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RIIO NIC NETWORK INNOVATION COMPETITION

Section 1: Project Summary	Project Code/Version Number: **UKPNEN01**
1.1. Project Title	**PowerFuL-CB**: **Power** Electronic **F**ault **L**imiting **C**ircuit **B**reaker
1.2. Project Explanation	Distributed generation (DG) is a vital enabler of the low carbon transition. However, in urban networks, fault level constraints may hinder DG deployment. We will conduct two trials to demonstrate both the feasibility and possible applications of Fault Limiting Circuit Breakers (FLCBs) for releasing additional fault level headroom to enable more DG connections.
1.3. Funding licensee	London Power Networks (LPN)
1.4. Project description	**Problem:** The decarbonisation of heat is a key element of the Government's Carbon Plan. A key enabler of this decarbonisation is the growth of district heating and DG in the form of combined heat and power (CHP). However, fault level constraints are becoming a barrier to connecting new DG in urban areas. With plans for increased local generation, especially CHP, the already limited headroom in substations will be quickly exhausted. In one scenario, London will see a greater than six-fold increase in connecting CHP by 2031, with 73% of LPN substations requiring fault-level reinforcement. Traditional reinforcement as a connection solution will make new DG financially unattractive to customers. **Method:** We are proposing a dual trial of two different, innovative, FLCB devices on 11kV networks. The first, produced by ABB, is designed for deployment in network substations. The second is designed for customer connection points and is produced by Applied Materials (AMAT). Parallel trials will provide insight to GB stakeholders on the relative suitability of each technology in different configurations, operational data on the performance of each solution in mitigating fault level constraints, and in meeting customers' expectations. **Solution:** The result of the trials will be that two new technology applications to address fault levels will be proven on a live network, accelerating the development of these devices towards being an option for customers and DNOs in the near and medium term. The learning disseminated will provide existing and new DG customers clear information of the options available to connect more quickly and cheaply than before. **Benefit:** We estimate that by 2050, FLCBs could save customers around £400m (in net present value terms) in reinforcement costs in GB. These savings would be associated with around 460MW of additional DG connections in GB. Moreover, the increase in distribution connected CHP has the potential to deliver up to 3,800 kilotonnes of cumulative reduction in CO_2 emissions by the year 2050, the equivalent of emissions generated by 800,000 vehicles in one year.

1.5. Funding			
1.5.1. NIC Funding Request (£k)	£4,594k	*1.5.2. Network Licensee Compulsory Contribution (£k)*	£518k
1.5.3. Network Licensee Extra Contribution (£k)	£120k	*1.5.4. External Funding – excluding from NICs (£k)*	£888k
1.5.5. Total Project Costs (£k)	£ 6,189k		
1.6. List of Project Partners, External Funders and Project Supporters (and value of contribution)	Project Partners: ABB, Applied Materials External Funders: ABB (£500k), Applied Materials (£388k) Project Supporters: Electricity North West, Greater London Authority, Imperial College London, Western Power Distribution		
1.7. Timescale			
1.7.1. Project Start Date	1 January 2017	*1.7.2. Project End Date*	31 August 2021
1.8. Project Manager Contact Details			
1.8.1. Contact Name & Job Title	Li-Wen Yip, Innovation Engineer	*1.8.2. Email & phone Number*	Li-Wen.Yip@ukpowernetworks.co.uk, 07812 262 985
1.8.3. Contact Address	Newington House 237 Southwark Bridge Road London, SE1 6NP		
1.9. Cross Sector Projects (only complete this section if your project is a Cross Sector Project, i.e. involves both the Gas and Electricity NICs)			
1.9.1. Funding requested the from the [Gas/Electricity] NIC (£k, please state which other competition)	N/A		
1.9.2. Please confirm whether or not this [Gas/Electricity] NIC Project could proceed in the absence of funding being awarded for the other Project.	N/A		

Glossary

Term	Description
ABB	Our technology partner for Method 1
AC	Alternating Current
AMAT	Applied Materials, our technology partner for Method 2
BAU	Business As Usual
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.
DFR	**Digital Fault Recorder** – a device that captures high-resolution voltage and current data during network faults.
DG	**Distributed Generation** - generators that are connected to the distribution network.
DC	Direct Current
DECC	Department of Energy and Climate Change. Now the Department of Business, Energy, Innovation and Skills.
DNO	Distribution Network Operator
EHV	Extra High Voltage (22kV, 33kV, 66kV)
ENA	The Energy Networks Association
ENWL	Electricity North West Limited
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 Rating	The maximum fault level that a circuit breaker, cable, or other electrical equipment can safely handle.
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.
FLMT	**Fault Level Mitigation Technology** – a technical solution that reduces fault levels on the network.
FCL	**Fault Current Limiter** – a FLMT that attenuates fault current by increasing its impedance (only) during a fault.
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.
FCS	**Fast Commutating Switch** – an innovative technology used in ABB's FLCB design

FNC	Frazer-Nash Consultancy
FPP	Flexible Plug and Play
GB	Great Britain
GLA	The Greater London Authority
HSE	The Health and Safety Executive
HVDC	High Voltage Direct Current
ICL	Imperial College London
IET	The Institution of Engineering and Technology
IGBT	Insulated Gate Bipolar Transistor, a type of power electronic switch.
Inhibit / Intertrip Scheme	A hard-wired protection system that automatically disconnects generators from the network under pre-defined conditions, typically in the event of a transformer outage or other abnormal network configuration that causes elevated fault levels.
IPR	Intellectual Property Rights
LTDS	**Long Term Development Statement** – a statement published annually by DNOs to make network information or constraints on the network available to the public domain. This enables anyone interested in connecting generation or load to the network to identify opportunities or constraints on the network.
LTP	**Long Term Parallel -** A generator that is allowed to operate in parallel with the network for any duration and at any time. These are typically CHP, which operate continuously, or standby diesel generators participating in flexibility or capacity markets.
LCNF	Low Carbon Networks Fund
LPN	London Power Networks
Method 1	Installation of a FLCB at a substation.
Method 2	Installation of a FLCB at a customer's premises.
N-1	A scenario where a substation has one transformer out of service, and an abnormal network configuration is required to maintain firm capacity.
NIC	Network Innovation Competition
PV	Solar photovoltaic generation
RIIO-ED1	The current electricity distribution regulatory period, running from 2015 to 2023
RMU	Ring Main Unit
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.
STP	**Short Term Parallel -** A standby generator that only operates in parallel with the network for a short duration (<5mins) to enable seamless transfer of load from generator supply back to mains supply, and only after obtaining permission from the DNO's control room.
Standby Generation	A standby generator that is not allowed to operate in parallel with the network and is not considered in fault level assessments.
TRL	Technology Readiness Level
WPD	Western Power Distribution

Section 2: Project Description

PowerFuL-CB aims to increase the range of fault level mitigation technologies (FLMTs) available to DNOs and customers, as all existing FLMTs have at least one showstopper preventing their use in London Power Networks (LPN). The project will give generation customers two new options to achieve quicker and more cost-effective connections to fault-level-constrained networks.

This section will describe the details of this aim, the objectives set to achieve it, and how the trial is designed to ensure robustness of the project outcomes.

2.1. Aims and objectives

The Committee on Climate Change (CCC) recently confirmed that the UK is behind in meeting its targets for decarbonising heat. This has created a renewed sense of urgency on behalf of policy makers to address this challenge. Rotating DG, such as CHP, is a key technology for low carbon heating. DNOs are realising that fault level constraints are starting to inhibit new connections and will likely become the primary barrier once policy and financial incentives take effect.

A range of smart solutions, i.e. FLMTs, are needed to enable continued growth of DG and low carbon heating in particular. This project will develop two new solutions for 11kV distribution networks based on FLCB technology, with the aim to increase the range of FLMTs available to DNOs and customers.

To achieve this aim, we will:

1. Work with industry to **advance new FLMTs** based on FLCB technology.
    a. Prototype and lab test a substation-based solution.
    b. Prototype and lab test a customer-based solution.
2. Trial the **technical suitability** of these two technologies including **effectiveness** and **safety considerations** for relieving fault level constraints for 11kV networks.
    a. Demonstrate the solution at an 11kV substation.
    b. Demonstrate the solution at a customer's premises.
3. Assess the suitability of the solutions against customers' needs;
    a. Review the customer needs for these two FLCB technologies on behalf of electricity network operators and DG stakeholders.
    b. Assess the (commercial) business case based on the technical and customer findings, focusing on investment decision criteria and trade-offs, such as cost, time to connect, space requirements, and impact on security of supply.
4. **Share the learning** throughout the project with the wider utility industry.

The long-term objective for this project is to increase the range of tools available to DNOs and generation customers to enable the most cost-effective solution that meets the needs of future investment in decarbonising heating and electricity.

2.1.1. Problems which need to be resolved

- **In dense, urban networks such as LPN, fault level constraints are preventing the rapid uptake of CHP and district heating.**
- **Traditional solutions are too expensive and/or too slow.**
- **Existing smart solutions are not feasible in LPN because of operational and physical space constraints.**

The context of this challenge includes the Government's Carbon Plan and DECC's[1] Community Energy Strategy which highlight the important of CHP in achieving the UK's carbon targets; the Mayor of London's target to generate 25% of London's heat and power requirements locally by 2025, which is encouraging CHP and district heating for new developments. The GLA[2] expects the demand for new CHP connections to significantly increase in the future, with the Coordinated Action scenario projecting a six-fold increase from the year 2020 to the year 2031, rising to nearly 1.7 GW of CHP connected in London from only 300MW today.

Already, requests for budget estimates and formal quotations for new CHP connections have been steadily increasing. The last two years have seen an increase of over 2900% in LPN's annual DG application rate. This is demonstrated in Figure 1 below.

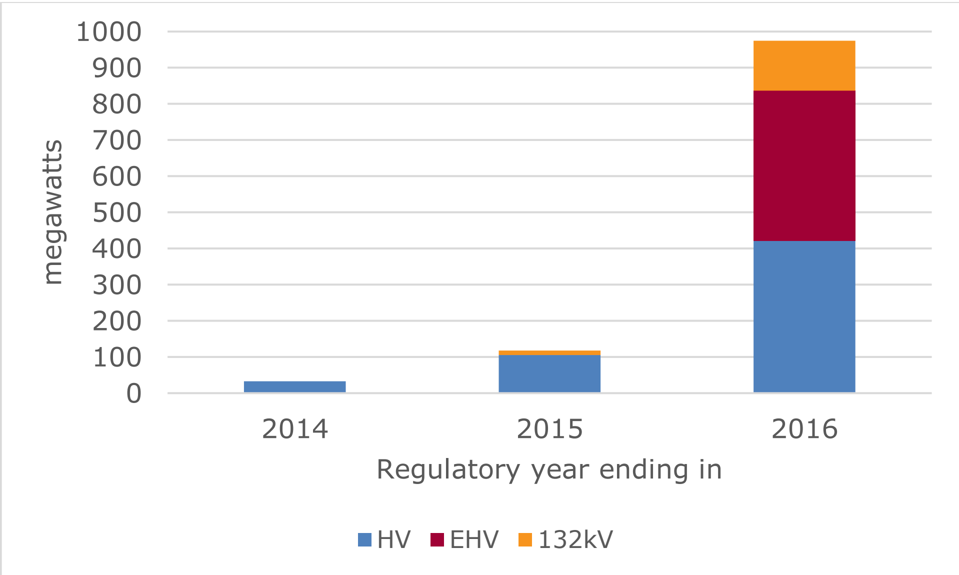

Figure 1 – Capacity of LPN DG connection offers >1MW issued, by connection voltage

Correspondingly, the ability of LPN to offer connections at 11kV is limited as a result of fault level constraints. As Figure 1 also shows, the alternative solution is currently to offer customers connections at Extra High Voltage and 132kV levels. This is much more expensive than connecting at 11kV, and will be unaffordable for all but the largest DG connections.

UK Power Networks is now seeing the number of connection offers accepted decreasing due to the subsequent high offer costs resulting from fault level constraints. For example, in 2016, no connection offers >1MW were accepted despite the increase in the number of offers.

We believe these trends show that a significant amount of DG connection enquiries in

[1] Now the Department of Business, Energy, Innovation and Skills
[2] https://www.london.gov.uk/what-we-do/environment/environment-publications/decentralised-energy-capacity-study-0

LPN are not realised because of fault level constraints.

Technically, the problem to be resolved is caused by the characteristics of dense urban networks, especially LPN, which lead to particularly high prospective fault currents, caused by:

- short cable distances;
- large diameter cables,
- direct transformation from 132kV to 11kV;
- high degree of interconnection between substations;
- the need, during a transformer outage, to connect the remaining transformers in parallel to share load evenly; and
- the load and DG already connected to the network.

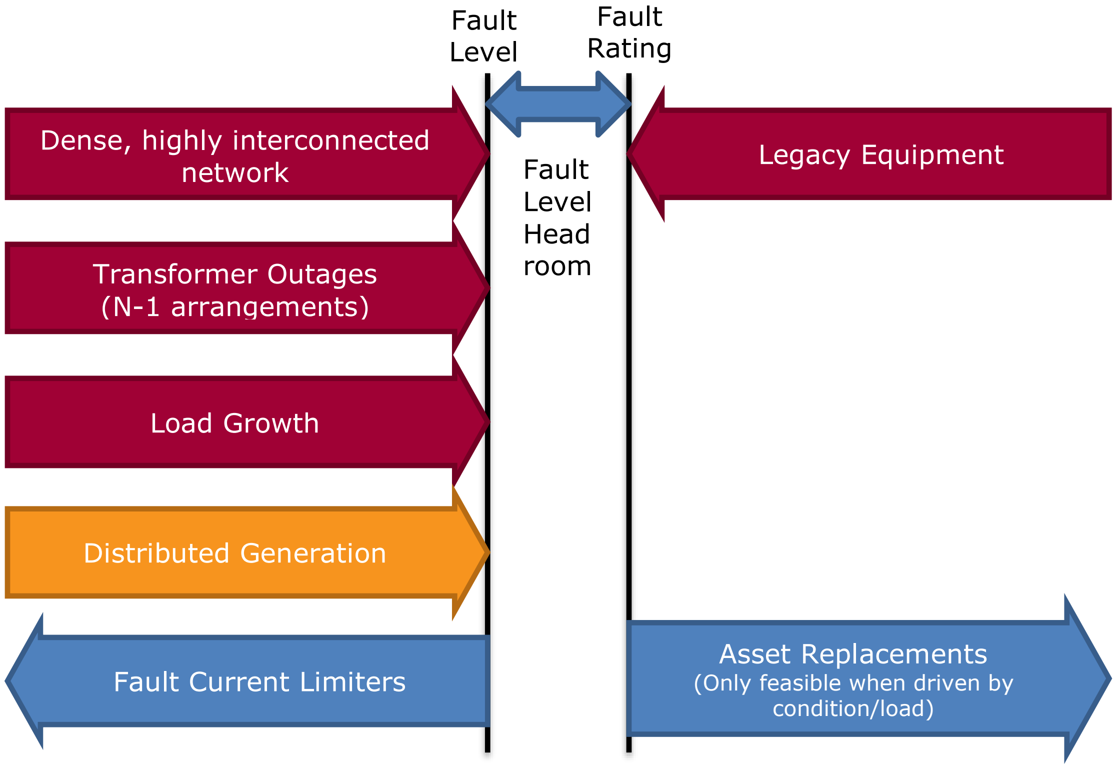

Figure 2 - Causes of fault level headroom constraints

Connecting new DG to the network further increases the local fault level. Thus, the network's fault rating limits the amount of DG that can be connected. This is largely because most DG connecting in dense urban areas is rotating DG, i.e. CHP and diesel standby generators, which have the highest impact on fault levels.

Existing solutions are either too expensive or do not meet the variety of different requirements of GB networks, especially in dense, urban areas.

LPN has unique physical and operational constraints, namely lack of space for new equipment, and a dependence on running several transformers in parallel to provide security of supply. Unfortunately, this means that smart solutions that would work in other types of network are unsuitable or of limited use in LPN and GB networks with comparable density (this is discussed in detail in Appendix 10.6). Therefore, the only option available is to reinforce the network, which is generally considered too expensive for generators requesting a connection.

Resolving this problem requires a larger range of tools that relieve fault level constraints that can meet the variety of combinations of customer and network requirements.

2.1.2. Method being trialled to solve the problem

PowerFuL-CB aims to prototype and validate the use of FLCBs to enable DG connections to substations that are otherwise "full" because of fault level constraints.

A **FLCB** is a power electronics device that **blocks 100% of fault level contribution** from a single transformer/bus coupler/generator, **but allows load current to flow normally before and after the fault**. Like an I_s-limiter, it disconnects the transformer /bus coupler/generator at a speed fast enough to prevent a contribution to the "break" or "make" fault level (i.e. before the first current peak); but unlike an I_s-limiter, it can reclose as soon as the fault has been cleared from the network.

PowerFuL-CB will demonstrate two methods that enable generation to connect to fault-level-constrained substations:

- **Installation of a FLCB at a primary substation;** in series with a transformer incomer or in parallel with a bus coupler. On a busbar fed from two transformers, this reduces the fault level by up to 50%, creating significant headroom for new generation connections. Unlike using an I_s-limiter or running busbars "split", it has no impact on security of supply. (This is explained in Appendix 10.6.)
- **Installation of a FLCB at a customer's premises;** in series with a generator. This prevents the customer's generators from causing any increase in network fault levels, which enables the connection of large amounts of DG; even if the network is "full" because of fault level constraints.

2.1.3. The Development or Demonstration being undertaken

PowerFuL-CB demonstration project will:

- **Build a trial-ready prototype of ABB's 2000A FLCB.** ABB has already developed their FLCB technology to TRL4, comprising a single-phase proof-of-concept prototype that has been lab-tested at full voltage and current. During the first two years of this project, ABB will build a three-phase, field-ready prototype suitable for trial at a LPN substation.
- **Demonstrate ABB's 2000A FLCB at a primary substation.** This demonstration will prove the technical performance required to release fault level headroom for new DG connections, and enable us to understand the engineering and safety requirements for deploying FLCBs at substations.
- **Build a trial-ready prototype of AMAT's 250A FLCB.** AMAT has already developed their FLCB technology to TRL6 and it is therefore nearly ready for demonstration.
- **Demonstrate AMAT's 250A FLCB at a customer's premises.** This project will prove the required technical performance to allow customers to connect DG to substations that have little or no fault level headroom, and enable us to understand the engineering and safety requirements for deploying FLCBs at customers' premises.

2.1.4. The Solution(s) which will be enabled by solving the Problem

The PowerFuL-CB project will give generation customers two new options to achieve quicker and more cost-effective connections to fault-level-constrained networks.

- **Method 1 will deliver a long-term solution for multiple DG connections**. We anticipate Method 1 will be available as a smart, cost-effective solution for investment in RIIO-ED2 to enable **multiple customers** to connect CHP and other DG to substations that have fault level, operational, and physical space constraints. We believe that Method 1 **could enable the business case for**

anticipatory reinforcement to create fault level headroom ahead of need.

- **Method 2 will deliver a near-term solution for individual DG connections.** We anticipate Method 2 will be available within RIIO-ED1 to enable **individual customers** to connect CHP and other DG to substations that have fault level constraints. Importantly, Method 2 does not require new substation equipment, and hence **completely avoids physical space constraints at substations**.

The learning from the project will inform DG customers about the two methods, and enable them to decide the best option for them to connect to the network.

2.2. Technical description of Project

A conventional circuit breaker interrupts fault current by physically separating its contacts, allowing the resulting voltage surge to form an arc between the contacts, then using various methods to extinguish the arc. A typical vacuum circuit breaker takes 40-60ms to open its contacts, then another 10-15ms to extinguish the arc, for a total interruption time of 50-75ms.

Conversely, a power electronic FLCB interrupts fault current by turning off Insulated Gate Bipolar Transistors (IGBTs), and uses a surge arrestor to absorb the voltage surge without forming an arc. There are no moving parts or arc to interrupt, so the fault current can be interrupted within 2ms or less.

Existing FLCB technologies, such as the GE/Alstom Active Fault De-coupler, suffer from limitations caused by conduction losses, as the IGBTs that interrupt fault current also have to carry normal load current. This means that the current FLCBs **need many IGBT modules** to handle the current at full load; and/or **need a large cooling system** to dissipate heat at full load. This is why existing FLCBs are too large for use at LPN substations, and why this characteristic is considered a showstopper for the solution to be considered as a viable alternative.

This project uses two different innovative solutions, based on FLCB technology, to solve this problem; one based on ABB's 2000A FLCB and the other on AMAT's 250A FLCB:

ABB's 2000A FLCB solution eliminates conduction losses by using an innovative "fast commutating switch" (FCS) that bypasses the power electronics during normal operation, and opens within 0.35ms in the event of a fault. This eliminates the need for a bulky cooling system, making this technology feasible to install in an existing indoor substation.

ABB propose that this prototype can be housed in three 1000mm-wide modular switchgear cubicles. This is much smaller than other FLCB designs seen to date, and further size reductions may be possible for a commercial product. The FCS also reduces network losses, which translates to lower operating costs. The FCS is of a novel design and has not been proven on any DNO distribution network in the world. Traditional switches would not operate quickly enough for this application.

AMAT's 250A FLCB solution currently forms part of a 2000A solid-state fault current limiter, which uses a 250A FLCB combined with a current-limiting mutual reactor to minimise physical size and conduction losses.

This project proposes to trial the 250A FLCB by itself (without the reactor), installed in front of a customer's generator at their premises. To our best knowledge, **this will be the first GB installation of a FLMT at a customer's premises** (other than an I_S-limiter). Installing a FLCB at a customer's premises completely avoids physical space constraints at existing substations. It also allows the customer to connect large amounts of generation even if the network is "full" because of fault level constraints.

Doing away with the reactor significantly reduces cost and physical size, but it does mean that the customer's generator may be disconnected in the event of a network fault, and that for some customers, this may be an unacceptable impact. For this reason, we will also investigate as part of the project whether customers would prefer a parallel/mutual reactor solution that enables a generator to "ride through" a network fault without contributing any significant fault current.

Full details of ABB's and AMAT's FLCB technologies are available in Appendices 10.3.1 and 10.4.1.

2.3. Description of design of Project

We have structured the Project in such a way that each workstream relates to one of the project objectives, as presented in section 2.1. Overarching project management will provide oversight throughout the Project. See Appendix 10.9 for an overview of the workstreams and their core outcomes.

