scheme

An electrical drawing of the above process on the schematic is shown below:

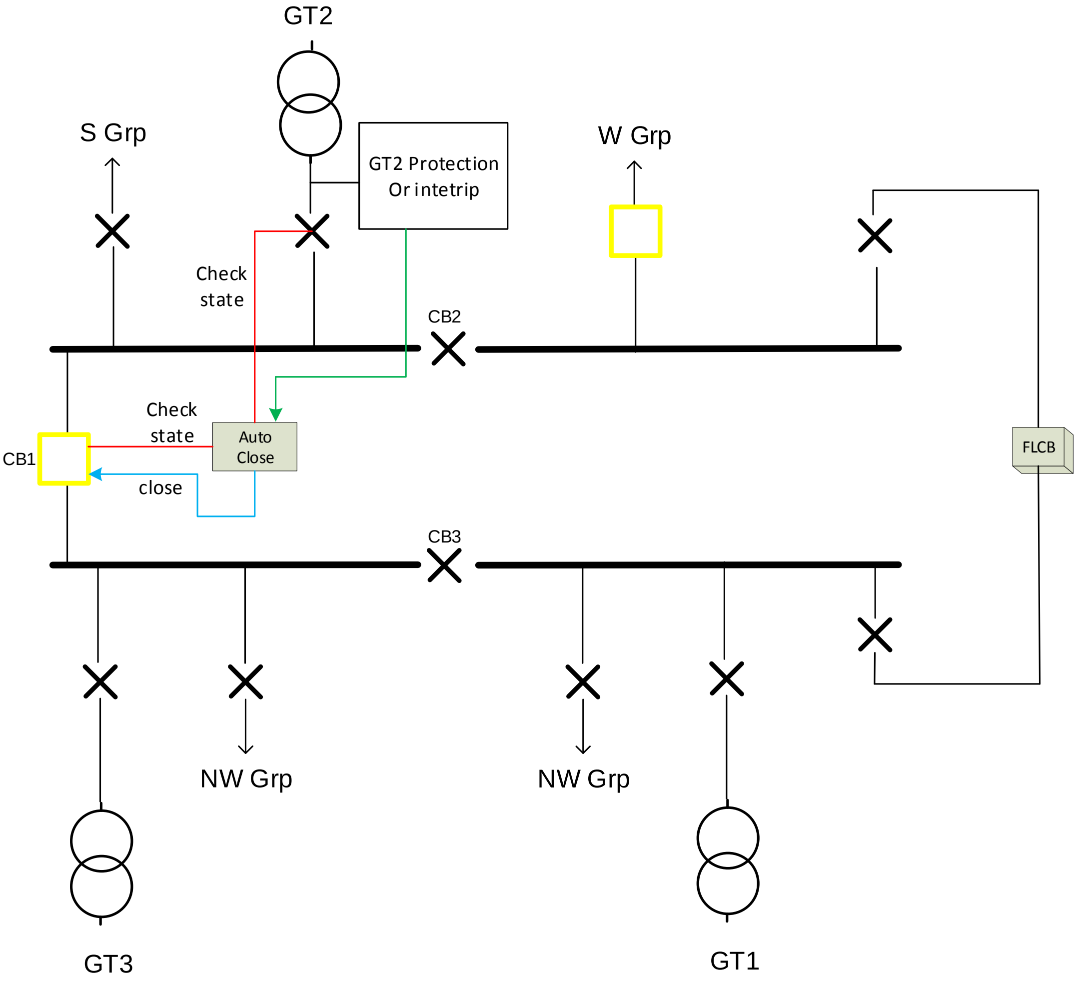


Figure 56 – Electrical schematic of autoclose scheme

If a different running arrangement was used where the GTs are placed on a different busbar, then the auto-close scheme would have to be modified to be tripped by the GT that supports "alone" a busbar and check that GT's CB if the auto-close is initiated. As proposed by engineering design this can be done by removing/adding links.

Alternatively if there is a requirement to run the substation in a different arrangement than presented here, then the auto-close will be disabled and the CB1 be closed. Examples of abnormal arrangement include:

1. West group feeders, *W Grp*, in Figure 56 above where the circuit breaker is normally open, to be closed; and
2. Disconnection of any GT, which leaves only 2 GTs supporting the load.