Workstream 1: Prototype and validation testing

The first workstream (WS1) will design, build and test the prototypes for the substation and customer FLCB.

ABB will progress their technology from TRL4 (single-phase proof-of-concept prototype) to TRL6 (three-phase field prototype), in accordance with defined specifications. For this workstream, ABB will design a three-phase prototype, build and integrate it into modular switchgear cubicles, and perform testing to ensure the prototype complies with DNOs' requirements.

AMAT have already tested their 250A units at KEMA (an independent, accredited high power test laboratory in Pennsylvania) several times. Any changes to the design based on customer specifications will trigger a further set of tests at their or at a similar lab.

The specifications for both devices will be developed in parallel with, and will be informed by, the preliminary safety cases, to ensure that safety is considered from the very beginning.

- **Method 1 – Substation:** ABB will build up to three prototypes: at least one will be type tested destructively to ensure the technology is reliable and safe, and one will be delivered to the demonstration site. All type testing will be performed at ABB's Ratingen laboratory, which is accredited to carry out high power testing in accordance with relevant international standards[3]. The type tests will include a short circuit test at 12kV / 25kA prospective fault current, witnessed by UK Power Networks.
- **Method 2 – Customer premises:** AMAT will design and build a prototype suitable for a customer premises. This will be based on the 250A FLCB currently used in their 2000A solid-state FCL, which has already been demonstrated in other countries.

The learning from this workstream will be captured in test reports, which we will make available to other Licensees. The results and learning from the prototype development, testing, and preliminary safety case will be disseminated via SDRC learning reports.

Workstream 2: Demonstration on the network

In the design phase of Workstream 2 (WS2), UK Power Networks will collaborate with ABB, AMAT, and our safety case expert, to develop the engineering knowledge necessary to safely and effectively demonstrate FLCBs on GB networks and customer premises. We will investigate issues such as:

- **Use cases for FLCBs** (e.g. in parallel with a bus section/coupler, in series with a transformer, or in series with a customer's generator).
- **Protection and control philosophy** (e.g. FLCB trip settings, reclosing, coordination and discrimination, how to handle FLCB failure).
- **How FLCBs could work together** with FlexDGrid and Respond methods.

[3] https://library.e.abb.com/public/8497393b166df0b7c1257be40039821e/2497%20Laboratories%20GB%202013.pdf

- **The safety case** which will be developed in parallel with the engineering investigations to ensure that safety is considered in every aspect of the solutions.

Additionally, where appropriate, we will seek to engage with the Health and Safety Executive (HSE), the Energy Networks Association (ENA), and other Licensees, especially Electricity North West (ENWL) and Western Power Distribution (WPD) who are investigating similar issues with the solutions explored in the Respond and FlexDGrid projects. The learning from this phase will be captured in engineering policies, standards, and procedures, and shared via learning reports.

Method 1 – Substation: One FLCB will be installed at a primary substation. We have conducted preliminary investigations to identify suitable trial sites and will conduct a detailed feasibility study at the start of the project to confirm a preferred site. We will install the FLCB either as a bus coupler or in a transformer incomer, depending on the configuration of the selected site.

At a 4x15MVA transformer site (about 60% of LPN sites), it is best to install the FLCB as a bus coupler, whereas at a 3x60MVA transformer site (about 20% of LPN sites) it is best to install it in the transformer incomer. (This is explained in Appendix 10.3.2.) We considered trialling both configurations (i.e. two network trial sites), but concluded that the opportunities for additional learning for customers and other DNOs would not justify the additional cost. Our experience from our Newhaven FCL trial is that a single trial site is sufficient to give confidence in the core technology. Furthermore, FlexDGrid and Respond are already trialling other FLMTs in both bus coupler and transformer-incomer configurations, and much of their configuration-specific learning will be applicable to FLCBs.

To verify that the FLCB provides the required technical performance, the substation and FLCB will be fitted with digital fault recorders (DFRs), which will capture high-resolution current and voltage data to verify that the FLCB operates as expected for real network faults.

Method 2 - Customer premises: One FLCB will be installed at a customer's premises, along with switchgear enabling the FLCB to be isolated and bypassed if necessary. The Method 2 FLCB will be used to connect generators with a capacity of 4.5MW or lower.

The results and learning from the field trials will be disseminated via SDRC learning reports. Site visits to the trial sites will be open to Licensees and some external stakeholders.

Workstream 3:
Assessment of suitability against customer needs

A key barrier identified in both ENWL's initial survey results[4] as well as DECC's "Call for Evidence"[5] is that a lack of understanding of the feasibility of CHP prevents customers from developing a robust business case. This workstream therefore seeks to leverage the learning we can gain from what customers need for network connection, how that impacts their business case, and how that applies to both Methods.

WS3a - Customer Dialogue. WS3a is designed to both inform stakeholders of what the two Methods are and what they can technically accomplish for them, as well as gather information on what their criteria would be to assess the suitability of the two Methods if connecting new generation. It aims to gain an insight on the customer requirements and expectations for potentially using either of the two Methods for a new connection. This will be achieved by engaging with relevant customers through focus groups and workshops. Our approach will be to target specifically those people most likely to connect new CHP generation and also those generation customers who see connections costs as a primary barrier to new connections. The result will be an open

[4] http://www.enwl.co.uk/docs/default-source/respond-key-documents/respond-customer-survey-interim-results.pdf?sfvrsn=6
[5] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/388981/Factors_affecting_the_uptake_of_gas_CHP_Final_v6.pdf, p36

dialogue with customers to understand their decision parameters. These may include space, cost/security trade-off, etc.

Additionally, through our relationship with the Greater London Authority we will seek to better understand CHP and district heating use cases for both methods, considering the needs of councils and developers. The user requirements and expectations will inform the work in WS3b.

The technical requirements will be based on the results from WS1 and WS2. These requirements define the constraints which are inevitable with the technology. The customer expectations for how the technologies will work best for their needs will be gained through customer dialogue in WS3a, from feedback from the trial participant, and, and from reviewing other similar projects like ENWL's Respond project's customer survey. The information gathering will be designed with the purpose of demonstrating the commercial feasibility of the FLCB technology. This may include cost benefit analysis of the FLCBs technology, market size and receptiveness.

WS3b - Suitability assessment. Once we have learned what customer needs are for using the two different Methods, we will conduct a desktop based exercise to match these expectations against technical constraints and variations. We will then combine those requirements against how the devices best meet customer needs from WS3a to develop the inputs which customers can use for their own individual commercial business cases. Specifically, the assessment will explore the trade-offs between different needs and technical constraints.

The results and learning will be captured in the 'Learning Report – suitability assessment' report, presenting the assessment of the suitability of the different trialled solutions. This will be based on the measured technical performance and identified customers' needs. The end result will present information DG customers can use as part of potential business cases to support investment in DG.

Workstream 4: Knowledge dissemination

Workstream 4 (WS4) will engage and disseminate lessons from the project to targeted stakeholders, such as Licensees, industry groups, and participants from WS3. We have detailed our approach to knowledge dissemination in Section 5.

2.4. Changes since Initial Screening Process (ISP)

2.4.1. An additional FLCB solution for customers

In our ISP we stated our intent to partner with ABB to develop this technology because we had not been able to identify any other suitable technology partners. However, we said we would publish an open expression of interest before our NIC full submission to ensure that we had exhausted all options for potential technology partners.

As promised, we published a Periodic Indicative Notice (PIN) in Tenders Electronic Daily - Supplement to the Official Journal of the European Union (http://ted.europa.eu/), calling for vendors who could build a FLCB. While we received no formal responses, we did identify in parallel discussions with AMAT that they can offer a cut-down version of their solid-state FCL that is effectively a FLCB suitable for connections up to 4.5MW.

We concluded that a dual trial was the best course of action for the following reasons:

1. **Different applications mean increased customer value**. Method 1 may be cheaper where the cost can be shared across multiple connections, but Method 2 may be cheaper for individual connections. We therefore believe that depending on specific scenarios and customer demand, a choice between the two devices would be needed to enable the most cost-effective solution to be selected for customers.
2. **Increases industry learning and risk mitigation.** The ability to choose from two different solutions that address fault level constraints can increase learning

and mitigate the risk that comes from trialling new technologies. By running two separate FLMT trials simultaneously, we mitigate the risk that one will not be viable following development and testing.

3. **Has the potential to enable more DG connections.** Method 1 has the potential to free up large amounts of headroom with a single device. We recognised, however, that the device would likely be used for connecting large generators or aggregated generators. The prospect of an alternative device opens the possibility of allowing connections regardless of generator size and removing fault level constraints as the barrier for DG uptake on urban networks.
4. **Timing and choice for customers.** Method 2 is based on mature technology and could be commercially available more quickly, as DNOs have sufficient confidence in the technology to approve their use. In other words, the Method 2 could facilitate connecting DG whilst waiting for other solutions to mature.

Given the benefits above, we have decided to increase the scope, and therefore the budget for this project. The addition of Method 2 will increase the cost to accommodate the second trial site. In an effort to keep this additional cost as low as possible, AMAT has agreed to a 100% cost contribution for their building of the trial prototype, with some minor costs added to the overall project to facilitate additional work relating to Method 2, such as the safety case, the learning report, workshops, and customer recruitment and support.

The nature of Method 2 has also led to a reworking of our originally designed stakeholder engagement and knowledge dissemination. Because Method 2 will be installed directly on customer premises, we realised customers may have specific needs concerning this new technology. We have hence added WS3 which represents a more personal and interactive level of engagement.

2.4.2. Cost Increase

The project cost has increased from £4.0m to £6.2m to allow for:

- additional safety case effort, identified by the safety case feasibility study we conducted since ISP (details in section 4.2.2),
- contingency to allow for a container switch room, and
- the addition to the project of Method 2.

Table 1 Changes to the project costs since ISP

Description		Cost (£k)	Total Cost (£k)
ISP Cost			4,000
Costs related to requirements identified since ISP	Safety Case	[redacted]	[redacted]
	Container Switchroom	[redacted]	
Costs related to addition of Method 2	WS1 (Development)	[redacted]	[redacted]
	WS2 (Demonstration)	[redacted]	
	WS3 (Customer Engagement)	[redacted]	
	Project Management	[redacted]	
	Contingency	[redacted]	
FSP Cost			6,189

2.4.3. Clarification of the TRL level for the ABB device

In the ISP, we stated that the project would develop the Method 1 device to TRL8. As ABB estimates additional time may be needed to bring the product to market, there was a question as to whether TRL7 or TRL8 was the correct level, as the NIC guidance describes TRL7 and 8 together in a common definition. To differentiate between TRL7 and 8, we referenced *Horizon-202*0 as a benchmark.[6] Upon consultation with ABB, we have refined the level to TRL7.

[6] https://ec.europa.eu/research/participants/data/ref/h2020/wp/2014_2015/annexes/h2020-wp1415-annex-g-trl_en.pdf

Section 3: Project business case

With the LPN network becoming more congested due to fault level issues, connecting new low carbon generation is proving more difficult. Section 2 outlines the context and drivers for these challenges. Traditional reinforcement is often costly and time consuming, particularly if access to equipment or cables is limited; and space often comes at a premium in urban environments. Finding the right alternative solution will prove beneficial, not only for customers within UK Power Networks but equally for UK plc.

Some of these benefits can be forecasted and quantified, such as the financial benefit of avoided reinforcement, additional capacity headroom created and carbon saved; Section 4 presents this quantification. However, there are also other benefits and drivers that justify why we have chosen to investigate this technology at this moment in time. The full range of benefits, including non-quantifiable benefits and drivers, are presented here. These benefits, including those quantified in the following section, are what can be unlocked by an investment in the FLCB methods today.

3.1. The merits of trialling this technology

The use of power electronics for distribution networks is now affordable

The large steps in progressing power electronics technology in transmission level HVDC have led to a better understanding of the technology and have driven the cost down. While previously the application of power electronics for distribution networks would either be technically unfeasible or financially unviable, the technology is now mature enough to justify investment to accelerate it towards technical and commercial readiness (criterion f).

Space constraints in urban environments limit the fault-level mitigation options available and the methods demonstrated use innovative arrangements of power electronics and other components in order to provide unique new capabilities at minimum size.

This will result in an increase in available headroom to connect new low carbon generators in cities, in particular CHP, which will accelerate the uptake of this low carbon technology (criterion a) and can result in significant carbon savings, as will be presented in Section 4.

3.2. A supportive regulatory framework

Three elements of the current regulatory framework are directly relevant to this Project:

- **Customer satisfaction**. Offering fit-for-purpose connections is incentivised by the Broad Measure of Customer Service and Incentive on Connections Engagement. In RIIO-ED1 Ofgem have increased emphasis on improving customer satisfaction.
- **Quicker Connections**. Ofgem introduced a package of connections incentives aimed at encouraging the DNOs to provide a better service for connecting customers, including those connecting low carbon technologies and DG. These include a time to connect incentive for smaller customers, customer satisfaction surveys and a connection engagement incentive for larger customers. Furthermore, Ofgem is currently investigating options to enable anticipatory investment to support quicker and more efficient connections.
- Encouraging **DNOs to play an active role** in delivering a low carbon economy.

This Project and the potential benefits it unlocks will directly support those drivers, as explained below.

3.3. Benefits unlocked

- **Attractiveness of connection offers**: the solution will enable lower cost connection alternatives with a shorter lead time to new generations and will improve customer satisfaction.
- **Reduced cost and carbon emissions**: the solution will reduce reinforcement costs and enable a potential increase carbon saving and demand side response.
- **Efficient anticipatory investment:** Method 1 will improve the business case for making anticipatory investment to create fault level headroom ahead of need.
- **Customer choice**: our customer-based solution will give customers an option to install a device at their premises instead of having to pay for an expensive connection at a higher voltage or wait for DNOs to reinforce the network.
- **Early delivery of benefits**: Method 2 can already deliver benefits in RIIO-ED1. Method 1 will provide the most efficient solution in some network scenarios in the long term, but is not expected to be available until c. 2022. Method 2 will allow customers to get connected in the meantime; strengthening the other benefits identified above.

Benefit example: FLCBs represent an opportunity for UK Power Networks to enable DG to connect more quickly and at a lower price.

Case Study: Customer seeking LTP operation of standby generators

We recently received a request to allow operation for 17.5MW of standby generation in a new development. The generators comprised seven units of 2.5MW each. We found that, due to fault level constraints:

- Without significant reinforcement, **only three of the seven generators** (7.5MW) can be LTP connected at a time, and only when the network is running in normal arrangement.
- The customer would need to modify the arrangement of their 11kV generator switchboard to enable the generators to be segregated into groups of three. This would **increase the switchboard's cost by up to £50k.**

This project was actually fortunate in that the switchboard had not yet been procured and therefore could be ordered to allow this from the outset. If this had been an established site, the modifications would have been much costlier and/or technically unfeasible.

A FLCB would potentially allow the other four units (10MW) to also operate LTP, enabling them to contribute to security of supply by participating in flexibility and/or capacity markets. In other words, these standby generators could be used to help balance the grid when wind and solar are not generating. Therefore, in this case, a FLCB would allow 10MW of high-carbon baseload generation to be replaced with an equivalent amount of low-carbon intermittent generation.

3.4. Impact on our business during RIIO-ED1, RIIO-ED2, and beyond

Within RIIO-ED1: Method 2 will be available as a smart, cost-effective solution for individual customers to connect CHP and other DG without causing any increase in fault level, enabling them to connect to substations that are "full" because of fault level constraints.

Within RIIO-ED2: Method 1 will be available as a smart, cost-effective solution to create fault level headroom at constrained substations, enabling multiple customers to connect CHP and other DG to substations that would otherwise be "full" because of fault level constraints.

A vision for the future beyond RIIO-ED2

By 2030, power electronic FLCBs could be mature enough that they are routinely used as incomers and bus couplers in new switchboards, which would allow the distribution network to be designed and operated with far higher unrestrained fault levels than today. The benefits of this are:

- It would enable a highly-interconnected high-voltage distribution network, i.e. normally open points could be run normally closed. This would allow load to be shared more evenly between transformers and feeders, which would **reduce losses**. It would also allow greater use of interconnectors to provide firm capacity, **reducing the need for load-related reinforcement**.
- New transformers could be specified with half the impedance they are today, so requiring less steel, less copper, and a smaller tap changer. **This would significantly reduce transformers' size, cost, and losses.** Currently, transformers are specified with relatively high impedance so that at least two transformers can be run in parallel without exceeding the network's fault rating.
- Voltage disturbances, which are a particular problem for industrial and data centre customers, would be far less severe.
- Harmonic voltages would also be far less severe (for the same amount of harmonic currents), allowing networks to tolerate much more inverted-connected generation and load (e.g. PV, fuel cells, heat pumps, electric vehicles, battery storage).

By 2040, advances in power electronics technology enable a FLCB that is the same size as today's conventional vacuum CBs. (This would require a three-fold reduction in volume, which is plausible with a move to wide bandgap semiconductor materials such as silicon carbide or gallium nitride). These FLCB's could then be retrofitted to existing switchboards as a direct replacement for the existing bus coupler or incomer CBs; much like how vacuum CBs are retrofitted to today's legacy oil CB switchboards. This means that it would no longer be necessary replace the entire switchboard to get these benefits.

By 2050, FLCBs could be cheap and compact enough that they completely replace vacuum and SF6 CBs. This would eliminate most fault level constraints from network design and operation, and **significantly reduce the risks of fire and explosion caused by catastrophic network faults**. Today, a cable strike on a high voltage cable would release a dangerous amount of energy, with the potential to cause serious burns to anyone standing in the vicinity. By 2050, using FLCBs on high voltage feeders could reduce this to a few sparks and a puff of smoke.

Section 4: Benefits, timeliness, and partners

The low carbon agenda is driving increased penetration of DG, particularly in urban areas where there is also a heat demand (i.e. CHP). Networks in these areas are often congested with fault level being the main issue, slowing down the uptake of low carbon energy. FLCBs can offer customers a cost effective way to connect in a safe and timely manner in dense urban areas.

This section sets out how our bid performs against the key criteria of the innovation competition: the wider benefit case of the Methods going forward, the efforts undertaken to provide value for money to electricity customers, involvement of the appropriate partners, external funding and the relevance and timeliness of the project. This assessment is structured following these criteria.

4.1. Evaluation Criteria (a)

Accelerates the development of a low carbon energy sector and/or delivers environmental benefits whilst having the potential to deliver net financial benefits to future and/or existing Customers

This is a crucial criterion in the Competition and to provide additional rigor to our assessment, we have engaged Navigant to compile the benefit case, with inputs from internal UK Power Networks managers from Innovation, Infrastructure Planning, Distribution Planning, Capital Programme Delivery, Connections, and Operations.

The analysis focusses on the three key benefit contributors:

- **Financial benefit:** FLCBs create the same or more fault level headroom than the traditional method (replacement of switchboards and ring main units (RMUs)), but at a far lower cost.
- **Capacity benefit:** The capacity for DG connections released by deploying FLCBs.
- **Carbon benefit:** Reduction in carbon emission per kWh of generated electricity as a result of changes in the energy mix. This considers the connection of CHP related to the fault level headroom enabled by FLCB deployment. As CHP provides both heat and power, they are more efficient than different forms of centralised generation and lead to emissions reductions.

The detailed analysis, including the methodology and assumptions, is available in Appendix 10.2.

Dealing with uncertainty

Given the uncertainty associated with the location and size of each generation connection request in the future, the analysis considered two scenarios in order to define a range of constrained substations:

- Best-case scenario: future generation connection requests use the maximum amount of available headroom across all unconstrained substations. In other words, no additional reinforcement is required as long as the cumulative headroom across the entire network exceeds the capacity of the generation that is to be connected.
- Worst-case scenario: future generation connection requests occur at those substations that have the least headroom available, and use exactly the minimum amount of headroom required to constrain each substation. In other words, the scenario that leads to the most number of additional substation constraints possible.

Combined with National Grid's four Future Energy Scenarios, this gave us eight possible scenarios to analyse.

For simplicity, the figures we present in the tables throughout this section represent the average across all eight scenarios.

4.1.1. Financial benefit: avoided network reinforcement

Given that FLCBs are deployed across the entire population of constrained substations identified in the fault current analysis, FLCB deployment allows the release of fault current headroom in a more cost-effective way compared to traditional reinforcement. Our analysis assumes that in the base case, additional forecasted DG connection is enabled by carrying out network reinforcement in order to create more fault level headroom. Those network reinforcements consist of replacement to substation switchgear such as circuit breakers and RMUs.

We estimate that FLCBs could save £403m of network reinforcement costs across GB by 2050. The analysis shows that Method 1 will result in more savings due to economies of scale. However, this largely depends on the number of connections for each substation. In areas where less DG is connected, Method 2 might be more cost-effective. In reality, an optimal solution would be achieved by a combination of the two methods, depending on the number of expected connections per substation and the size of each connection.

Table 2: Scenarios average for net financial benefits (£m)

Scale	Type	2020	2030	2040	2050
Licensee	Method 1	£0.53	£14	£32	£49
	Method 2	£0.58	£12	£23	£34
GB rollout scale	Method 1	£0.53	£113	£256	£403
	Method 2	£0.58	£124	£247	£370

4.1.2. Capacity Benefit: Increased DG Connections

Given the high number of substations with fault level constraints across GB distribution networks, we assume that without further measures to release headroom, the level of DG will not reach the forecasted levels. This is particularly true for rotating DG, i.e. CHP and diesel standby generators, which have a much larger impact on fault levels than other types of DG.

We estimate that by the year 2050, FLCBs could enable 462MW of DG connections that would otherwise have been unfeasible because of fault level constraints.

Table 3: Scenarios average for Capacity benefit (MW)

Type of benefit	2020	2030	2040	2050
Capacity Benefit (MW)	170	315	386	462

4.1.3. Environmental Benefit: Carbon Reductions

The release of network capacity can enable the uptake of CHP connections in areas that were previously considered constrained and where new connections quotes were in many cases uneconomic. This is particularly true in large metropolitan areas, such as London and Birmingham, where fault current levels are usually high.

FLCBs can potentially contribute towards meeting future carbon budgets. As described earlier, FLCBs can accelerate the deployment of DG, specifically CHP which has a dual purpose in heating. The higher efficiency of CHP compared to separate electricity and heat generation contributes to a reduction in carbon emissions. CHP captures the heat created as a by-product from electricity generation, which in normal thermal generation is lost in cooling towers or otherwise left unused. CHP technologies can lead to thermal efficiency rates of over 80% in comparison to around 60% in new Combined Cycle Turbines (CCGTs). Therefore, generating electricity using CHP reduces emissions that would have otherwise been emitted by gas boilers.

In the carbon benefit calculation, we assumed an average amount of carbon dioxide emitted in 2015 amounted to around 300 kg/MWh carbon intensity of electricity supplied as calculated by DECC[7][8]. We compare the calculated carbon intensity to the carbon intensity of CHP including savings as a result of a reduced need for gas boilers.

We estimate that the increase in CHP has the potential to deliver 3814 kt.CO_2 cumulative reductions in carbon emissions by the year 2050, equivalent roughly to the emissions emitted by 800,000 vehicles taken off the roads for one year.

Table 4: Average scenarios ranges for Carbon Reduction

Type of benefit	2020	2030	2040	2050
Carbon Reduction benefit (kt.CO_2)	144	951	2209	3814

4.2. Evaluation Criteria (b)

Provides value for money to distribution customers

Identifying competitive costs has been a key focus during the full submission preparation. Throughout the development of the bid, we have worked to ensure the project costs will be competitive, deliver direct benefits to customers, and bring about new learning for solutions to fault level constraints.

4.2.1. Potential direct impact on the network

The configuration and ratings of the current network for urban areas are not designed to accommodate large amounts of DG. The fault current level constraints must be resolved in an innovative way to enable the integration of new DG and allow existing DG to have access to become a firm connection. In line with these needs, this project will have a direct positive impact of:

- enabling quicker and more efficient connections for **individual DG customers** in **RIIO-ED1**; and
- enabling quicker and more efficient connections for **multiple DG customers** in **RIIO-ED2**.

This project will be a source of learning for other Licensees in areas with similar network constraints, specifically those in urban areas. Learning reports and dissemination of the results will immediately provide valid operational data to other Licensees to provide new alternatives which they may choose to incorporate into their investment planning.

4.2.2. Ensuring the project is competitively priced

To ensure this project is delivered at a competitive cost, values have been calculated with a bottom-up approach based on the project plan, across each of the project workstreams with inputs from UK Power Networks internal managers, ABB, and AMAT. The values have been reviewed by multiple levels of relevant internal stakeholders, including fellow innovation project managers, up through key directors as part of our

[7]https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/511684/20160331_2015_Provisional_Emissions_Statistics.pdf#page=15
[8] Now the Department of Business, Energy, Innovation and Skills

innovation funding review process.

Our costs estimates are based on:

- inputs from a number of UK Power Networks' experts for labour requirements, including for procurement, legal and dissemination activities;
- inputs from UK Power Networks' technical specialists including labour elements for technical specification documentation activity and equipment installation for the trials;
- quotations received from the partners and suppliers; and
- project management costs, considering previous experience of delivering similar projects, particularly other Low Carbon Network Fund tier 2 projects.

As described in section 2.4, we believe the addition of the Method 2 trial to the project represents good value for money to customers as trialling two solutions in one project provides efficiency benefits in innovation overheads and increases confidence in achieving the benefits in full. We have committed effort to keep this additional cost as low as possible and AMAT has agreed to 100% cost contribution for their building of the Method 2 trial prototype.

We have also secured a partner contribution from ABB to the project of £500k.

UK Power Networks will on this project continue its track-record of investing in innovation beyond the minimum level contribution. In this case, we will be contributing 12% of the project cost, which – above the 10% minimum level - represents the labour committed by our technical standards and design teams to the project. Innovation remains a core business activity for UK Power Networks and NIC funding is not being sought for the specification and standards development related to the project solutions.

Competitive procurement for the Safety Case

In our ISP, we allowed a budget of [redacted] to produce the safety case, benchmarking other examples of fault-level-related safety case work. However, having now completed a detailed feasibility study, we believe this project will require much more effort to develop the safety cases for Method 1 and Method 2, because of:

- the lower TRL level of the project Methods (i.e. FLCBs are an emerging technology);
- a best practice approach to developing the safety case as a "living document" throughout the entire project (i.e. at design phase, testing phase, and through operational assessments);
- uncertainty of scope and effort required to deliver the safety case for a solution that has not yet been designed; and
- a risk of cost overruns due to unforeseen test results, design changes, or other challenges.

Frazer-Nash Consultancy (FNC), who completed the feasibility study, have advised us that, based on their experience of developing similar safety cases in other industries, we need to allow a budget of [redacted]. We emphasise that this is a worst-case cost. We will likely be able to confirm a lower cost once we have developed the initial stages of the safety case, but this needs to be done in parallel with project activities and could not have been done prior to full submission.

We believe that FNC are suitably qualified to deliver the safety case, as they have extensive experience in developing similar safety cases in other industries, combined with significant domain knowledge of electricity distribution networks. We also believe that, having done the feasibility study, they are well positioned to estimate the effort required to deliver the safety case.

However, we recognise that this is a significant cost to the project that was not allowed for in the ISP, and we propose the following steps to minimise it:

- We will use a competitive procurement process to select a suitably-qualified supplier to develop the safety case, and ensure that their proposed approach is fit for purpose and cost-effective. FNC have confirmed that they intend to bid for this work.
- We will award the safety case work in stages of fixed price and scope. This will allow us to manage any scope creep and avoid unexpected cost overruns.

UK Power Networks has a robust procurement process which endeavours to acquire the best value for money for customers. The process involves advertising an invitation to express interest (ITEI) using the ENA Smarter Networks Portal, the trade press, Achilles category searches, and our existing vendor list. Those who express an interest will receive subsequent invitations to tender (ITT). Bidders will be evaluated and reduced to a shortlist of suitable suppliers. The final selection will be based on a scored technical evaluation and a commercial evaluation.

This activity will be carried out in advance of the project start to enable the supplier to start at project kick-off with the rest of the project team. This will be at UK Power Networks' expense.

4.2.3. Summary Cost Tables

Table 5 - Breakdown of Labour Costs

Project Participant	Workstream	Total (£k)	FTEs	Days	Person Days	Cost(£) / Person Day
UK Power Networks	WS1	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	WS2	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	WS3	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	WS4	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	PM	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
ABB	WS1	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	WS2	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Applied Materials	WS1	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Imperial College	PM	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Safety Consultant	WS1	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	WS2	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Total		**3,037**			**5,722**	

Table 6: Breakdown of project costs (£k)

Workstream	Project Participant	Type of Cost	Method 1	Method 2	Other	Total
WS1	UK Power Networks	Labour	[redacted]	[redacted]	[redacted]	[redacted]
		Travel & Expenses	[redacted]	[redacted]	[redacted]	[redacted]
	ABB	Equipment	[redacted]	[redacted]	[redacted]	[redacted]
		Labour	[redacted]	[redacted]	[redacted]	[redacted]
	Applied Materials	Equipment	[redacted]	[redacted]	[redacted]	[redacted]
		Labour	[redacted]	[redacted]	[redacted]	[redacted]
	Safety Consultant	Labour	[redacted]	[redacted]	[redacted]	[redacted]
WS2	UK Power Networks	Contingency	[redacted]	[redacted]	[redacted]	[redacted]
		Contractors	[redacted]	[redacted]	[redacted]	[redacted]
		Decommissioning	[redacted]	[redacted]	[redacted]	[redacted]
		Equipment	[redacted]	[redacted]	[redacted]	[redacted]
		Labour	[redacted]	[redacted]	[redacted]	[redacted]
		Payments to users	[redacted]	[redacted]	[redacted]	[redacted]
	ABB	Equipment	[redacted]	[redacted]	[redacted]	[redacted]
		Labour	[redacted]	[redacted]	[redacted]	[redacted]
	Safety Consultant	Contingency	[redacted]	[redacted]	[redacted]	[redacted]
		Labour	[redacted]	[redacted]	[redacted]	[redacted]
WS3	UK Power Networks	Labour	[redacted]	[redacted]	[redacted]	[redacted]
		Travel & Expenses	[redacted]	[redacted]	[redacted]	[redacted]
WS4	UK Power Networks	Contractors	[redacted]	[redacted]	[redacted]	[redacted]
		Labour	[redacted]	[redacted]	[redacted]	[redacted]
		Travel & Expenses	[redacted]	[redacted]	[redacted]	[redacted]
PM	UK Power Networks	Labour	[redacted]	[redacted]	[redacted]	[redacted]
	Imperial College	Labour	[redacted]	[redacted]	[redacted]	[redacted]
General Contingency	UK Power Networks	Contingency	[redacted]	[redacted]	[redacted]	[redacted]
Totals		**Labour**	1,942	378	717	**3,037**
		Other	1,652	1,038	462	**3,152**
		Grand Total	3,594	1,416	1,179	**6,189**

4.2.4. Benefits are poised to be large compared to project scale

In comparison to substation switchgear replacement, such as circuit breakers and RMUs, FLCBs are poised to provide better value for money for customers. Switchgear reinforcement costs are estimated at more than £2.48 million per substation (see Appendix 10.2 for details). In comparison, Method 1 is expected to cost £500k per substation, and Method 2 is expected to cost £300k per connection. With a project cost of £6.19 million, the scale of the project cost is small in relation to the potential direct impact to connecting customers and to UK Power Networks' broader customer base through lower reinforcement expenditure.

As quantified for direct benefits earlier in this section, the majority of benefits will accrue to customers by enabling them to connect more quickly and cheaply than with existing solutions. There could also be benefits for the System Operator, in that the increased uptake of DG is also an enabler for providing balancing services. **National Grid expects the requirement for Frequency Response to be 3-4 times higher than the current level between 2025 and 2030.**[9] This requirement will increase as renewable intermittent generation is expected to be between 30-50% of installed capacity by 2040.[10] Rotating DG are ideally suited to meet the increasing requirement for balancing services due to their ability to provide flexibility. Consequently, higher uptake of DG as a result of FLCBs, can support increased renewable intermittent generation due to their ability to provide balancing services, indirectly contributing to environmental benefits.

Note that this is an indirect benefit, so we have not included it in our benefits case. This is primarily due to the uncertainty surrounding which generators may decide to participate in balancing services and the nature of the balancing service markets out to 2050. However, we believe that this solution will enable more DG to participate in network flexibility markets at lower cost in the future, providing benefits across the electricity system value chain.

4.3. Evaluation Criteria (d)

Is innovative and has an unproven business case

Deployment of the FLCB will provide DNOs with an alternative tool to be utilised during the lifecycle of network design, delivery and operation. DNOs will have the ability to improve switching capability and manage fault levels at primary substations without the need to replace and upgrade existing assets or install space consuming FCL plant.

- **Technological innovation**: A full discussion of the technical advantages has already been provided in section 3. To summarise: the unique selling point that makes them suitable for integrating in a dense urban environment is size. Both devices provide small, reclosing FLMTs which can be tested without destroying the device.
- **These technologies have not been proven**: To our best knowledge, Method 1 will be the world's first demonstration of FLCB with a fast commutating switch, and Method 2 will be GB's first demonstration of a FLCB, or any kind of FLMT (other than an I_s-limiter), at a customer's premises. Method 1 needs to be proven on a live network to give ABB confidence to invest in development of a commercial product. Method 2 needs to be proven on a live network to give DNOs confidence to approve its use as a customer-side solution.
- **Why this project justifies NIC support:** We stated in our RIIO-ED1 business plan, Smart Grid Strategy Annex 10 that the immaturity of FLMTs and the technical challenges in LPN substations meant that we were not in a position to

[9] http://www2.nationalgrid.com/UK/Industry-information/Future-of-Energy/System-Operability-Framework/
[10] National Grid FES 2016

include Method 1-type FLMTs in our RIIO-ED1 plan. Without NIC support it would not be expected that this new technology, which addresses both maturity and space constraint challenges, would be available in a timeframe that supports achieving the 2030 and 2050 carbon targets. Method 2 would not be funded from our existing RIIO-ED1 allowances because, although it will deliver benefits in RIIO-ED1, these benefits will accrue exclusively to connections customers given the customer-specific sole-use nature of the Method 2 device. No customer would be able to fund either Method 1 or Method 2 until they are proven and accepted by DNOs.

4.4. Evaluation Criteria (e)

Involvement of partners and external funding

PowerFuL-CB represents a genuinely innovative project to address the challenges facing DNOs.

At the outset of this year's NIC, we consulted with internal and external stakeholders to compile an initial list of project ideas relevant to distribution companies. Subsequently, we carried out a shortlisting process based on literature reviews and expert panels. Our shortlisting criteria drew from Ofgem's NIC requirements and included benefits to customers, value for money and degree of innovation.

As we reviewed the shortlist, we worked with a number of manufacturers to understand the status of their products. We selected the FLCB idea because:

- It had the most support from our internal stakeholders, particularly from the frontline engineering teams developing the network and connecting DG customers. It addresses an issue that is expected to be a major barrier to future DG uptake.
- We believe the technology is well positioned to create value for money for customers while addressing both future and emerging energy network challenges.
- It complements other fault-level solutions currently being developed.
- To our best knowledge, Method 1 will be the world's first demonstration of FLCB with a fast commutating switch, and Method 2 will be GB's first demonstration of a FLCB, or any kind of FLMT (other than an Is-limiter), at a customer's premises.
- An extensive engagement with stakeholders supported that FLCB is first of its kind and is truly innovative.
- Furthermore, to check for other similar solutions available, we published a PIN in Tenders Electronic calling for vendors who could build a FLCB.

As mentioned in section 2.4, we initially proposed a sole partner. However, by the end of June 2016, our stakeholder engagement led to our awareness of a second device and for the reasons mentioned, we increased the scope to carry out a parallel trial of Method 2.

When forming the project structure and collaboration partners, we drew on our experience delivering innovation projects to date and on our knowledge of the value that partners can bring to project. We have learned through experience how best to leverage those partnerships to bring about the greatest learning.

- **ABB:** ABB is a global leader in power and automation technologies with a long tradition in developing state of the art technologies and products. They have a solid track record of working on LCNF/NIC projects involving power electronics and fault level solutions.
- **Applied Materials (AMAT)**: is the world leader in supplying tools to the semiconductor fabrication industry. The 'Fault Current Limiter Project' has been

running for eight years and has seen two technologies developed. One is based on superconductors and has seen four installations around the world, including two at 115kV recently energised in Thailand. The second is based on solid state switches and a mutual reactor. An installation demonstrating the switches alone (with low currents) has been installed in a novel 'Bush Fire Prevention' installation in Australia. AMAT are committed to identifying more mainstream demonstration applications.

We have been fortunate to gain the support of a variety of external companies and organisations, including WPD, ENWL, as well as the Greater London Authority. Letters of support can be found in the Appendix 10.12.

External funding

Table 7 - Cost assessment and external contributions (£k)

Project Participant	Total Costs Incurred	Voluntary Contribution	DNO Compulsory Contribution	Outstanding funding required
AMAT	417	388	3	26
ABB	2,614	500	211	1,903
UK Power Networks	3,158	120	304	2,734
Total	**6,189**	**1,008**	**518**	**4,663**

The contributions made by UK Power Networks and the FLCB project partners are evidence of our commitment to innovation.

4.5. Evaluation Criteria (f)

Why this project is both relevant and timely

4.5.1. Headroom is already low and will further shrink on LPN network

LPN is already facing fault level constraints on its network. An analysis carried out by Navigant estimates that as of the year 2016, new DG seeking connection on 62% of LPN's substations would be required either to contribute to network reinforcement or use an intertrip scheme disconnecting the DG in N-1 conditions[11] in order to safely connect. We recognise the increasingly pressing need to release DG capacity in urban networks, described in Section 2. Whilst DNOs already employ these intertrip, or inhibit, schemes in certain circumstances to manage the network as an alternative to network reinforcement, this is a limited connection solution for customers.

An intertrip system is a hard-wired system protection scheme that will automatically disconnect a generator or demand from the distribution system under some pre-defined conditions, typically in the case of a transformer outage or when there is some particular reconfiguration of the network that could lead to unacceptable fault currents on the network. For example, normally-open points may be closed during an N-1 scenario to maintain firm capacity. Disconnecting the generators in these scenarios prevents them from contributing to network fault levels. There are only two possible states: situation normal where all generators are allowed to operate, or situation N-1 in which no generators are allowed to operate. This provides a limited amount of non-firm DG capacity. The intertrip system does have installation and maintenance costs, and hence increases the cost of connecting DG.

4.5.2. Connection opportunities are already being missed

Increasing penetrations of DG will increase the complexity of future networks, which will drive significant investment. Traditional reinforcement will not be able to keep pace with

[11] This data is from data tables used by Navigant to develop estimates for the 2020, 2030, 2040, and 2050 values as required by Ofgem.

the demands facing our network. New CHP, requests to convert standby generators to LTP operation, and district heating are already not accepting connection offers or are forced to scale down their plans due to expensive traditional reinforcement being the only way to relieve this headroom constraint.

Case Study: CHP in a new development

We recently investigated the feasibility of connecting 40MW of CHP as part of a new development in central London. We found that, due to fault level constraints:

- **10MW connection cost ≈ £150k (£15k/MW)** – maximum possible at 11kV without reinforcement. CHP can only operate when network is running in normal arrangement.
- **16MW connection cost ≈ £300k (£19k/MW)** – maximum possible at 33kV
- **40MW connection cost ≈ £4,000k (£100k/MW)** – must be connected at 132kV

In the absence of any smart solutions, it is clear that the maximum feasible CHP size is 16MW. A FLCB installed at either UK Power Networks' substation or the customer's premises would potentially allow 40MW of CHP to connect at 11kV. A method cost of £500k equates to a per-MW cost of £12.5k/MW, which is less than all of the traditional options. Therefore, in this case, **a FLCB could enable connection of an additional 24MW of low-carbon generation and heating at this development.**

4.5.3. This will complement previous and existing network innovation projects

The Low Carbon London (LCL) trials were designed to assess the use of ANM as a method for monitoring DG connections and facilitating new DG through intelligent control that manage constraints. The LCL project screening analysis indicated that around an additional 620MW of DG could be connected across 88 primary substations.

Although real-time ANM can free the most headroom, the LCL project uncovered there was a lack of monitoring of existing generators to enable real-time control. Existing generators may not have the required monitoring equipment, since this was not necessary for their own connection. When trying to relieve fault level constraints, real-time monitoring and control is required to manage the brief durations (minutes) during which the risk to the network may occur as generators temporarily operate in parallel with the network.

As such, enabling new generation involves detecting the existing connection status to inform real-time ANM control of other DG. The project found that there was limited appetite for this amongst the owners/operators of existing DG, with reasons including technical compatibility, a lack of commercial incentive, and high connection costs.

Section 5: Knowledge dissemination

One of the main purposes of the network innovation funds provided by Ofgem, currently through the yearly Allowances and the Competitions, is to generate and share learning amongst the DNOs and industry. The goal is to aid their understanding of what they need to do to provide security of supply at value for money as GB moves to a low carbon economy. Knowledge dissemination is key to achieving this goal.

This section outlines the new learning expected to be developed by our proposed Project; the way it has been designed to maximise learning; and how it is applicable to other DNOs. This section also presents our approach to learning dissemination based on UK Power Networks' Knowledge Dissemination Roadmap, a tested and proven Handbook, used by our previous successful LCNF Tier 2 projects. Lastly, this section covers the arrangements of the ownership of learning developed by the Project.

5.1. Learning generated

The aim of the Project is to increase the range of FLMTs available to DNOs and customers as existing solutions all have at least one showstopper for LPN and for other DNOs with dense urban networks.

This project has been designed to develop and understand the technical and commercial suitability of two FLMTs based on power electronic FLCBs. These solutions will be developed in in cooperation with industry and in dialogue with customers, to make sure they are fit for purpose.

In achieving this aim, we expect the following incremental learning to be developed:

- understanding of safety, reliability and environmental issues related to the two FLCB technologies at the development stage of the prototype;
- experience with design, installation, commissioning, operation and maintaining FLCBs on an 11kV network, both in substations and on customers' premises;
- understanding of the technical suitability of FLCBs on an 11kV network; and the relative differences between Methods 1 & 2 and other smart technologies such as I_s-limiter and Active Fault De-coupler;
- insight in users' expectations regarding connection offers based on an alternative solution; these expectations will focus on investment decision criteria (and trade-offs) such as cost, time to connect, and impact on security of supply; and
- understanding of the commercial suitability of FLCBs on an 11kV network for different use cases, business cases and customers' propositions, following the previous learning point.

The quality of the learning is ensured by the combination of our experienced staff, our knowledgeable and respected project partners and our expert advisers and reviewers.

The learning is directly applicable to other Licensees with dense urban networks, as is confirmed by the positive feedback we have received from FlexDgrid (WPD) and Respond (ENWL) who indicated a high level of interest in FLCBs. Their areas of urban network such as Manchester and Birmingham could benefit from the installation of these two types of FLCBs.

Apart from DNOs, we believe that a large spectrum of stakeholders can benefit from the learning generated throughout this trial:

- **Regulators and associated departments & bodies:** The trial can enable Ofgem to gain valuable information regarding the potential of alternatives to network reinforcement and their costs. Furthermore, the trial findings will enable the Department of Business, Energy and Industrial Strategy, to shape a more informed strategic view in regard to the potential deployment of DG, particularly CHP in the future. Regulators such as the Health and Safety Executive (HSE) will gain better insight to the safety risks/benefit of installing FLCBs at an 11kV level.

- **Industry groups & professional bodies:** These stakeholders can benefit from learning related to new design standards related to FLCBs and various system configurations. Specifically, technical forums such as the Electricity Network Association (ENA), Institution of Engineering and Technology (IET) and the Distribution Code Review Panel can benefit from close engagement related to the impact of the project for fault level constraints.
- **Current and future DG customers:** Method 2 will trial the impact of the project co-located with customer generator units. The trial will demonstrate the effectiveness of Method 2 in addressing fault currents, as well as identify any further impacts or issues for customers, such as impacts of abruptly disconnecting the generating unit. We will reach DG operators through designated learning events, the DG forum and dialogue meetings.
- **Academic institutions:** As expressed in ICL's Letter of support, this Project will accelerate the use of power electronics on distribution networks, which can revolutionise the way we design, build and operate networks. Electrical engineering departments and institutions will get access to trial findings of the project results to continue this work.
- **Other manufacturers:** PowerFuL-CB will demonstrate the need, technical/commercial feasibility, and benefits of FLCB commercial products, not just to the project participants and GB DNO community, but also to third parties who could bring competing FLCB technologies to market. The learning from this project will de-risk, remove technical and regulatory barriers, and stimulate further innovation across the market in the development of FLCB technologies.
- **Local Authorities:** We intend to collaborate with the GLA and take active part in local events in which we will inform and update the audience on different aspects of the project. The aim is to facilitate discussion and explore ways to accommodate issues related to fault level constraints which are unique to dense urban networks such as LPN.

5.2. Learning dissemination

Facilitating knowledge transfer is key for project learning dissemination and ultimately for gaining maximum return of investment for the customer. Our approach to learning dissemination is based on UK Power Networks' Knowledge Dissemination Roadmap (see Appendix 0), originally developed and proven for FPP and used for all our large innovation projects after that.

The purpose of this Knowledge Dissemination Roadmap is to inform stakeholders what knowledge the project will share, how it will be shared, with whom and at what stages throughout the project.

Over the years we have gathered an extensive contact list of stakeholders on which we can build. We will seek input from other DNOs who have run or are still running fault level related projects. In addition, as we have done in previous projects, we will conduct market research to identify stakeholders who would be interested and how they could benefit from this project.

A particular target group for this project is the DG community. We aim to raise awareness and understanding of this potential new opportunity to connect to urban networks, thus promoting the take up of new DG.

We will make our progress and findings transparent and easily accessible through a variety of dissemination channels which will give stakeholders the discretion to choose the way they would like to be informed. This will include direct engagement such as seminars and access through various online platforms.

Table 8: We will use a multitude of channels depending on the message and audience

Channel	Description	Outputs
Websites	Our innovation UK Power Networks microsite includes a diversity of information. (www.ukpowernetworks.co.uk/innovation) Alongside written documents, users can find videos, tutorials and online learning events. Relevant information will also be made available via the ENA Smarter Networks Portal.	Reports, tutorials, data, training material, news
Workshops and Seminars	Frontal knowledge transfer will allow question time and engagement between the different stakeholders.	Face to face communication, video documentation, leaflets and printed material
Social Media	Regular updates through Twitter, Blogs and Linkedin.	Notifications, news, announcements
Press releases	Publications in industry magazines, websites, working groups and forums.	Notifications, news, announcements, articles
Other DNOs	We will collaborate directly with ENWL and WPD to pool the learning from Respond, FlexDGrid, and PowerFuL-CB to enable all GB DNOs and customers to understand the available solutions.	Share knowledge and lessons learned
Targeted communication	We aim to approach directly organisations involved in developing codes and standards, e.g. the ENA and the IET.	Collaboration in standards and codes development
Presentations at conferences and industry events	We will present FLCB in high profile industry events such as the annual LCNI conference and ENA DG Fora. This will enable a wider audience such as STEM students, academics and policy makers to be exposed to the PowerFuL-CB projects.	Reach a wide audience and facilitate new opportunities for knowledge transfer and collaboration

We will publicise the outcomes from each of the workstreams. As described in our work plan and SDRCs, the output comprises seven reports and several main stakeholder events.

To ensure those activities will be effective, well-coordinated and of a high quality, we have a dedicated workstream which focuses on knowledge dissemination. We will ensure that this workstream is led by a person with the appropriate combination of technical and customer engagement skills.

5.3. Intellectual Property rights (IPR)

PowerFuL-CB will conform to the default IPR arrangements set out in the NIC Governance Document.

- All contracts with project partners/participants will include terms and conditions that reflect the default IPR arrangements.

- ABB and Applied Materials have both reviewed the default IPR arrangements and confirmed that they will conform to them.
- Conformance with the default IPR arrangements will be an eligibility criterion for all project partners yet to be appointed, e.g. the safety case consultant.

5.3.1. General IPR Treatment

The following table illustrates some of the key components of Background and Foreground IPR related to this project.

Table 9 - IPR relevant to PowerFuL-CB

Method	Method 1 (ABB)	Method 2 (AMAT)
Relevant Background IPR	The design of the Method 1 FLCB apparatus, i.e. the power electronics, fast commutating switch, and tripping unit, as described in Appendix 10.3.1	The design of the Method 2 FLCB commercial product, i.e. the power electronics, tripping unit, and the modular cubicles, as described in Appendix 10.4.1.
Foreground IPR	Knowledge required to integrate a FLCB apparatus into a modular switchgear panel to create a Method 1 FLCB commercial product.	N/A
Relevant Foreground IPR	Knowledge required to safely roll out Method 1 FLCBs on existing electricity distribution networks.	Knowledge required to safely roll out Method 2 FLCBs on existing electricity distribution networks.

For the avoidance of doubt: **all Relevant Foreground IPR for both Methods will made fully and freely available to other Network Licensees and interested third parties including academia and other manufacturers.** This will include, as a minimum:

- Functional/technical specifications for procuring a FLCB
- Network design standards, including independent backup protection strategies
- The safety case
- Laboratory and type test results, including short-circuit and other safety tests
- Field trial results, including learning from installation, commissioning, operation, and maintenance activities
- Technical/commercial feasibility studies

5.3.2. Method 1 IPR treatment if ABB does offer a commercial product

In this scenario, ABB will offer a FLCB commercial product to Licensees, comprising an ABB FLCB apparatus housed inside ABB switchgear panels.

ABB will also provide switchgear manufacturers with the IPR necessary to build competing FLCB switchgear products:

- ABB will manufacture and sell FLCB apparatus (the Relevant Background IPR) to other switchgear manufacturers[12], and
- Licence **royalty-free** any knowledge required to integrate the FLCB apparatus

[12] ABB already offers many other products to competing switchgear manufacturers, such as circuit breakers, I_s-limiters, and protection relays.

into the other manufacturer's switchgear (the Foreground IPR).

This will:

- Enable Network Licensees to purchase an ABB FLCB housed inside non-ABB switchgear panels;
- **Enable competition** for the switchgear-panel component of a FLCB commercial product; and
- Maximise opportunities for Network Licensees to integrate FLCBs with their existing switchboards.

5.3.3. Ensuring fair and reasonable terms for future use of commercial products

We recognise the need to ensure fair and reasonable terms for the future use of any Background IPR and Commercial Products needed for other Licensees to reproduce the Project outcomes (clause 5.53v of the NIC Governance Document). **We recognise that pricing of Method 1 FLCBs is of particular concern.**

To encourage fair and reasonable pricing of Method 1 FLCB commercial products:

- **We will encourage competition** by allowing competing switchgear manufacturers to offer their own FLCB commercial products based on ABB's FLCB apparatus (as described in section 5.3.2);
- **We will enable and encourage academia and other manufacturers to develop competing FLCB technologies** by sharing Relevant Foreground IPR with them (as described in section 5.3.1);
- We also note that **Method 1 will have to compete with the other fault level solutions available at the time**, such as PowerFuL-CB Method 2, and (where physical space and operational constraints permit) methods currently being proven by FlexDGrid (fault current limiters) and Respond (Is-limiters, adaptive protection, and FCL service).

We believe that these actions will enable the market to deliver FLCB commercial products at fair and reasonable prices for DNOs and their customers. We believe that funding this project, particularly Method 1, via the NIC, greatly increases opportunities to share knowledge and stimulate development of competing FLCB technologies.

5.3.4. Method 1 IPR treatment if ABB decides not to offer a commercial product

Much of the Method 1 Foreground IPR and Relevant Background IPR will be contained within FLCB commercial products. Network Licensees will need to purchase these products in order to reproduce the project outcomes.

It is possible that ABB may decide for commercial reasons to not invest in developing a Method 1 FLCB commercial product for the GB market, despite it being technically viable.

In this scenario (Refer Appendix 10.11, risk R13), to ensure that we comply with clauses 9.14 and 9.20 of the NIC Governance document:

- Foreground IPR that would have been contained within a commercial product, i.e. the knowledge required to integrate a FLCB apparatus into a modular switchgear panel, will be treated as Relevant Foreground IPR.
- ABB will licence its Relevant Background IPR to a suitable third party for the specific purpose of developing a Method 1 FLCB commercial product for the GB market, upon terms to be agreed.
- ABB will also licence its Relevant Foreground IPR to third parties, upon arms-length terms, **royalty-free**.

This approach ensures that the Relevant Foreground and Background IPR can be used for customers' benefit regardless of whether ABB makes available a commercial product.

Section 6: Project Readiness

Requested level of protection against cost over-runs	0%
Requested level of protection against Direct Benefits that they wish to apply for	0%

Some innovation projects, across all sectors, have a reputation to take longer than expected or not deliver according to budget. However, when the source of the funding is the customer, there must be certainty that the money is well spent from 'day one'. It is with that philosophy in mind that UK Power Networks have put together this bid and have produced the documents, plans, project governance and relationships to be ready to start on 'day one'.

This section will present:

- the evidence that we can start in a timely manner,
- the measures in place to minimise the risk of project overruns,
- confirmation of our information verification process,
- how we will ensure learning even when the uptake of low carbon technologies slows down, and
- how we manage change control.

6.1. Evidence this Project can start in a timely manner

As part of developing this bid, we have invested in a significant amount of preparatory work to enable the project to start in a timely manner. The outcomes of this work are:

- A clearly defined project management and governance structure,
- Engaged, committed, and qualified project team members, including the partners developing the FLCB devices,
- Strong support within UK Power Networks across multiple business units,
- A robust project plan suitable to enable the project to commence on 'day one', and
- A safety case feasibility report to support development of the full safety case.

6.1.1. Project management and governance structure is clearly defined

We will create a Project Handbook, based on those that we developed for Flexible Plug and Play (FPP) and all our subsequent large innovation projects. The Handbook has earned its credentials through the Low Carbon London (LCL) and FPP projects, both of which received Successful Delivery Reward recognition as being well run projects.

The document acts as a guide to the project as it moves from bid into the design and delivery stages. It describes the overall aims of the project and the key success criteria, the organisational structure of the project, the governance structure which will enable clear decision making, the key reporting and control processes that support that governance structure.

This project will have a tailored version and be used as a 'living document' which will be updated and further developed as the project progresses.

The project team comprises stakeholders from multiple companies (i.e. UK Power Networks, ABB, AMAT, ICL, and a safety consultant). This approach will provide transparency, facilitate cohesion and collaboration amongst the stakeholders, and avoid duplication of work.

We have defined the project management and governance structure to enable the project to commence in a timely manner. A detailed description of each workstream can be found in section 2.3.

The key project roles and responsibilities are:

- **The Project Steering Group** comprises key stakeholders and decision makers within UK Power Networks, including the Project Sponsor Suleman Alli (Director of Safety, Strategy & Support Services) and chaired by Senior Responsible Owner Colin Nicholl (Head of Innovation). This group is ultimately responsible for the project and will make decisions that have an overall impact on the benefits and outputs that the project will deliver.
- **The Project Manager** will be responsible for the day-to-day management of the project. This includes but is not limited to reviewing the project progress against plan, presenting the project progress report to the Project Steering Group, updating the project plan, monitoring project risks and project budget.
- **The Design Authority** reviews and approves all key project deliverables. However, ultimate responsibility for the delivery of the solutions rests with the project delivery team.
- **Project Management Office** provides support to the Project Manager as required.

6.1.2. Committed and qualified project team members

UK Power Networks and the project partners have the experience and capability to successfully deliver large complex technical projects to time, cost, and quality targets.

To advance the technologies used in the solutions, we have two committed global technology providers participating in this project - ABB and AMAT. Both companies recognise the potential of their devices and the impact they could make on distribution networks. They are both keen to bring functioning and commercially viable products to benefit GB networks and ultimately GB customers. These committed and qualified project partners have been actively engaged in the development of our full submission to ensure that the project can commence in a timely manner.

To minimise technology-related risks to the project, **ABB has committed to invest US$300k (£250k) in further R&D, at their own cost and risk, prior to project kick-off**. This is in addition to ABB's £500k in-kind contribution to the project, and R&D investment to date of US$900k (£650k).

To ensure our solutions are safe for deployment on the network and will not create unacceptable risk to network equipment, we have worked with Frazer-Nash Consultancy to complete a feasibility study for the safety case for the FLCB technology and will let a competitive tender for the full safety case to be conducted during the project.

For the UK Power Networks team, we have identified and appointed the appropriate people to fulfil the project team roles. We selected staff who had the right mix of seniority, technical skills and knowledge, with experience delivering innovation projects.

Full details of the project team can be found in Appendix 10.9.

6.1.3. Strong support from UK Power Networks internal staff and the business

The project is developed in conjunction with the business in order to gain their input and commitment. This includes support from:

- Key members of the **Executive Management team,** who have committed management time and ensured the availability of input and support from in-house specialists.
- **In-house specialists** who have provided input and committed to continued support. They are engaged through regular meetings in the development of the project plan with internal senior managers and other senior discipline leaders with expertise in a number of areas including power electronics and fault levels.

The project has progressed through UK Power Networks' business as usual internal **Innovation and Project Governance and Control Governance processes** and the technical **Design Review Board**. This ensures that all the relevant internal stakeholders are fully engaged and formally committed to the project.

6.1.4. Robust project plan

The project plan has been drawn up using the experience from our innovation team managers and lessons learned from earlier large Low Carbon Network innovation projects such as LCL, FPP and SNS to develop the project plan. The plan has been validated by our senior management team and our project partners' management for their inputs on the project scope and delivery phases. This combined input, feedback and guidance ensures that the resulting project is robust.

The project plan provides a clear line-of-sight between project aim, objectives, methods, deliverables and SDRCs. It was developed based on an in-depth analysis of the project objective, methods, deliverables and Successful Delivery Reward Criteria.

The detailed project plan is in Appendix 10.7. This robust project plan will enable the project to commence in the first quarter of 2017.

6.1.5. Safety feasibility report already conducted to support the safety case

We appreciate that FLCBs are not intrinsically failsafe, and that their failure to operate correctly may result in an unsafe condition, i.e. network equipment may be exposed to fault currents exceeding their design ratings. We have taken the following steps to address this risk:

- We will develop a robust **safety case** to ensure that FLCBs and our approach to deploying them is safe, reliable, and compliant with current UK legislation. We note that ENWL is also using safety cases to ensure the safety of I_s-limiters, Adaptive Protection, and the FCL service.
- Prior to submitting our FSP, we commissioned Frazer-Nash Consultancy (FNC) to investigate and **confirm that it is feasible to produce this safety case** as part of the project.
- FNC has confirmed that **there are no insurmountable issues** that would prevent the successful development of a safety case. They have also identified the key challenges that need to be overcome, and a strategy for developing the safety case.
- **We have liaised directly with the HSE** to confirm that there are no insurmountable issues that would prevent the use of FLCBs on GB distribution networks.
- **We will use an integrated, safety-led approach** to design the Methods, whereby the safety case is developed in parallel with, and drives, the FLCB specifications and engineering standards for its installation, operation, and maintenance.

6.2. Evidence of how the possibility of cost overruns or shortfalls of direct benefits will be minimised

UK Power Networks has a strong track record for not only minimising project overruns, but delivering projects under budget. For example, the FPP project was able to deliver the same benefits at a lower cost, which delivered a 3% savings to customers. This was possible due to good project management practices, as outlined in our Handbook, which defines in detail the project control processes and provides effective mechanisms to manage and control the project scope, cost and schedule.

We will implement the same five key control measures. These defined processes and document controls will help the project board and steering committee to initially agree to the workstream initiation documents, plans and designs and then maintain control of the project to ensure the project delivers to its overall aims, as defined in the project proposal.

A summary of these processes are provided below:

1. **Review Process.** All formal outputs from the project must be put under formal review process (configuration management). Each output must go through the formal specialist or management product review. An output is not deemed completed until it has passed this review process. It is the responsibility of the workstream managers and project manager to ensure all outputs are placed under review.
2. **Approval Process**. This process will be implemented to ensure all deliverables are adequately approved before they are agreed as complete and released. The governance boards will check to ensure each deliverable is completed to the quality, cost and time levels as agreed in the initiation documents and detailed plans and designs for each workstream.
3. **Sign off Process**. This is the process to formally sign off all formal documents
4. **Risk and Issue Management**. This process allows for the communication and escalation of key risks and issues within the project and defines where decisions will be made and how these will be communicated back to the workstream where the risk or issue has arisen.
5. **Change Management**. The purpose of this process is to control and agree any changes to the agreed baseline of the project, whether the change relates to time, cost or quality. A key interaction in this process is between the design authority board and the project board to check and approve proposed quality changes. Approvals for changes will have to be within the board's delegated authority; otherwise the change will need to be escalated further up the governance structure.

We will adopt project monitoring and reporting procedures as follows:

- Monthly reporting to the Steering Group and to the UK Power Networks' Executive Management Team by the Project Sponsor to provide regular review points and allow full financial and project control;
- The project management team comprising the Project Manager, Workstream Managers and Programme Management Officer, will meet fortnightly to monitor the project progress against its plans, project risks and project issues;
- Workstreams will be managed in accordance with milestone plans supported by detailed project plans and a clearly defined list of deliverables for each workstream. These will be produced in consultation with our project partners to ensure a strong foundation for clarity of scope, objectives, approach; and deliverables.

In addition to the project monitoring and reporting procedures, we will embed risk management within project roles and responsibilities by:

- The Project Steering Group will assess change requests, review the impact on the project business case, and identify and review risks and issues associated with major change requests;
- The Board is responsible for the operational management of the project, focused on reviewing progress against plan, and resolving risks and issues. They will also approve change requests within a defined tolerance and prepare change requests for submission to the Steering Group for changes;
- Regular risk reviews undertaken by the Project Manager with results reported to the Project Sponsor and Project Steering Group;

- A Design Authority who will review and approve all key project deliverables to ensure they are fit for purpose. Change requests may be initiated by the Design Authority directly or by the Workstreams. Change requests initiated by the Workstreams will be reviewed by the Design Authority prior to submission; and
- Quarterly project partner/supplier reviews will track and discuss progress and risks to project delivery.

We have produced a risk register and risk management process for the project that demonstrates how these roles interact. The risk register details the identified risks and mitigation strategies in Appendix 10.11.

6.3. Accuracy of information

UK Power Networks has endeavoured to ensure all of the information included within this full submission is accurate. Information included within the proposal has been gathered from within UK Power Networks, the project partners, suppliers and other subject matter experts. All of this information has been reviewed to confirm and refine understanding, whilst evaluating the validity and integrity of the information.

6.4. Managing change and contingencies

Through our strong track-record of delivering successful innovation projects, it is clear that the nature of innovation projects inherently includes the unexpected. It is essential, therefore, that there are effective mechanisms to manage change. The process used is one of the five project controls presented earlier and illustrated below.

6.5. How the Project plan would still deliver learning in the event that the take up of low carbon technologies and renewable energy in the trial area is lower than anticipated in the Full Submission

We do not anticipate any issues with the delivery of learning due to a slow-down in low carbon technologies. For our project we need to select only one substation with fault level constraints; we already have a list of substations with constraints today, irrespective of the low carbon uptake.

The same applies for the recruitment of a customer. We have currently identified 111 CHP connections in LPN. As we plan to trial only at a single consumer premise, there is a sufficient pool of potential trial participants. We will draw on our experience and recruitment process from the FPP project, where our engagement strategy for DG customers enabled us to recruit 14 participants when our target was only one.

6.6. The processes in place to identify circumstances where the most appropriate course of action will be to suspend the project, pending permission from Ofgem that it can be halted

As part of the UK Power Networks' internal governance, there are number of processes in place to identify, assess and manage any issues that may affect the project. These processes help to maintain the smooth running of the project, whilst also aiding identification of the most appropriate course of action at any point.

The internal UK Power Networks' Project Governance and Control process, based upon the PRINCE2 methodology, has a gate approval process which reviews the project at critical stages throughout its life-cycle. The project must meet the mandatory entry/exit criteria for any particular gate (which takes into account business case, risks, issues, benefits realisation and financial position), which the Project Manager will need to provide evidence. If the project does not meet the mandatory entry/exit criteria, the Project Steering Group has the authority to suspend the project where it is the most appropriate course of action, pending permission from Ofgem that the project can be halted.

The Project Steering Group is also able to suspend the project outside the gate approval process if it is the most appropriate course of action. This could be triggered by an escalation from the Project Manager for a risk or issue that has exceeded the agreed tolerance.

Section 7: Regulatory issues

We do not expect that the Methods will require any derogation, licence consent or licence exemption for its delivery.

We believe a robust safety case will allow us to deploy FLCBs in BAU in full compliance with our existing regulatory obligations. However, we recognise that there is no established due process for the review, approval, and regulatory acceptance of safety cases produced by DNOs. We look forward to working through these processes with Ofgem, the HSE, and ENWL (who are also planning produce safety cases as part of Respond).

We note that Method 1 may require a review of Common Connection Charging Methodology and specifically the Fault Level Cost Apportionment Factor[13]. We look forward to participating in the discussions on this issue that ENWL will initiate through Respond.

[13] http://www.enwl.co.uk/docs/default-source/respond-key-documents/respond-full-submission.pdf?sfvrsn=6, Appendix J

Section 8: Customer Impact

8.1. Method 1: Substation-based solution

Method 1 will require extensions and/or connections to existing 11kV switchboards. We expect that we will be able to use existing redundancy in the network to complete this work without any planned outages that affect customers. The solution will be designed so that in the event of an unplanned FLCB failure, it can be isolated and bypassed to restore normal system configuration with minimal or no impact on customers.

8.2. Method 2: Customer-based solution

Method 2 will be installed at the customer's premises at the point between a generator and the network. This will require direct customer participation in the trial. For the generation customer – who will agree to participate via a specific connection offer made by UK Power Networks including the Method 2 solution as part of the connection design – there are several ways that the project may impact them. These are presented in the table below including our mitigation action to minimise the impact.

Table 10: Customer impact and mitigation actions

Impact on customer	How we will minimise it
FLCB will take up space at the customer's premises	We will design the solution to fit within physical space constraints agreed with the customer.
Project activities may disrupt customer's normal activities	We will plan installation, commissioning, and maintenance activities, and any planned supply interruptions in consultation with the customer to minimise their impact.
Customer's energy costs increase due to FLCB losses	We will compensate the customer for the cost of any energy that the FLCB consumes during the trial.
FLCB failure may prevent customer from operating their generator	We will install additional switchgear to ensure that the FLCB can be isolated and bypassed if it is out of service.
Customer's generator will be disconnected for network faults that normally wouldn't affect that customer	In order to robustly test the FLCB while not increasing network risk, we will configure the FLCB to disconnect the customer's generator for network faults that would not normally affect that customer. We understand that this will have an impact on the customer, and we will take steps detailed below to minimise it: **In BAU:** The FLCB would only be enabled when the fault level is close to or exceeds equipment ratings, and will be disabled and bypassed at all other times. This would be achieved by repurposing an existing inhibit scheme, or by a more-intelligent active network management system such as the ENWL Respond Fault Level Assessment Tool (FLAT). **During trial:** The traditional post-fault inhibit scheme will operate as normal, i.e. the generator will be disconnected whenever abnormal network arrangements mean that its operation would cause

	unsafe fault levels, so that there is no risk to the network should the FLCB fail to operate correctly. This means that the FLCB will need to be enabled at all other times until it has had sufficient opportunity to operate for real network faults, and we have collected sufficient data to support the safety case. As we develop the safety case we will be able to quantify this requirement, and work with the customer to minimise its impact.
Unplanned generator shutdown due to FLCB operation may affect the customer's normal activities, or prevent them from participating in balancing services	We will work with the customer to ensure that their generator is able to restart and re-synchronise quickly after a FLCB operation to avoid any adverse impact on their normal activities. If possible, we will also investigate whether placing a current-limiting reactor in parallel with the FLCB could allow the generator to "ride through" network faults without contributing any significant fault current.
Risk of damage to customer's generator caused by abnormally rapid disconnection	We will work with the customer and their generator vendor to understand the impacts of disconnection by FLCB (much faster than disconnection by normal CB), and ensure that the generator is able to shut down safely.
Customer uncertain about if/when the FLCB will enable them to connect more generation, which affects their ability to make investment decisions	We intend to recruit a customer who has already accepted a non-firm generator connection, i.e. subject to an inhibit scheme that disconnects them during a transformer outage. This means that: The customer's investment is viable regardless of whether the FLCB is successful; and Once the FLCB is proven safe and reliable, they can obtain a firm connection for their existing generator, i.e. an immediate benefit with no additional investment.

Section 9: Successful Delivery Reward Criteria (SDRCs)

The Successful Delivery Criteria are used to test whether the Project has achieved what it set out to do and for which it has received funding. The PowerFuL-CB project is designed to provide a clear line-of-sight between project aim, objectives, methods, outcomes and SDRCs. This direct linkage provides a strong focus throughout the project.

Based on this, we propose the following Criteria and related Evidence.

All learning reports will be published on UK Power Networks' innovation website and on the smarter networks portal, and will be sent directly to key stakeholders.

Table 11: Criteria and evidence proposed to show success in achieving the objectives

	Criteria	Evidence	Due Date
9.1	**Work with industry to advance new FLMTs based on FLCB technology**		
9.1.1	Prototype and lab test a substation-based solution (Method 1)	**Publish Learning Report – Development of a FLCB for substations**, which will include: recommendations for specifying a substation-based FLCB; results and learning from type tests (including a short circuit test) conducted at an accredited high power laboratory; and requirements for integrating FLCBs into existing networks and ensuring safety	End of May 2019
9.1.2	Prototype and lab test a customer-based solution (Method 2)	**Publish Learning Report – Development of a FLCB for customers**, which will include: recommendations for specifying a customer-based FLCB; results and learning from type tests (including a short circuit test) conducted at an accredited high power laboratory; and requirements for integrating FLCBs into existing networks and ensuring safety	End of August 2019
9.1.3	Independent review of safety case	**Issue preliminary safety case to relevant ENA panel(s) for independent review** which will include: Definition and justification of acceptable levels of risk; analysis of failure modes and effects; details of proposed mitigations; and claims, arguments, and evidence to demonstrate that the proposed mitigations reduce the overall level of risk to an acceptably low level	End of May 2018

9.2	**Trial the technical suitability of these two technologies including effectiveness and safety considerations for relieving fault level constraints for 11kV networks**		
9.2.1	Install and commission solution at an 11kV substation (Method 1)	**Publish Interim Learning Report – Demonstration of a FLCB for substations**, which will include results and learning from installation, commissioning, and operation to date of a FLCB at a substation.	End of July 2020
9.2.2	Install and commission solution at a customer's premises (Method 2)	**Publish Interim Learning Report – Demonstration of a FLCB for customers**, which will include results and learning from installation, commissioning, and operation to date of a FLCB at a customer's premises.	End of July 2020
9.2.3	Demonstration of solution at an 11kV substation (Method 1)	**Publish Final Learning Report – Demonstration of a FLCB for substations**, which will include results and learning from operating and maintaining a substation containing a FLCB, and technical performance of the FLCB and overall solution under real network conditions	End of June 2021
9.2.4	Demonstration of solution at a customer's premises (Method 2)	**Publish Final Learning Report – Demonstration of a FLCB for customers**, which will include results and learning from operating and maintaining a FLCB at a customer's premises, and technical performance of the FLCB and overall solution under real network conditions	End of June 2021
9.3	**Assess the suitability of the solutions against customer's needs**		
9.3.1	Review the customer needs for these two FLCBs technologies on behalf of DNOs and DG stakeholders	**Publish Learning report – Understanding customers' requirements**, which will describe our findings from customer dialogue sessions, i.e. understanding their requirements and concerns about FLCBs, and customer feedback	End of October 2017

9.3.2	Assess the (commercial) business case based on the technical and customer findings, focusing on investment decision criteria and trade-offs, such as cost, time to connect, space and impact on security of supply	**Publish Learning report – Suitability of FLCBs**, which will inform generation customers of the solutions, answer frequently-asked questions, and provide enough information for customers to assess whether the solution meets their requirements (e.g. cost, time to connect, space required, operational impacts)	End of March 2020
9.4	**Share the learning throughout the project with the wider utility industry**		
9.4.1	Share overall learning from the project with customers, regulators, other DNOs, other manufacturers, and academia via a stakeholder event	Publish key materials from the stakeholder event (e.g. slides), and provide Ofgem with a list of invitees and attendees	End of September 2021

Section 10: Appendices

List of appendices

10.1. Benefits Tables

KEY

Method	Description
Base Case	Connect all CHP and Diesel generation forecast in the FES (Future Energy Scenarios) by using **traditional reinforcement.**
Method 1	Connect all CHP and Diesel generation forecast in the FES (Future Energy Scenarios) by **installing FLCBs at substations.**
Method 2	Connect all CHP and Diesel generation forecast in the FES (Future Energy Scenarios) by **installing FLCBs at customers' premises.**

Note that we have only provided a table for **financial benefits** because we have used a base case where traditional reinforcement is used to achieve the same capacity and carbon benefits as the methods.

Electricity NIC – financial benefits

Scale	Method	Method Cost	Base Case Cost	Cumulative net financial benefit (NPV terms; £m) Benefit 2020	2030	2040	2050	Notes	Cross-references
Post-trial solution *(individual deployment)*	Method 1	£0.50	£2.48	£0.53	£1.11	£1.46	£1.67	– The trial site for Method 1 is configured in 4x15 MVA. A different configuration would result in a different level of expected benefits. This is reflected in the benefits calculations for the licensee scale and GB rollout scale below. – It is assumed that one unit is installed in 2020 for Method 1, following product development between 2017 and 2019. – It is assumed that five units are installed in one site for Method 2, spread across five years, starting 2020.	Section 10.2.3 (Financial Benefits)
	Method 2	£1.50	£2.48	£0.58	£0.67	£0.83	£0.93		
	-	-	-	-	-	-	-		
Licensee scale *If applicable, indicate the number of relevant sites on the Licensees' network.*	Method 1	£0.50	£2.48	£0.53	£14.46	£31.71	£49.47	– Number of sites by 2050: 70 – Range of sites by 2050: 62-76 – Range of financial benefits by 2050: £44.97m-£53.06m (Method 1); £30.52m-£37.31m (Method 2) – Method cost and base case cost are constant on a per installation basis. Method 2 allows for five devices per substation installed over five years. – It is assumed that implementation across LPN starts in 2021, following product development commencing in 2019.	Section 10.2.3 (Financial Benefits)
	Method 2	£1.50	£2.48	£0.58	£11.74	£23.02	£34.15		
	-	-	-	-	-	-	-		
GB rollout scale *If applicable, indicate the number of relevant sites on the GB network.*	Method 1	£0.50	£2.48	£0.53	£113.32	£255.68	£403.30	– Number of sites by 2050: 762 – Range of sites by 2050: 697-827 – Range of financial benefits by 2050: £369.60m-£437.30m (Method 1); £338.48m-£401.52m (Method 2) – Method cost and base case cost are constant on a per installation basis. Method 2 allows for five devices per substation installed over five years. – It is assumed that implementation across GB networks starts in 2021, following the installation of the post-trial solution in 2020 in LPN.	Section 10.2.3 (Financial Benefits)
	Method 2	£1.50	£2.48	£0.58	£123.60	£247.25	£369.82		
	-	-	-	-	-	-	-		

10.2. Benefits Calculations

10.2.1. Summary

Navigant has been engaged by UK Power Networks to calculate the potential benefits of the proposed solution, in accordance with the NIC Full Bid Submission Guidelines and the NIC Governance Document.

The proposed solutions are expected to be lower-cost alternatives to traditional network reinforcement for the release of fault level headroom. Currently, the release of headroom is achieved through the upgrade of substation switchgear such as circuit breakers and ring main units to higher fault current ratings; it is estimated that on average such upgrades could cost £2.48 million per substation. The proposed solutions are expected to be able to provide similar level of fault current headroom release at a much lower cost (Method 1: £0.5m-£1.25m per substation, Method 2: £0.3m per generation connection).

A high-level fault current level analysis was prepared in order to quantify the population of substations that the proposed solutions can be applied to across the entirety of the GB distribution networks. The results of this analysis demonstrate that between 697 and 827 substations could be constrained due to potential fault current violations by 2050. The potential benefits of using the proposed solutions over conventional substation reinforcement at these substations could be between £338 million and £434 million.

In conjunction with the savings that can be achieved over conventional network reinforcement, the proposed solutions will deliver benefits in the form of released headroom for DG connections. It is estimated that the amount of DG capacity that could be enabled by 2050 can be 462MW, given the high number of constrained substations.

It is expected that a major beneficiary of the release of fault level headroom will be combined heat and power connection customers, given the high fault current contribution of the technology. An uptake in CHP installation, particularly in urban areas, can lead to significant benefits in the form of carbon emission reductions. It is estimated that the annual level of CO_2 emissions savings could be approximately 176 ktonnes.

10.2.2. Methodology

Base Case

A large proportion of equipment located on the 11kV network in London, as well as across the entirety of the GB distribution networks, is rated at a fault level of 13.1kA, mainly due to the ratings of 11kV circuit breakers and ring main units. The increase in load and generation connected on the distribution network over time has contributed to the increase in fault current levels in several locations across the 11kV network. In some locations, fault currents have risen to levels close to the network's fault current rating (under normal running arrangements), thus not allowing further connections without the replacement of the circuit breakers and the ring main units with modern equivalents of higher fault current rating (usually higher than 20kA). The problem is further exacerbated if N-1 conditions are considered; several substations already present fault currents that exceed the equipment rating, thus requiring the curtailment of generation when operating under fault or during an outage for regularly scheduled maintenance.

Replacing circuit breakers and ring main units with modern equivalents of higher fault current rating is costly. According to UK Power Networks' Final Determination for RIIO-ED1[14], the average cost of replacing an 11kV circuit breaker and ring main unit is £32,770 and £14,169 respectively. Based on data from UK Power Networks' Asset Register (Ellipse), there are on average 64 11kV circuit breakers and 159 11kV ring main units per substation. This would mean that the cost of upgrading a substation's fault current level by replacing all low-fault current rated assets can exceed £2 million (see

[14] UK Power Networks, Regulatory Instructions and Guidance (RIGs), table CV3

Table 12 below).

Table 12 Cost of conventional reinforcement to release fault level headroom, per substation

	11kV circuit breakers	11kV ring main units	Total
Unit cost	£32,770	£14,169	
Average number of assets per substation	64	159	
Proportion of assets rated below current standard	67%	49%	
Reinforcement cost, per substation	**£1,390,564**	**£1,093,693**	**£2,484,257**

The proposed smart solutions have the potential to release fault current headroom at a much lower cost than the traditional reinforcement method. The substation-sited solution (Method 1) is expected to have a unit cost of approximately £500,000. The number of units required per substation will depend to a large extent on the configuration of the substation; in substations configured as 4x15 MVA (see Figure 8 for representative diagram), it is expected that one unit will be sufficient to significantly reduce fault current contribution, whereas in other configurations the number of units required varies between two and three.

Table 13 Expected reinforcement cost savings per substation for Method 1 and Method 2

	Method 1 (4x15 MVA configuration)	Method 1 (Other configuration)	Method 2
Number of "smart" units required, per substation	1	2.5 (on average)	5
Cost, per unit	£500,000	£500,000	£300,000
Total cost, per substation	£500,000	£1,250,000	£1,500,000
Expected benefit over conventional reinforcement	**£1,984,257**	**£1,234,257**	**£984,257**

The generator-sited solution (Method 2) is expected to have a unit cost of approximately £300,000. The number of units required per substation depend on the number of connection requests, since one unit will be required per customer. In order to estimate the expected savings per substation, we assume that each constrained substation will require five units over the span of five years. This assumption is based on the fact traditional reinforcement from 13.1kA to 20kA creates fault current headroom of approximately 131 MVA, which can allow the connection of approximately 5 rotating machine generators, assuming that the average capacity per generator is 4MW[15] and their fault current contribution is equal to six times their capacity.

Data Sources

In order to calculate the benefit potential for the proposed solution across the LPN network, as well as across all fourteen of the GB DNOs, a high-level fault current analysis was conducted. The aim of the analysis was to calculate the available fault current headroom at each substation. Subsequently, the analysis was used to identify the number of substations that are constrained due to high fault current levels for each network in different points in time (2020, 2030, 2040, and 2050) and under different load and generation conditions.

The analysis is based on publicly available data on fault current levels and ratings that can be found in the GB DNOs' *Long Term Development Statements (LTDS)*[16].

Data relating to future network conditions, and specifically incremental load and

[15] This is based on the average capacity of CHP units with a capacity between 1 and 10MW, as reported in the 2014 Digest of UK Energy Statistics (DUKES), Table 5.11
[16] Available at each DNO's website

generation added to the network, were based on *National Grid's 2016 Future Energy Scenarios (NGET FES)*[17]. It should be noted that only the incremental fault current contribution from combined heat and power (CHP) and diesel reciprocating engines was considered in the analysis, since the contribution of inverter-connected generation (such as solar PV and battery storage) is minimal compared to the contribution of rotating machine generation (such as CHP and diesel engines)[18].

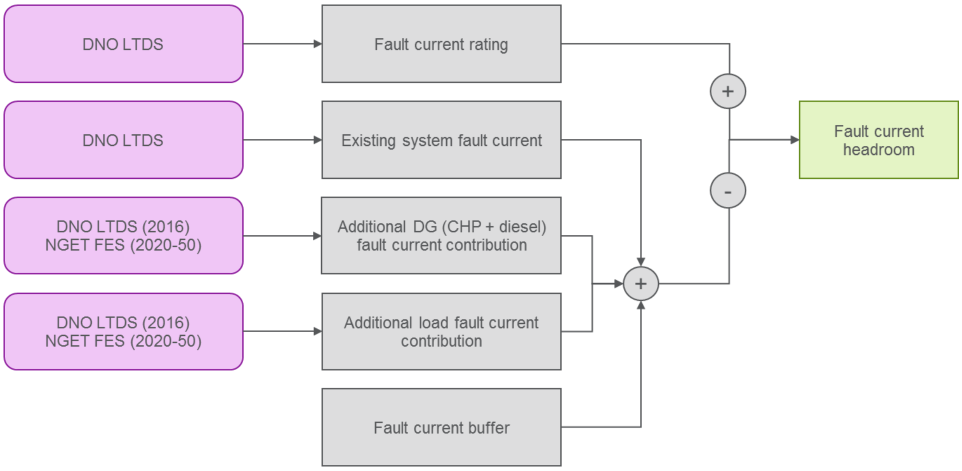

Figure 3 Schematic representation of data sources used to calculate fault current headroom

Derived metrics

The data collected from the DNOs' LTDS and NGET's FES were used to calculate the fault current levels for each substation in the 11kV network under normal running arrangements, as well as under N-1 conditions (i.e., when operating with one network component at failure). The fault current levels were also extrapolated to future points in time (2020, 2030, 2040, and 2050).

It has been assumed that the fault current level under N-1 conditions in 4x15 MVA substations is 50% higher than the fault current level under normal running arrangements. This is because under N-1 conditions, there is contribution by three transformers in parallel, whereas under normal running arrangements from only two (see Figure 8 for schematic representation). For other substation configurations, it has been assumed that the N-1 fault current level is 20% higher. This was based on engineering judgement, but is also in line with the average level on N-1 fault current levels in LPN substations derived by UK Power Networks in prior studies.

The fault current contribution multipliers for distribution-connected load and generation were based on values used internally by LPN Distribution Planning Engineers, which are, in turn, based on Engineering Recommendation G74[19]. For simplicity, it has been assumed that all additional generation connects directly to the substation busbars (i.e., assuming zero electrical distance between substation and generation source).

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[17] Available at http://fes.nationalgrid.com

[18] UK Power Networks' planning engineers consider the contribution from rotating machine generation equal to six times the installed capacity, whereas for inverter-connected generation the contribution is equal to the capacity

[19] Engineering Recommendation G74, Procedure to meet the requirements on IEC 909 for the calculation of short-circuit currents in three-phase AC power systems, Energy Networks Association, 1992.

Table 14 Assumptions used for fault current analysis derived metrics

Metric	Value
N-1 fault current level, per substation (4x15 MVA configuration)	1.5 x (N-0 fault current)
N-1 fault current level, per substation (other configuration)	1.2 x (N-0 fault current)
Generation make fault current contribution	10 x capacity
Generation break fault current contribution	6 x capacity
Generation power factor	0.90
Load make fault current contribution	2.1 x capacity
Load break fault current contribution	0 x capacity
Load power factor	0.90 lagging
Fault current safety buffer	5%

Identifying constraints on the network

The combined contribution of load and generation has been considered in order to identify which substations are constrained at each point in time. Specifically, the load growth and level of generation prescribed in each of the four NGET FES were applied on the available 2016 fault current data in order to create a forecast of the expected fault current headroom per substation.

Given the uncertainty associated with the location and size of each generation connection request in the future, the analysis considered the two most extreme scenarios in order to define a range of constrained substations:

- The *best-case scenario* is defined as the scenario in which future generation connection requests use the maximum amount of available headroom across all unconstrained substations. In other words, no additional reinforcement is required as long as the cumulative headroom across the entire network exceeds the capacity of the generation that is to be connected.
- The *worst-case scenario* is defined as the scenario in which future generation connection requests occur at those substations that have the least headroom available, and use *exactly* the minimum amount of headroom required to constrain each substation. In other words, the scenario that leads to the most number of additional substation constraints possible.

We consider the total number of constrained substations for both of the scenarios separately as the range of the proposed solution's *addressable population*.

10.2.3. Results

Constrained Substations

As described in section 10.2.2, the output of the fault current analysis was a range for the potential number of substations that could be constrained due to high fault current levels. The constraints identified relate to violations under N-1 conditions, which is consistent with the approach followed by UK Power Networks Distribution Planning Engineers. The results are summarised in Table 15 below.

It can be seen that out of the 4,351 substations across the 14 GB distribution networks, between 697 and 827 are expected to be constrained under N-1 conditions by 2050, or 16%-19%.

Table 15 Total number of constrained substations, across all DNOs

		Gone Green		Slow Progression		No Progression		Consumer Power		Avg
		Min (Best)	Max (Worst)	Min (Best)	Max (Worst)	Min (Best)	Max (Worst)	Min (Best)	Max (Worst)	
4x15	2020	40	40	40	40	40	40	40	40	40
	2030	41	41	40	40	40	40	41	41	41
	2040	43	44	40	44	41	45	41	45	43
	2050	43	44	40	41	41	43	42	43	**42**
Other	2020	654	726	654	727	655	730	655	730	691
	2030	670	733	650	674	655	709	658	792	692
	2040	705	800	654	772	658	826	670	851	742
	2050	729	783	657	709	664	749	686	779	**720**
Total	2020	694	766	694	767	695	770	695	770	731
	2030	711	774	690	714	695	749	699	833	733
	2040	748	844	694	816	699	871	711	896	785
	2050	772	827	697	750	705	792	728	822	**762**

Table 16 Ratio of constrained substations to total number of substations, across all DNOs

	Gone Green		Slow Progression		No Progression		Consumer Power		Average
	Min (Best)	Max (Worst)	Min (Best)	Max (Worst)	Min (Best)	Max (Worst)	Min (Best)	Max (Worst)	
2020	16%	18%	16%	18%	16%	18%	16%	18%	17%
2030	16%	18%	16%	16%	16%	17%	16%	19%	17%
2040	17%	19%	16%	19%	16%	20%	16%	21%	18%
2050	18%	19%	16%	17%	16%	18%	17%	19%	18%

Financial benefits - reduction in reinforcement costs

As discussed previously, the use of the proposed smart solutions allows the release of fault current headroom in a more cost-effective way compared to traditional reinforcement. If the proposed solutions are applied across the entire population of constrained substations identified in the fault current analysis, the benefits for the entirety of the GB networks can be as high as £437m by 2050 (see Table 17 and Table 18 below).

The financial benefits in the tables below are expressed in 2016/17 prices and are stated in NPV terms using a discount rate of 3.5% for the first 30 years and 3.0% thereafter. The values reported in the benefits summary tables (Appendix 10.1) are the average values across the eight scenarios that were calculated for each year (best-case and worst-case across the four NGET FES).

We have assumed that an equal number of substations are addressed each year between 2021 and 2050, i.e. for GB-scale benefits we have assumed

- 4x15MVA: 42 substations / 30 years = 1.4 substations per year
- Other configurations: 720 substations / 30 years = 24 substations per year

The level of financial benefit is determined by the number of constrained substations for each NGET scenario, and the cost savings of using the proposed solutions over conventional reinforcement at each substation. *Consumer Power* and *Gone Green* are the two scenarios with the highest number of constrained substations (see Table 15 and Table 16), and therefore have the highest level of expected financial benefits.

Table 17 Summary of financial benefits potential for Method 1, across GB distribution networks [£m, cumulative]

	Gone Green		Slow Progression		No Progression		Consumer Power		Average
	Min (Best)	Max (Worst)	Min (Best)	Max (Worst)	Min (Best)	Max (Worst)	Min (Best)	Max (Worst)	
2020	£0.53	£0.53	£0.53	£0.53	£0.53	£0.53	£0.53	£0.53	£0.53
2030	£115	£123	£104	£112	£105	£118	£109	£122	£113
2040	£259	£277	£234	£252	£237	£266	£245	£275	£256
2050	£409	£437	£370	£397	£374	£419	£386	£434	£403

Table 18 Summary of financial benefits potential for Method 2, across GB distribution networks [£m, cumulative]

	Gone Green		Slow Progression		No Progression		Consumer Power		Average
	Min (Best)	Max (Worst)	Min (Best)	Max (Worst)	Min (Best)	Max (Worst)	Min (Best)	Max (Worst)	
2020	£0.58	£0.58	£0.58	£0.58	£0.58	£0.58	£0.58	£0.58	£0.58
2030	£125	£134	£113	£122	£114	£129	£118	£133	£124
2040	£251	£268	£226	£243	£229	£257	£236	£267	£247
2050	£375	£402	£338	£364	£342	£385	£354	£399	£370

It should be noted that the two investigated Methods are complementary and one of the aims of the project is to develop an understanding of the use cases that would lead to the use of either method. The current understanding is that Method 1 is more suitable for sites with increased DG connection requests, whereas Method 2 is more suitable for constrained substations where connection requests are few.

The eventual level of benefit realised across the GB distribution networks by the combination of the use of the two Methods will be determined by the relative level of use for each, however based on our analysis, the benefit is expected to be between £370m (expected benefits of Method 2 only) and £403m (expected benefits of Method 1 only).

Benchmarking reinforcement benefits potential against previous studies

The issue of fault current constraints in the 11kV network has been the subject of two Ofgem-funded projects in the past: Western Power Distribution's FlexDGrid (2011 Low Carbon Networks Fund), and Electricity North West's FLARE (2014 Low Carbon Networks Fund).

The benefits case used by either DNO in their submissions is not dissimilar to the benefits case for PowerFuL-CB (i.e., reduction in network reinforcement costs), however the methodologies used to calculate the benefits potential across the GB distribution networks are significantly different. In addition, benefits in FlexDGrid and FLARE were reported in nominal values, with no discounting in present value of money.

Table 19 Comparison of financial benefits potential with previous submissions

	FlexDGrid (WPD) (FCL only)	FLARE (ENW) (Is-Limiter only)	PowerFuL-CB (UKPN)
Benefits at project-scale	£7,681,000	£215,500	£1,984,257
Number of sites across the GB by 2050	140	3,585	762

	FlexDGrid (WPD) (FCL only)	FLARE (ENW) (Is-Limiter only)	PowerFuL-CB (UKPN)
Expected benefits across the GB by 2050	£1,075m (Nominal)	£771m (Nominal)	**Method 1:** £403m (NPV) £972m (Nominal) **Method 2:** £370m (NPV) £826m (Nominal)
Reinforcement assumptions	Reinforcement includes replacement of all CBs and RMUs in substation	Reinforcement is incremental – does not include replacement of CBs and RMUs	Reinforcement includes replacement of CBs and RMUs rated below 25kA
Scaling assumptions	Solution is applicable to 5 substations per large city, assuming 2 large cities per licence area	Solution is applicable to all substations with rating of 13.1kA	Solution is applicable to sites where fault currents exceed rating based on load growth and expected generation connections

Increase in DG connections

The proposed smart solutions have the potential to release significant amount of headroom in substations that were previously considered constrained due to high fault current levels. Specifically, for 4x15 MVA substations in London, it is expected that the use of the distribution-sited solution (Method 1) can reduce the N-1 fault current by 50%, or in other words, keep the fault current at the same level as it is under normal operating conditions.

For other configurations, such as the 3x60 MVA configuration found in London (see Figure 9), the use of the Method 1 has the potential to decrease the contribution from transformers and generators by as much as 50% under normal operating conditions and 33% under N-1.

Method 2 does not release fault current headroom in substations, however it eliminates the contribution from new generation connections to the substation's fault current levels.

Given the high number of substations with fault current constraints across the GB distribution networks, it is possible that without the release of headroom, the level of DG will not reach the forecasted levels. This is particularly true for generation technologies with high fault current contribution (such as CHP and diesel reciprocating engines connected in long-term parallel), and moreover if we consider that the substations that are constrained are usually in densely populated areas where generation connections for CHP and diesel generators are more likely to occur.

The above was validated through analysis of UK Power Networks' DG database; the analysis demonstrated that substations that were found to be constrained due to fault current levels have 1.6 times higher likelihood to receive a connection request compared to unconstrained substations. Using the relative likelihood of receiving a connection request in conjunction with the percentage of constrained sites at each DNO, we estimate that the release of headroom by the combination of the proposed solutions can enable approximately 462MW (average across eight scenarios) of rotating machine generation connections by 2050, which would have otherwise been at risk due to the network constraints.

Note that the capacity benefits are highest in the Consumer Power scenario because this sees the highest uptake of CHP/Diesel generation.

Table 20 Cumulative enabled capacity (CHP and diesel generators), across GB distribution networks (MW)

	Gone Green		Slow Progression		No Progression		Consumer Power		Average
	Min (Best)	Max (Worst)	Min (Best)	Max (Worst)	Min (Best)	Max (Worst)	Min (Best)	Max (Worst)	
2020	154	168	158	173	167	183	168	185	170
2030	231	252	253	272	349	378	366	417	315
2040	272	297	293	318	429	476	463	536	386
2050	317	345	336	364	522	579	575	661	462

The level of enabled capacity is determined primarily by the number of constrained substations and the expected uptake in CHP and diesel generation for each NGET scenario. Consumer Power has the highest expected capacity benefit due to a relatively high uptake of CHP/Diesel generation, per NGET FES.

Reduction in carbon emissions

The release of network capacity described above can enable the uptake of CHP connections in areas that were previously considered constrained, and thus closed to new connections. This is particularly true in large metropolitan areas, such as London, where fault current levels are usually high.

An increase in CHP connections has the potential to deliver significant benefits in the form of reduced carbon emissions. This is due to the more efficient use of fuel to generate both heat and electricity compared to the separate generation of heat and electricity via a conventional gas boiler and centralised power generation.

Table 21 Expected annual emissions of CHP compared to alternatives, per MW installed

	Units	CHP	Centralised electricity	Gas boiler
Capacity released	MW	1	-	-
Assumed load factor		52%[1]	-	-
Electricity required, per annum	MWh_e	4,555	4,935[3]	-
Emissions per unit of electricity	kg/MWh_e	610[2]	300[6]	-
Heat required, per annum	MWh_{th}	9,566	-	9,566[5]
Emissions per unit of electricity	kg/MWh_{th}	-[4]	-	241[2]
Carbon emissions, per annum	**tonnes CO_2**	**2,779**	**1,481**	**2,305**

[1] Digest of UK Energy Statistics (DUKES), 2015, Chapter 7, Table 7A
[2] A detailed guide for CHP developers, DECC, Part 3 – Environmental
[3] Includes 6% distribution network losses based on UK Power Networks losses strategy, and 1.7% transmission network losses based on NGET transmission losses figures for England and Wales
[4] No emissions as heat is by-product of electricity generation in CHP
[5] Heat-to-power ratio is assumed to be 2.1:1, from Digest of UK Energy Statistics (DUKES), 2015, Chapter 7, Table 7A
[6] Provisional estimates of UK Greenhouse Gas emissions for 2015, including quarterly emissions for 4th quarter 2015, page 15

Every MW of CHP generation connected to the distribution network can save approximately 1,007 tonnes of CO_2 emissions per annum compared to alternative power and heat generation methods (see Table 21). Considering the level of CHP connection requests that can be enabled (see section above on increase in DG connections), we estimate that by 2050, the CO_2 emissions savings potential can be as high as 233 ktonnes per year (Table 22) or a cumulative total of 4,853 ktonnes (Table 23).

Table 22 Expected annual emissions savings potential from CHP connections, across GB distribution networks (ktonnes/year)

	Gone Green		Slow Progression		No Progression		Consumer Power		Average
	Min (Best)	Max (Worst)	Min (Best)	Max (Worst)	Min (Best)	Max (Worst)	Min (Best)	Max (Worst)	
2020	44	48	40	44	49	54	50	55	48
2030	112	122	81	86	100	108	117	133	107
2040	150	164	101	109	125	139	157	183	141
2050	192	209	122	132	152	169	202	233	176

Table 23 - Expected cumulative emissions savings potential from CHP connections, across GB distribution networks (ktonnes)

	Gone Green		Slow Progression		No Progression		Consumer Power		Average
	Min (Best)	Max (Worst)	Min (Best)	Max (Worst)	Min (Best)	Max (Worst)	Min (Best)	Max (Worst)	
2020	133	145	121	132	147	161	151	166	145
2030	947	1,032	745	802	916	998	1,019	1,146	951
2040	2,277	2,482	1,663	1,789	2,054	2,251	2,407	2,751	2,209
2050	4,010	4,370	2,790	3,009	3,451	3,804	4,222	4,853	3,814

10.2.4. Breakeven Analysis

In addition to Navigant's benefits calculations, we have prepared a breakeven analysis to show how many FLCB deployments are required to pay back the Outstanding Funding Required for each Method.

The analysis shows that:

- For Method 1, **three FLCB deployments** are sufficient to deliver a net financial benefit (Table 26).
- For Method 2, **one FLCB deployment** is sufficient to deliver a net financial benefit (Table 27).
- Sensitivity analysis: For both Methods, **doubling the Method cost does not increase the number of deployments needed to deliver a net financial benefit** (Table 28 and Table 29)**.**

Assumptions were as follows:

Table 24 - Assumptions for breakeven analysis

Assumption	Method 1	Method 2
Outstanding Funding Required (£m)	3.27	1.41
Base case cost, per site (£m)	2.48	2.48
Method cost, per site (£m)	0.50	0.30
Method available for deployment	2024/25	2021/22
Deployment rate	One FLCB per year	One FLCB per year
Discount rate	3.5%pa	3.5%pa

Outstanding Funding Required was apportioned to Method 1 and Method 2 as follows:

Table 25 - Apportionment of Outstanding Funding Required to Method 1 / Method 2 (£k)

Description	Method 1	Method 2	Total
Method 1 trial costs	3,594		3,594
Method 2 trial costs		1,416	1,416
Other costs (split 50/50)	589	589	1,179
Total Project Costs	**4,183**	**2,006**	**6,189**
Partner Contributions	(500)	(388)	(888)
DNO Voluntary Contribution	(49)	(49)	(98)
DNO Compulsory Contribution	(363)	(157)	(520)
Outstanding Funding Required	**3,271**	**1,412**	**4,683**

Details of the breakeven analyses are as follows:

Table 26 - Method 1 Breakeven Analysis

Year	FLCBs Deployed	NIC Expenditure	Base Case Cost	Method Cost	Net Cash Flow	Cumulative NPV
16/17		(0.20)			(0.20)	(0.20)
17/18		(0.93)			(0.93)	(1.09)
18/19		(1.51)			(1.51)	(2.50)
19/20		(0.47)			(0.47)	(2.93)
20/21		(0.06)			(0.06)	(2.98)
21/22		(0.10)			(0.10)	(3.07)
22/23						(3.07)
23/24						(3.07)
24/25	1		2.48	(0.50)	1.98	(1.57)
25/26	1		2.48	(0.50)	1.98	(0.11)
26/27	1		2.48	(0.50)	1.98	**1.29**
Total	**3**	**(3.27)**	**7.44**	**(1.50)**	**2.67**	

Table 27 - Method 2 Breakeven Analysis

Year	FLCBs Deployed	NIC Expenditure	Base Case Cost	Method Cost	Net Cash Flow	Cumulative NPV
16/17		(0.07)			(0.07)	(0.07)
17/18		(0.30)			(0.30)	(0.49)
18/19		(0.70)			(0.70)	(1.14)
19/20		(0.17)			(0.17)	(1.29)
20/21		(0.07)			(0.07)	(1.35)
21/22	1	(0.10)	2.48	(0.30)	2.08	**0.40**
Total	**1**	**(1.41)**	**2.48**	**(0.30)**	**0.77**	

Table 28 - Method 1 Breakeven Analysis with Method cost doubled

Year	FLCBs Deployed	NIC Expenditure	Base Case Cost	Method Cost	Net Cash Flow	Cumulative NPV
16/17		(0.20)			(0.20)	(0.20)
17/18		(0.93)			(0.93)	(1.09)
18/19		(1.51)			(1.51)	(2.50)
19/20		(0.47)			(0.47)	(2.93)
20/21		(0.06)			(0.06)	(2.98)
21/22		(0.10)			(0.10)	(3.07)
22/23						(3.07)
23/24						(3.07)

Year	FLCBs Deployed	NIC Expenditure	Base Case Cost	Method Cost	Net Cash Flow	Cumulative NPV
24/25	1		2.48	(1.00)	1.48	(1.94)
25/26	1		2.48	(1.00)	1.48	(0.86)
26/27	1		2.48	(1.00)	1.48	**0.19**
Total	**3**	**(3.27)**	**7.44**	**(3.00)**	**1.17**	

Table 29 - Method 2 Breakeven Analysis with Method cost doubled

Year	FLCBs Deployed	NIC Expenditure	Base Case Cost	Method Cost	Net Cash Flow	Cumulative NPV
16/17		(0.07)			(0.07)	(0.07)
17/18		(0.30)			(0.30)	(0.49)
18/19		(0.70)			(0.70)	(1.14)
19/20		(0.17)			(0.17)	(1.29)
20/21		(0.07)			(0.07)	(1.35)
21/22	1	(0.10)	2.48	(0.60)	1.78	**0.15**
Total	**1**	**(1.41)**	**2.48**	**(0.60)**	**0.47**	

10.3. Method 1 Detailed Technical Description

This section describes how the Method 1 (ABB) FLCB works, how it is used to create fault level headroom, and how we will select a trial site.

10.3.1. How the Method 1 (ABB) FLCB works

The Fault Limiting Circuit Breaker, FLCB, is based on a combination of a fast mechanical commutation switch, a power electronic switch and a surge arrester, all connected in parallel as shown in Figure 4.

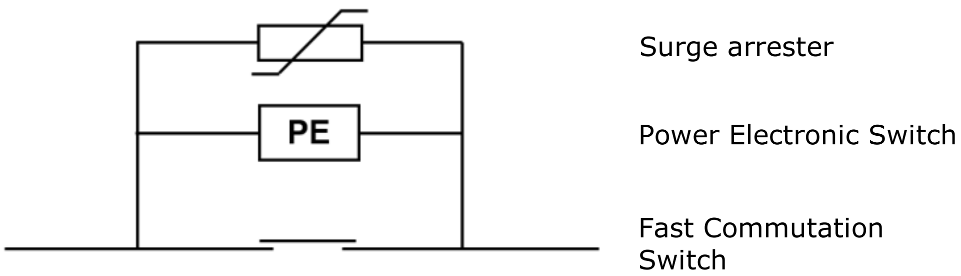

Figure 4 - Principle layout of the FLCB.

Power electronic switches such as IGBTs have very good switching properties and can turn-off a current without waiting for a current zero crossing. However, power electronic switches or semi-conductors are by definition poor conductors when comparing with a mechanical switch and therefore give high on-state losses. These losses are costly and also requires a large external cooling system to prevent the IGBTs from overheating. The mechanical switch on the other hand is not as good in switching and is not able to switch off a current prior to current zero crossing in order to achieve current limiting functionality. However, by combining the good properties of the power electronic switch and the mechanical switch and excluding the poor properties we get a very good FLCB with multi-shot capability.

The switch off sequence starts with the line current flowing through the closed mechanical switch to enable conduction of the nominal current with negligible losses. When a fault occurs and the FLCB is tripped, the mechanical switch is opened and the current is commutated into the power electronic switch which is used for turning off the current in that branch. The current is then commutated to the parallel surge arrester and will produce a counter voltage based on the surge arrester protective level. This counter voltage will be higher than the system voltage and will force the current to zero before the natural current zero crossing and it will during that process also absorb the trapped magnetic energy in the system short circuit inductance.

The function of the FLCB during a current limiting operation is illustrated by the line current and the currents through the 3 branches of the fault current limiter in Figure 5.

The upper graph shows the line current and the second graph the current through the mechanical switch. The short circuit occurs at 145 ms causing the line current shown in the upper graph and the current through the mechanical switch in the second graph to rise fast. The mechanical switch starts to open when the trip conditions are exceeded and the FLCB is tripped. The current is commutated into the power electronic branch when the switch has opened and created a voltage high enough to enable fast commutation into the power electronic branch. The line current is now flowing through the power electronic branch as shown in the third graph. Meanwhile the mechanical switch continues to open. The power electronic switch is being turned off when the required electrical withstand of the mechanical switch is higher than the surge arrester protection level. The line current is now commutated into the surge arrester and the line current starts to decrease towards zero by the counter voltage created by the surge arrester.

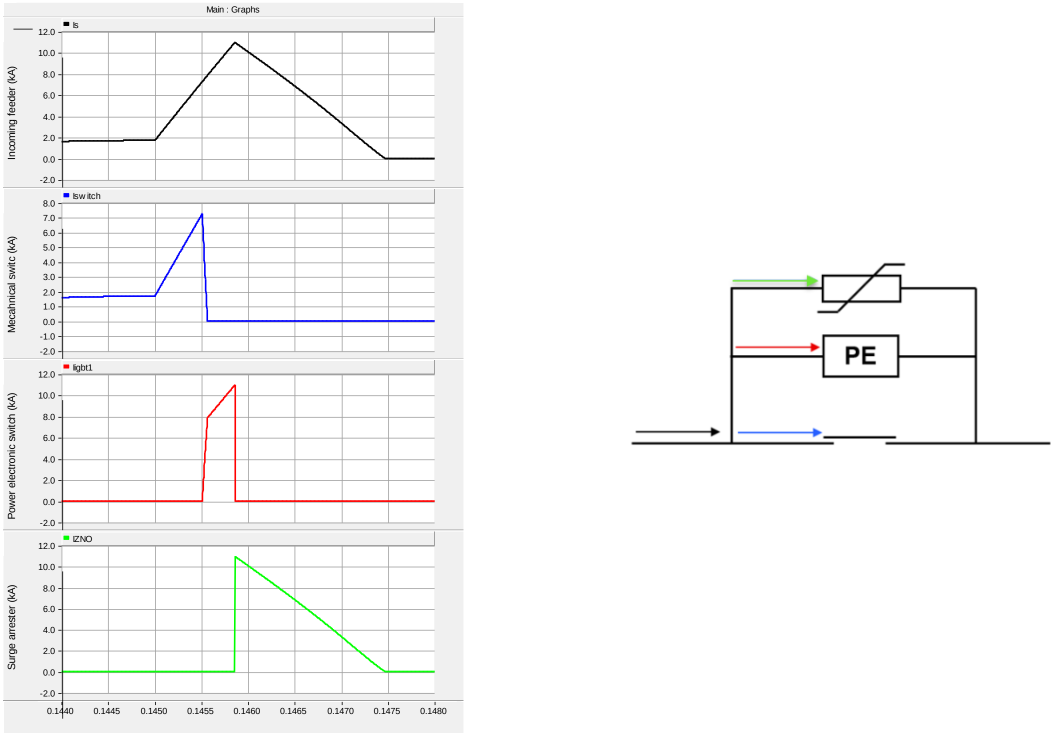

Figure 5 - Line current and currents through the mechanical switch and the power electronic switch and the surge arrester.

The requirements on the fast mechanical commutating switch has until now not been fulfilled by any available switch. The switch should open very fast (<0.5 ms) since the short circuit current is rising fast. It should also be able to create a voltage high enough to ensure a fast and reliable commutation into the power electronic switches. The commutation voltage has to exceed the forward voltage drop of the power electronic switches and the voltage drop caused by the combination of the high di/dt during the commutation and the stray inductance of the loop formed by the switch and the power electronic switches. In addition, the switch in open position should withstand the voltage when the power electronic switches are turned off.

A concept for the fast commutating switch have been developed and protected by patent by ABB (Patent application US7235751B2). The switch utilises a novel contact system with a number of contacts connected in series and with every second contact moving and every second contact fixed. The number of series connected contacts ensure the high arc voltage required for the fast commutation. The series contacts also ensure a high electrical withstand with short stroke of the contact system enabling a fast operation. The contact system is connected to a bi-stable Thomson actuator which ensures both a fast opening and fast closing operation.

A single phase FLCB has been built and tested. Figure 6 shows the lab demonstrator in the high power laboratory and Figure 7 shows the measured prospective 25 kA_{RMS} short circuit current compared with a short circuit current limited by the FLCB. The diagram verifies that the fault current limiter is able to limit a 25 kA_{RMS} short circuit current to 13 kA_{peak}.

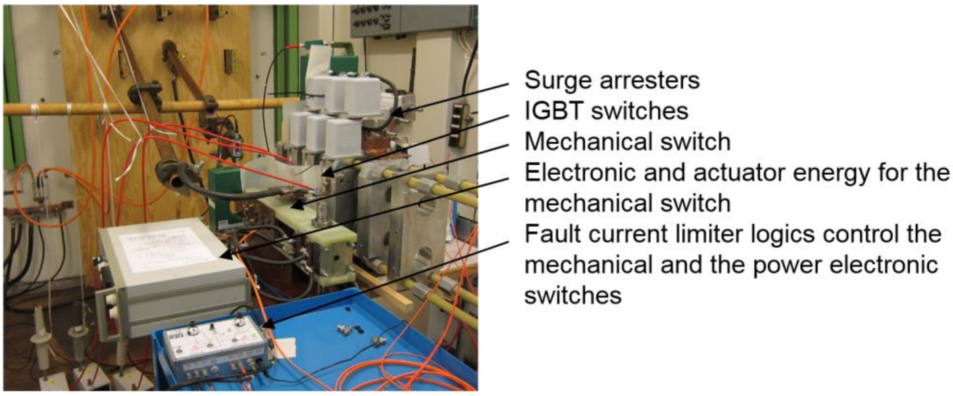

Figure 6 - Single phase 12 kV FLCB during high power testing

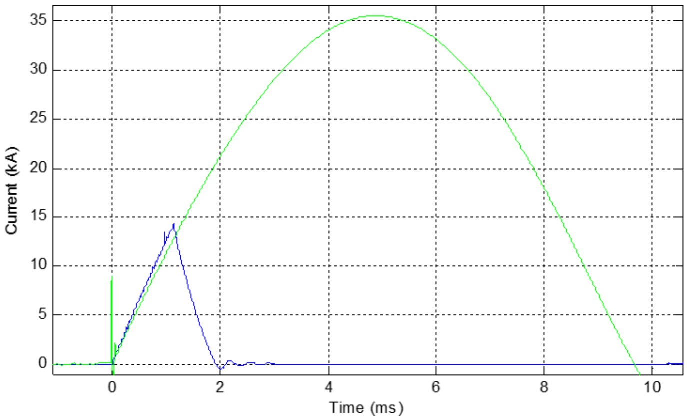

Figure 7 - Measured prospective and limited short circuit currents during high power testing.

10.3.2. How Method 1 creates fault level headroom

LPN substations predominantly of two different configurations: approximately 60% are 4x15MVA, approximately 20% are 3x60MVA, and the remaining 20% are of non-standard configurations.

4x15MVA substations are designed to operate with transformers in pairs in normal conditions and three transformers together in N-1. This means that there would be 2x fault level headroom in normal conditions (Figure 8a, where x is the FL contribution from a single transformer), but little or no FL headroom in N-1 (Figure 8b). To date, generators have been allowed to connect to these substations on an inhibit scheme, whereby they are automatically disconnected whenever the substation is running in N-1.

Installing a FLCB as a bus coupler enables a 4x15MVA substation to tolerate loss of any transformer with no increase in fault level. Furthermore, modifying the normal running arrangement increases non-firm FL headroom to 5x (Figure 8c) and firm FL headroom to

3x (Figure 8d). A fault current limiter (FCL) in the same position would create less headroom, because FCLs only attenuate fault current, whereas FLCBs completely block it. Note that a FCL/FLCB installed in a transformer incomer would be no use if that transformer was out of service, so **the best place to install a FLMT at a 4x15MVA substation is as a bus coupler/section**. Note that this requires new 2000A CBs or busbar cable termination boxes to be added to the existing switchboard.

3x60MVA substations are designed so that FL contributions from transformers do not increase in N-1. However, any headroom on the busbars normally fed from the out-of-service transformer is lost, so FL headroom decreases by 1/3 (Figure 9a/b). Installing a FLCB in a transformer incomer increases FL headroom by x (Figure 9c), where x is the FL contribution from the transformer winding. This additional headroom is maintained for an outage on a different transformer (Figure 9d), but not for an outage on the same transformer (Figure 9b, imagine the FLCB was installed on T1), so **the additional capacity is not firm**.

Installing a FLCB as a bus section is impossible (not possible to make a new connection to busbar Front/Rear 2); installing a FLCB as a bus coupler is likely to be difficult (3x60MVA sites tend not to have space for switchboard extensions); and neither position provides any advantage over the transformer incomer position. Therefore, **the best place to install a FLMT at a 3x60MVA site is in a transformer incomer**.

Table 30 - FL capacity for generation (where x is the FL contribution from a single transformer, y is the existing headroom on each busbar. "With FCL" assumes 50% current attenuation.)

Type	Arrangement	Base Case	With FCL	With FLCB
4x15MVA	Normal	2x	3x	5x
	N-1	0	1x	3x
3x60MVA	Normal	3y	3y+0.5x	3y+x
	N-1 best case	2y	2y+0.5x	2y+x
	N-1 worst case	2y	2y	2y

Note in Figure 8d, if the FLCB were replaced with an I_s-limiter, T3 could potentially be overloaded by 50% until the I_s-limiter is replaced. In Figure 9d, T2A would be overload by 200%, which could cause it to overheat and trip within minutes, and is an unacceptable risk to security of supply. **This demonstrates why a FLCB's ability to reclose gives it a significant advantage over I_s-limiters**.

Note that FLCBs will always be installed with a conventional circuit breaker in series. The reasons for this are:

- To provide a point of isolation and earthing for safe access to the FLCB itself or the equipment either side of it;
- To automatically isolate the FLCB from the network in the event of an internal fault; and
- To provide means of independent backup protection in the event that the FLCB fails to operate on demand.

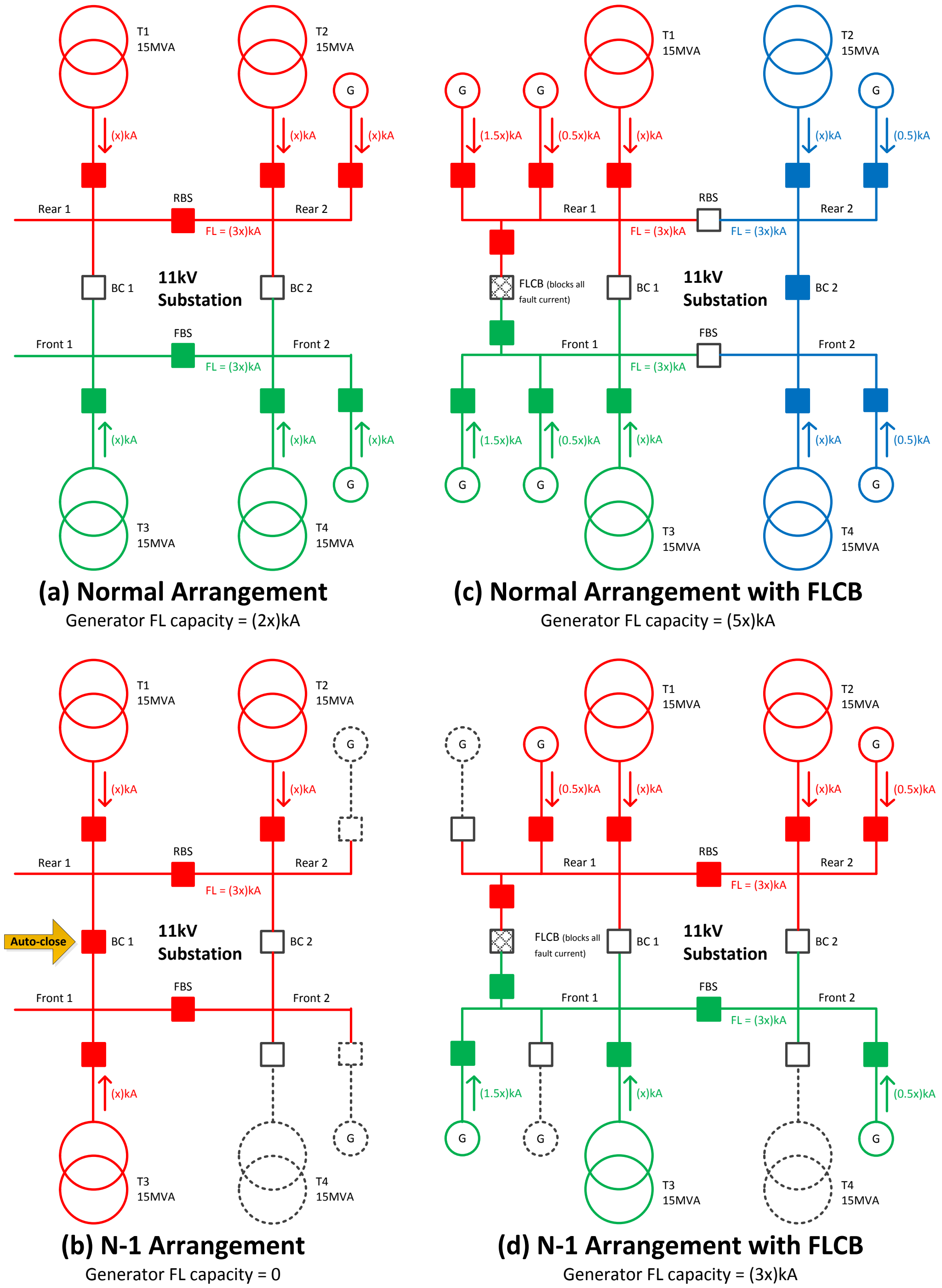

Figure 8 - Operating scenarios for a 4x15MVA substation, with/without a FLCB

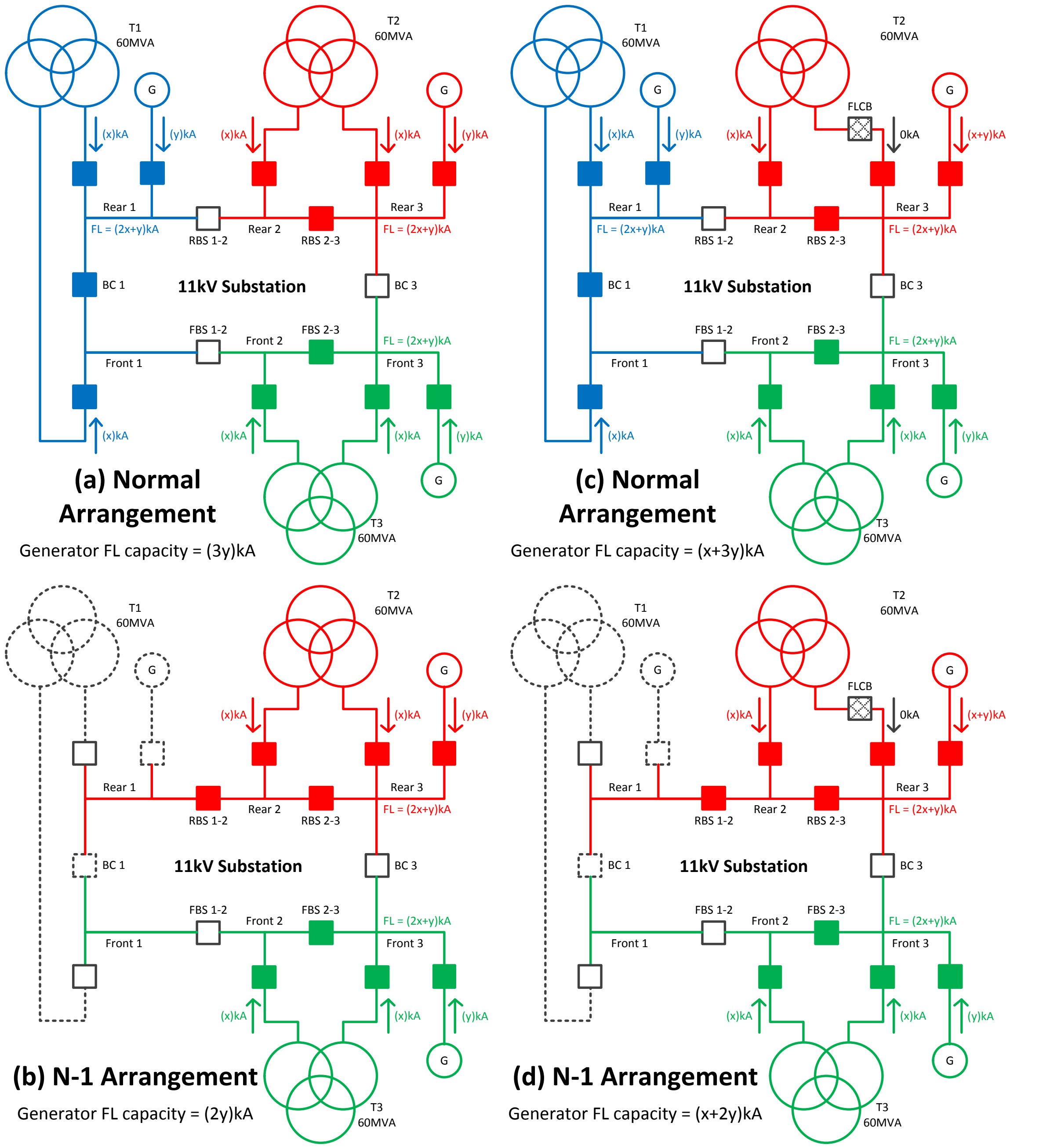

Figure 9 - Operating scenarios for a 3x60MVA substation, with/without a FLCB. NB FLCB isolation/bypass CBs are omitted for clarity

10.3.3. Method 1 trial site selection criteria

Trial site selection is a key activity at the start of the project, in order to ensure that the device will be able to be successfully trialled and deliver maximum learning. The first key principle for our site selection is to ensure that the trial site represents those sites where the solution will be rolled out and will achieve benefits once proven. The second principle is to choose a trial site that will allow the device functionality to be fully tested.

Specifically, for the substation trial site we will apply the following site selection criteria:

- 11kV primary substation located in LPN.
- Fault level above 80% of fault rating (indicating that fault level issues are likely in RIIO-ED1 or RIIO-ED2).
- Fault level currently does not exceed fault rating in intact or N-1 conditions (this

is essential for the trial, as unrestrained fault levels cannot be allowed to exceed fault ratings until the FLCB has been proven safe and reliable).

- No asset replacements planned or likely before the end of the trial.
- History of faults on outgoing circuits (this is essential for the trial, to maximise the opportunity for the FLCB to operate for real network faults).
- Ideally, already has generators on non-firm connections (i.e. they must disconnect in N-1 conditions), so that the FLCB, once proven safe and reliable, can enable these customers to benefit immediately by obtaining firm connections for their existing generators. Furthermore, this would likely also avoid the cost of upgrading the existing inhibit schemes which will stop working in 2020 when BT analogue phone lines are withdrawn. (UK Power Networks is currently undertaking a dedicated project to deal with this issue.).
- Evidence of a high demand for future DG connections will also be considered for site selection.
- Physical constraints / site visit (e.g. is the site operating in standard configuration? Is there adequate space to install new equipment? Is there adequate site access? Can the installation be done without planned outages?).

Note that we will consider either a 4x15MVA or 3x60MVA substation configuration equally. As discussed in section 10.3.2, Method 1 provides benefits to both configurations, and both could provide the required learning outcomes, subject to the criteria listed above.

10.3.4. Safety Considerations

The key risk associated with the use of FLCBs is the **risk that the FLCB fails to operate on demand**, resulting in downstream network equipment being exposed to fault current exceeding its rating. In the worst case, this could result in dangerous failure of the downstream equipment.

The relevant regulations (Electricity at Work Regulations 4.1/5/11 and Electricity Safety, Quality and Continuity Regulations 3.1/6) do not prescriptively prevent the use of a FLCB to mitigate increased fault levels. **The regulations do require that the risk of danger is reduced to an acceptably low level.**

To construct an adequate safety case for the use of FLCBs, it will be necessary to design the FLCBs and the overall solution so that the **risk of danger (probability x consequence) is reduced to an acceptably low level**. This can be achieved by:

- Designing the FLCB to be **highly reliable** and **detect failures in advance of demand**. This reduces the **probability** of the FLCB failing to operate on demand; **and/or**
- Implementing **independent backup protection** that protects downstream equipment from excessive fault current. This reduces the **consequence** of the FLCB failing to operate on demand.

10.3.5. Designing Method 1 FLCB to be highly reliable and detect failures

This section outlines how the Method 1 FLCB can be designed so that the **probability** of the FLCB failing to operate on demand is acceptably low.

A preliminary hazard identification workshop was conducted for Method 1 on 12 July 2016.

The most significant failure modes identified were:

- The **Fast Commutating Switch (FCS) fails closed (i.e. fails to open on demand)** due to mechanical failure, actuator failure, lack of stored charge, or welded contacts

- **Tripping Unit fails to detect fault or issue trip command**.

Existing mitigation measures include:

- The FCS uses a **proven reliable operating mechanism** (bi-stable Thomson actuator).
- The tripping unit is of a **proven reliable design** (based on the Is-limiter) and can accept dual-redundant DC supplies.
- The FLCB comprises **independent systems for each phase.**

Proposed additional mitigation measures (to be trialled) include:

- **Running automated self-tests to check that the FCS is working correctly.** This will involve opening the FCS under load, checking that the current successfully commutates to the power electronic switch, then re-closing the FCS. **This test does not have any impact on the network** because it does not disconnect the load. This test can therefore be conducted frequently to minimise the time at risk in the event of a hidden failure. Note that this is not possible with an Is-limiter.
- It is possible to perform **a secondary injection test on the FLCB, which simulates an actual fault and tests the entire system** except the current transformers (CTs). In most cases the FLCB will be one of two circuits feeding a busbar, meaning that this test can be performed without causing any (planned) outages. Note that this is also not possible with an Is-limiter.
- If necessary, **the FCS and the tripping unit can be duplicated to achieve the required level of reliability**. These are relatively small components and duplicating them will not significantly increase the size of the FLCB.

Failure of the power electronics switch is not considered a significant risk because of the following existing mitigation measures:

- (Power electronic) components are bypassed in normal operation which minimises current/voltage/thermal stress resulting in **high reliability**.
- Risk of **components failing open is eliminated by design** (components are designed to fail closed)
- The power electronics switch comprises several sets of components in series. There is one more set of components than needed, so **that if one component fails closed, the remaining components will still be able to interrupt the rated fault current**.
- **Failed components can be detected** by the gate control unit.

10.3.6. Potential approaches to independent backup protection

This section describes three potential approaches to providing independent backup protection for a FLCB, to reduce the **consequence** of the FLCB failing to operate on demand to an acceptably low level.

Option 1: Adaptive Protection

Adaptive Protection (AP) is a fault level solution currently being trialled as part of ENWL's Respond project. AP works by disconnecting an existing transformer or feeder breaker to reduce the fault level, and slowing down the feeder breaker so that it doesn't operate until the fault level has been successfully reduced. Using AP and a FLCBs together (Figure 10) would be more reliable (safer) than using AP or FLCBs separately.

Pros: Doesn't cause (additional) customer interruptions; AP already being proven by Respond project

Cons: Complex intertripping and/or blocking schemes may only be practical with numerical relays; limited effectiveness if the FLCB fails when a feeder breaker makes onto a fault.

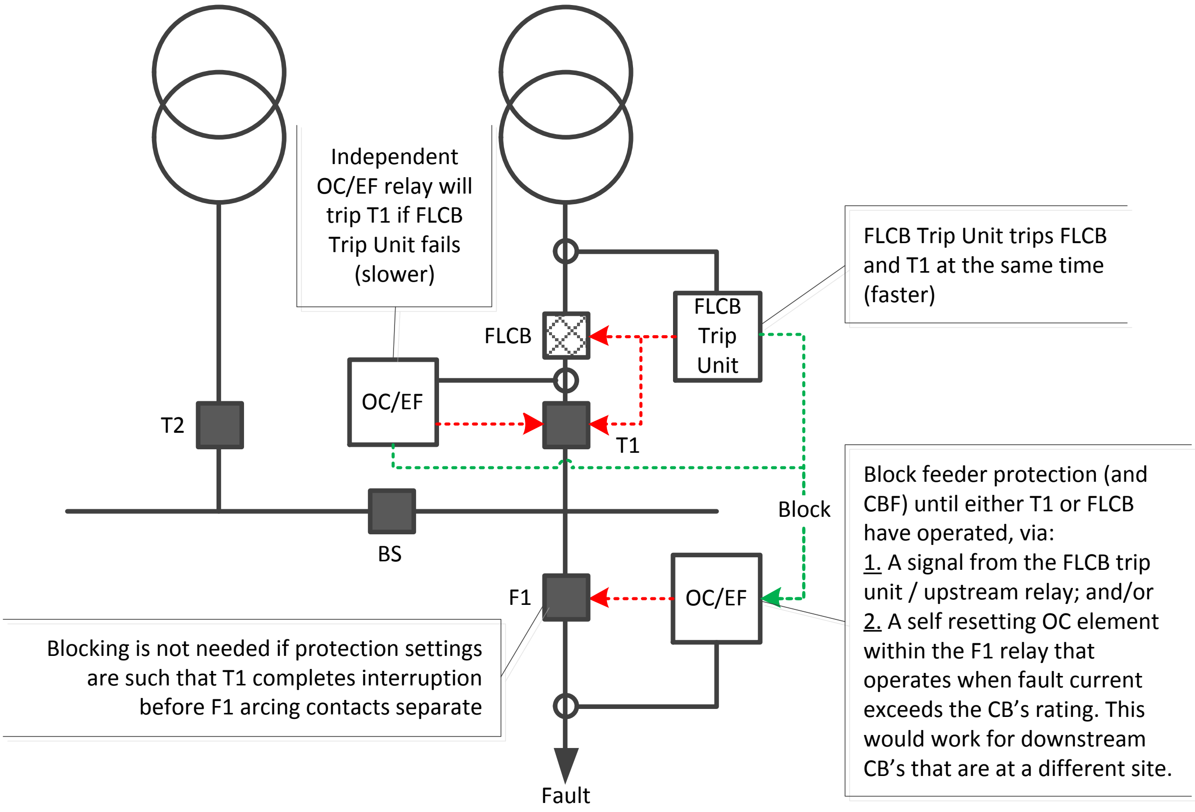

Figure 10 - Independent backup protection option 1 - Adaptive Protection

Option 2: CB Fail Approach

This approach (Figure 11) is based on a hardwired CB Fail scheme, whereby the CB Fail protection operates instantaneously if the feeder protection relay detects fault current exceeding the breaker rating – which would only happen if the FLCB has failed to operate on demand.

Pros: Makes use of existing CB Fail scheme/wiring; somewhat effective if the FLCB fails when a feeder breaker makes onto a fault.

Cons: Requires numerical relays (or an additional IOC relay) on feeder CBs; Risk of interruption to all customers fed from the same busbar.

Option 3: Ultra-Fast Earth Switch

This approach (Figure 12) uses an ultra-fast earth switch to divert fault current away from the feeder breaker and operate the upstream protection.

Pros: Fault throw switches already familiar to GB DNOs; No modifications to existing protection; No increase to FLCB footprint (mounts on top of cubicle); Effective if F1 makes onto a fault exceeding its rating and FLCB fails to operate; Eliminates arc flash hazard.

Cons: Risk of spurious operation (if UFES and FLCB trip units race); Stress on switchgear and transformers.

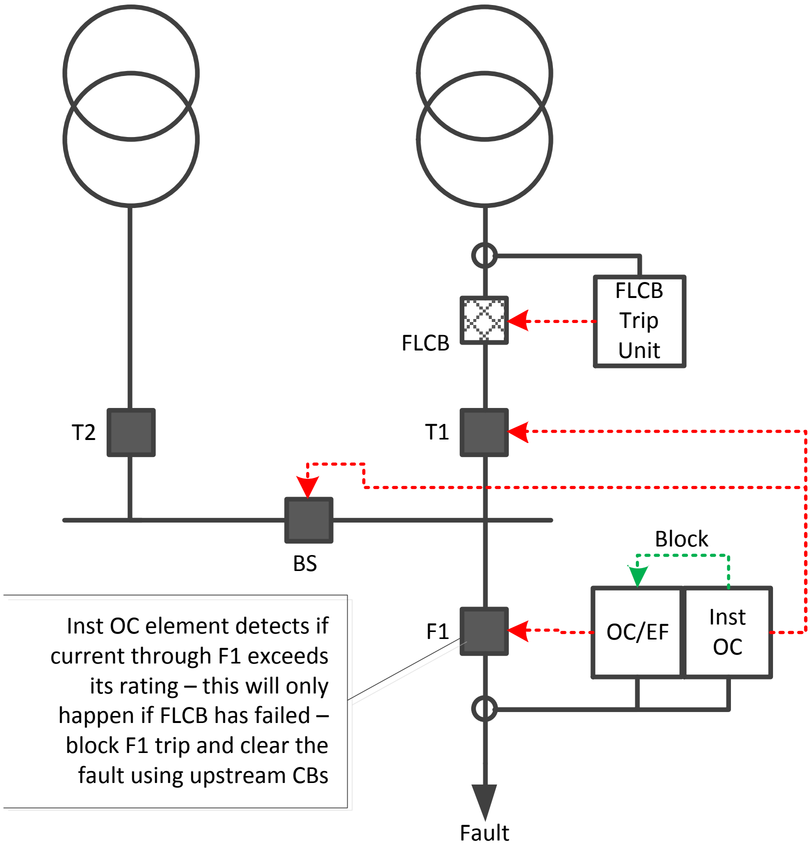

Figure 11 - Independent backup protection option 2 – CB Fail Approach

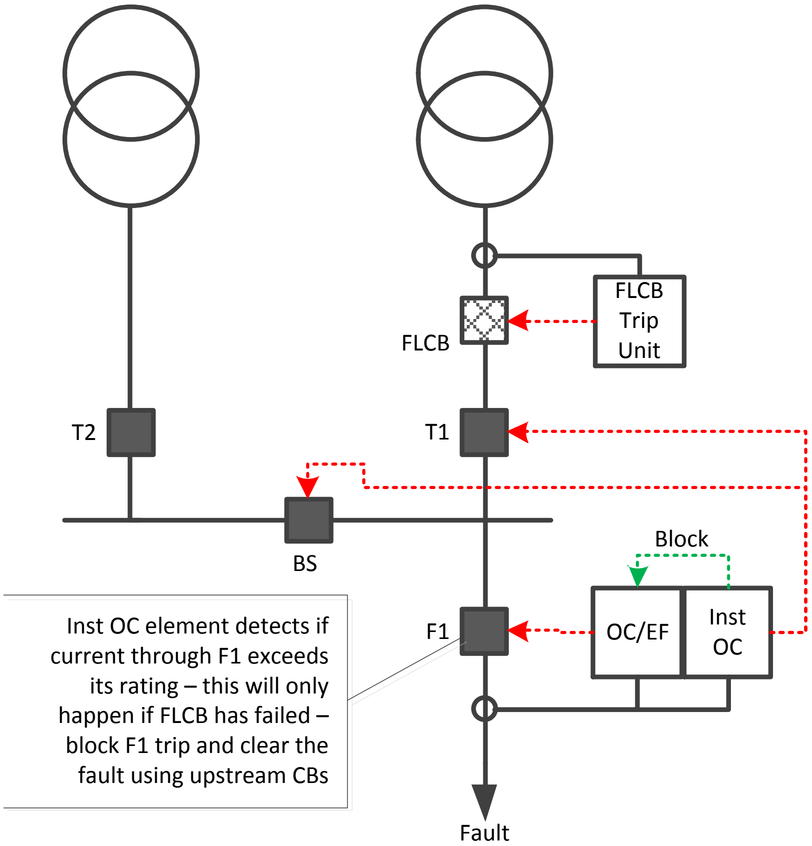

Figure 12 - Independent backup protection option 3 - Ultra-Fast Earth Switch

10.4. Method 2 Detailed Technical Description

This section describes how the Method 2 (Applied Materials) FLCB works, how it allows customers to connect DG, and how we will select a trial site/participant.

10.4.1. How the Method 2 (Applied Materials) FLCB works

AMAT's proprietary solid-state fault current limiter (SSFCL) topology employs a mutual reactor as a current-splitter, which is designed so that a single series circuit of solid-state components that are sharing voltage will not experience an over-current condition. For a load current (N+1) times the operational current of the IGBTs, a mutual reactor splits the current into 2 paths. The first path carries the operational current, and this flows through the IGBTs while the second path carries the rest of the current, N times the operational current, as shown below

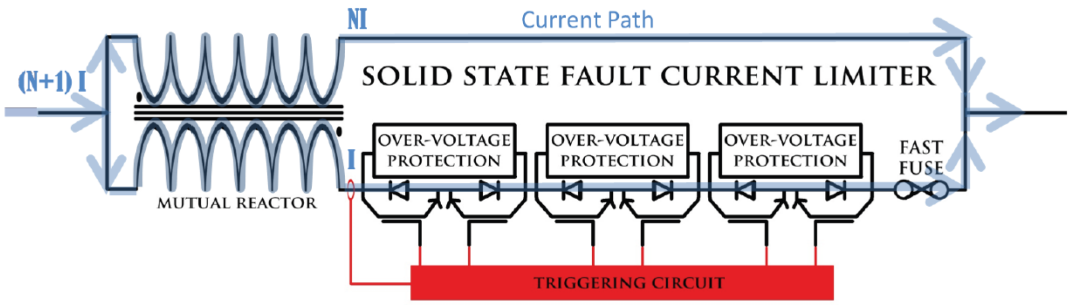

Figure 13: SSFCL sharing current: in the normal condition the mutual reactor has zero reactance

In the normal state, most of the current in the SSFCL flows through the primary winding of the mutual reactor and a smaller amount flows through the secondary winding of the mutual reactor. Because the mutual reactor has the two currents flowing with opposite helicity, the magnetic fields virtually cancel, and there is almost no reactance. There is also a small voltage-drop across the IGBTs. When a fault condition is detected, the IGBTs switch off, and all of the current is then forced through the primary coil. This unbalances the mutual coil, and the primary coil impedance is then seen in the circuit.

The mutual reactor in the SSFCL is designed with more turns in the secondary than in the primary. The ratio of the number of turns, N, is selected to match the current capacity of the IGBTs and the current requirement in the external circuit. For example if we desired that the low current or operational current path in a 2,500A mutual reactor is 500A, then the mutual reactor would have N=4, resulting in 2,000A flowing through the primary winding and 500A flowing through the secondary winding.

When a fault occurs, the triggering circuit in the SSFCL identifies that the current has risen above the specified threshold, and it causes the solid-state switch to open (in ≈0.5μs), thus opening the secondary winding. The mutual reactor primary winding now produces a large magnetic induction and is transformed into a series reactor with the required impedance to limit the fault. This is shown below. The primary winding is designed with sufficient impedance to limit fault currents to safe levels, sufficient thermal cooling capacity to carry the maximum total load current continuously and sufficient insulation to handle the maximum voltages foreseen. Likewise, the secondary winding is designed with sufficient thermal cooling capacity to carry the split current continuously and sufficient insulation to handle the maximum voltages foreseen.

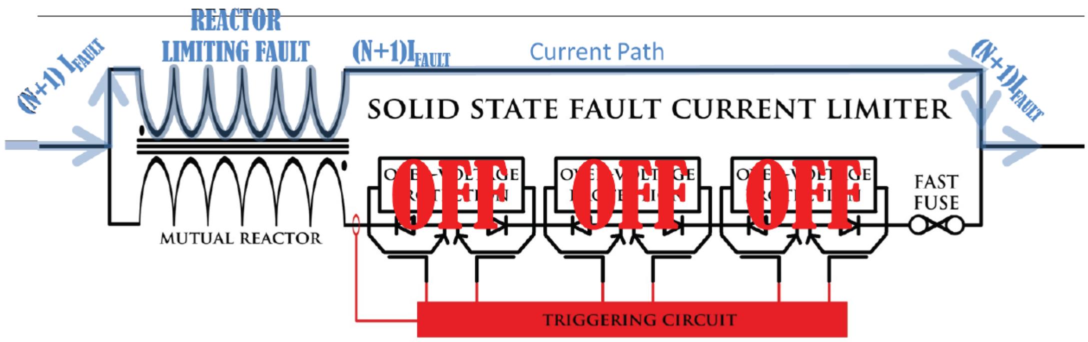

Figure 14: SSFCL reactor limiting the Fault Current

Once the current returns to safe levels or after a pre-determined period of time, the solid-state switch is re-closed, and the limiter returns to its low impedance state until the threshold current is exceeded once again.

To further enhance the robustness, reliability and service life of the SSFCL, AMAT significantly reduced the rating of the commercially available, industry standard IGBTs. Failure modes such as IGBT failure to short circuit and trigger circuit failure are covered by a fast-acting fuse which ensures protection of the electric grid. While the unit would then be out of service and require repair, the fault would have been limited, and the network remain in a safe condition.

Components

Mutual Reactor

The mutual reactor is a wire-wound device built around an iron core or cores, insulated in oil or cast resin. There are two windings, interleaved and wound in opposite directions such that the flux in the iron core is largely (>99%) cancelled during normal operation, as shown below. Since it is not possible to have a perfectly wound mutual reactor, some insertion impedance is present. This is limited typically to ≪1% of phase-to-earth voltage drop.

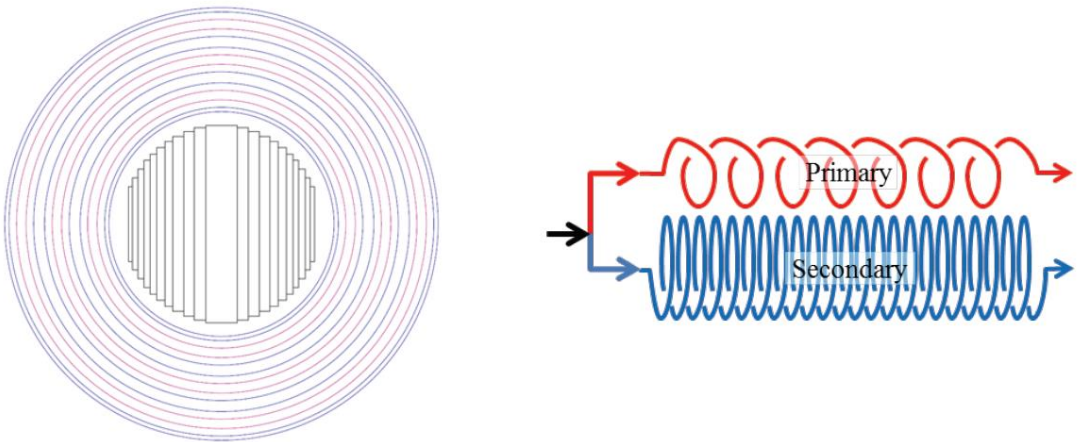

Figure 15: Mutual reactor winding scheme: use of standard transformer design specifications and materials produce a robust, high efficiency module

One winding – the primary or passive winding – is designed to have such impedance that prospective peak and symmetrical fault currents (whichever is the worst case) are limited to a safe level. The other winding – the secondary or control winding – is designed to have more turns suchthat the current is split, and under normal operation it does not overheat the IGBTs.

Solid-State Switch

a. IGBT modules

The solid-state switch comprises a number of commercially available IGBT modules in series, selected so that the maximum voltage is divided among the IGBTs. The IGBTs are secured to heat sinks to remove the heat from conduction and resistive heating and are cooled by a fan.

Over-voltage is protected against in three ways. First, during the fast switching an over-voltage occurs due to the inductive load of the circuit. This is reduced to low levels by a simple snubber circuit. Second, when the FCL is switched off, voltages across the IGBTs are maintained at the design level by a simple potential divider circuit across all the modules. Third, when there is a network overvoltage, for example caused by a lightning strike, or a slight difference in IGBT firing, there is a Metal Oxide Varistor (MOV) which protects the unit. To ensure there is sufficient protection, a minimum of two modules are always supplied. The modules are protected from over-voltage by two devices as shown below:

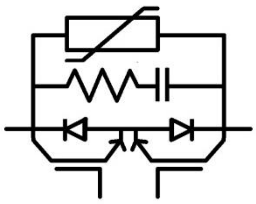

Figure 16: IGBT protection

Snubber Circuit: The first protective device is a snubber circuit designed for a 100% inductive load. Suddenly switching off an inductive load would lead to a sharp rise in voltage across the IGBT. If the voltage generated across the device is beyond what the IGBT is intended to tolerate, it may damage or destroy it. The snubber provides a short-term alternative current path around the current switching device so that the inductive element may be discharged more safely. The capacitor needs to absorb a large amount of energy. Applied Material's RC snubber uses a resistor in series with a capacitor. This combination suppresses the rapid rise in voltage across the IGBT, preventing the erroneous turn-on of the IGBT; it does this by limiting the rate of rise in voltage (dV/dt) across the IGBT to a value which will not trigger it. The voltage across a capacitor cannot change instantaneously, so a decreasing transient current will flow through it for a small fraction of a second, allowing the voltage across the switch to increase more slowly when the switch is opened.

Metal Oxide Varistor: The second protection device is a Metal Oxide Varistor (MOV), again connected in parallel across the IGBT module to limit the voltage seen by the device. The MOV has a highly nonlinear currentvoltage characteristic, in which the MOV has a high resistance at low voltages and a low resistance at high voltages. It is designed to trigger its low resistance before the IGBT voltage is exceeded, thus providing a short term parallel path to limit voltage spikes.

Gate-Firing Board: The gate drive circuit is a commercially available circuit. It takes a fiber optic input and an isolated DC power supply and switches on/off the IGBT as the light source goes on/off. This enables a "failsafe" aspect of the SSFCL in that a failure of the fiber optic supply will cause the FCL to go into a high-impedance state.

DC Power Supply: The IGBT gate-firing board requires a DC power supply. The DC power supplies are fed from a commercial AC/DC power supply. Once again, failure of a power supply places the SSFCL into a high impedance state.

Fast-Fuse: Despite these protection and operational considerations, it is possible that at some point the IGBT could fail to open due to the IBGT itself or possibly an item in the firing chain malfunctioning. The SSFCL, therefore, incorporates a high-voltage fast-fuse, which protects the IGBTs in the case of detection or switching failures, and which protects the network in the same detection/switching case or if there is an IGBT failure to short circuit. The network is always protected as the fast-acting fuse will blow, resulting in the reactor going into its high-impedance state.

b. Detection and Switching

Fault detection is from a CT in the control leg. If this exceeds a pre-set threshold, the custom-built comparator circuit switches off the LEDs that are used to light the fiber-optic interface to the gatefiring boards for the modules. The firing circuit is very fast, and the IGBTs take approximately 0.5μs to switch off, and measurements of 'exceeding threshold' to 'current off' take between 6-66 μs depending on the amount of signal filtering deployed.

For the most rapid return to service, after a pre-determined period of time the IGBTs are turned on again, and the current is monitored. If the current exceeds the threshold value, the fiber optics are again turned off. The turning on/off can be repeated until the current is less than the threshold, and it remains on.

For a slower return to service, the current through the passive leg of the reactor is monitored and when the current is safe to be switched on, the IGBTs are closed.

c. Monitoring and Customer Interface

A custom-built monitoring and customer interface module monitors the operation of the SSFCL, including detailed information on the IGBT modules, the fast-acting fuse, the balance between the reactor legs and the status of the detection and switching board. It reports faults and other information to the customer through an agreed user interface. A common implementation usually incorporates some hard-wired or wireless alarms and indications integrated with the customer's SCADA system, and some web-based user interface pages.

Figure 17 - SSFCL installed in Australia

d. Module Housing

The IGBT module housing externally contains two bushings for the high-voltage connections, a mains supply position and a customer interface cable position.

One of the high-voltage connections is connected first to one module, then the next and so on in series and ultimately to the fuse and finally the second high voltage connection bushing. The mains is connected to the monitoring and customer interface boards, the detection and switching module, to each solid-state module and to the cooling fans.

The customer interface cable(s) connect to the monitoring and customer interface board. If internet access or a direct SCADA system port is not provided by the customer, an aerial to achieve some data transfer over a cellular network or some other wireless network could be provided. There are ventilation fans to ensure air movement within the module to keep the IGBTs and other equipment cool.

The module housing also contains all of the necessary structural integrity and mounting points to contain the modules along with the necessary bus work and auxiliary enclosures. The housing is fitted with support points for lifting the entire SSFCL (the housing, all of the associated IGBT modules and all auxiliary equipment) for installation. These include crane lifting points, jacking points for skidding and forklift truck slots. The entire module housing is dust and waterproof to IP64 as shown in Figure 17, so it is suitable for use outside without further covers or enclosures.

10.4.2. How Method 2 enables customers to connect DG

The FLCB will be installed at the customer's premises, along with some switchgear enabling the FLCB to be isolated and bypassed if necessary. Because the FLCB effectively blocks 100% of fault level contributions, it prevents the generator from having any impact on network fault levels, and therefore the customer could connect large amounts of generation even if the network is "full" because of fault level constraints. Installing a FLCB at a customer's premises also completely avoids physical space constraints at existing substations.

The Applied Materials FLCB is currently limited to 250A/4.5MW, but future versions may have a higher current rating. Alternatively, customers who require a FLCB with a higher current rating could use ABB's 2000A FLCB.

To minimise impacts on the customer, the FLCB will only be enabled when the fault level is close to or exceeds equipment ratings, and will be disabled and/or bypassed at all other times. A simple solution would be to use an inhibit scheme to enable the FLCB when a 4x15MVA substation is running in N-1. More intelligent control could be provided by an active network management system such as the ENWL Respond Fault Level Assessment Tool (FLAT).

It could be possible to further minimise impact on the customer by placing a reactor in parallel with the FLCB, which would limit the fault current contribution to an insignificant amount, but allow enough power to flow to keep the generator running and synchronised with the grid.

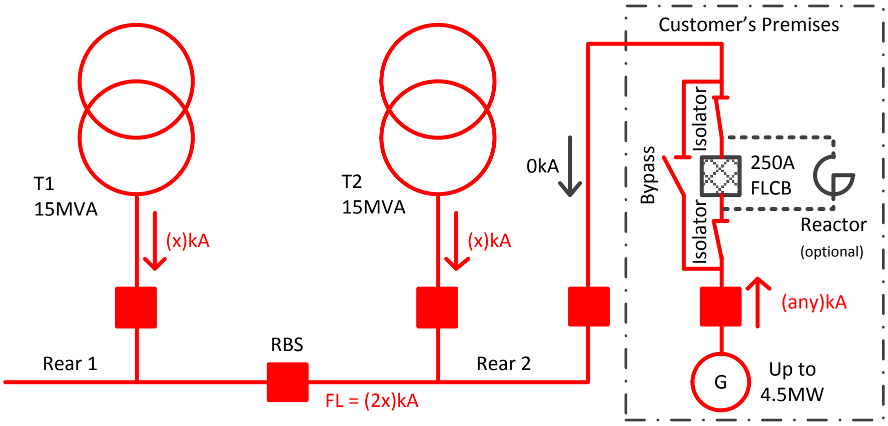

Figure 18 - Schematic diagram of Method 2 trial

This method has a lot of overlap with the Respond FCL Service, and we expect to be able to use learning from the Respond project to help us develop and implement this method.

10.4.3. Method 2 trial site selection criteria

For the customer trial site, we will apply the following site selection criteria:

- We intend to recruit a customer who has already accepted a non-firm generator connection, i.e. subject to an inhibit scheme that disconnects them during a transformer outage. This means that:
  - The customer's investment is viable regardless of whether the FLCB is successful; and
  - Once the FLCB is proven safe and reliable, they can obtain a firm connection for their existing generator, i.e. an immediate benefit with no additional investment.
- A customer whose normal/business activities will not be adversely impacted by the trial
- Adequate space to install the FLCB and bypass/isolation switchgear

- Adequate space to install a parallel reactor (if investigations show that this is feasible and worth trialling)
- Generator(s) rated less than 250A (4.5MW) and run continuously i.e. CHP
- History of faults on outgoing circuits at the primary substation
- Ideally, two or more similar generators at the same site. This is so that DFRs can be fitted to both generators, to allow direct comparison of fault current contributions with/without the FLCB. If it is not possible to obtain a trial site with multiple generators, then a second DFR will be installed on a generator at a different site connected to the same substation. High-resolution voltage and current data from the DFRs will be used to verify that the FLCB operates as expected for real network faults.

10.4.4. Designing Method 2 FLCB to be fail-safe

This section outlines how the Method 2 FLCB is already designed to be fail-safe, and proposed mitigations that can further improve safety.

- Method 2 has **independent backup protection** built into the FLCB in the form of a fast acting fuse (see Figure 13).
- Known failure modes (e.g. overheating, overcurrent, overvoltage, high electric field, ionising radiation/cosmic rays, trip circuit malfunction) are eliminated by design:
  - **The FLCB fails safe for loss of auxiliary supply or disconnection of the trip circuit.** The power electronic switch must receive a continuous signal from the trip circuit in order to remain switched on. If the signal from the trip circuit is lost, the power electronic switch simply switches off, disconnecting the circuit.
  - Like Method 1, the Method 2 FLCB uses several sets of power electronic components in series and **can still safely interrupt fault current if one set of components fails.**
  - The power electronic components are significantly de-rated (i.e. operated at a fraction of their full capability) which minimises current/voltage/thermal stress resulting in **high reliability**.
- As part of the Powerful-CB project, we will trial **Automated self tests**. These will involve turning off the power electronic switch around a for approximately 50μs to confirm its integrity. Performing this test close to a current zero will minimise or eliminate any impact on the connected generator.

10.5. Safety case feasibility report - executive summary

FRAZER-NASH CONSULTANCY

Fault current limiting technologies can be used to solve fault level constraints that are often pinch-points, limiting the growth of low-carbon generation on electricity distribution networks in the UK. Under the PowerFuL-CB project, UK Power Networks (UKPN) proposes to develop and trial two 11 kV fault limiting circuit breaker (FLCB) devices with project partners ABB and Applied Materials (AMAT). Neither device has ever been used before on UK distribution networks.

A limited set of fault limiting devices have been trialled on UK distribution networks; however, the FLCB devices proposed for development and trials under the PowerFuL-CB project have advantages over existing devices: they use less auxiliary power, are smaller so require less physical space, and do not require replacement of a charge (unlike equivalent explosive devices) so can auto-reclose after interrupting a fault.

Whilst there are multiple advantages of using FLCBs, the safety case and regulatory compliance case for their use on UK distribution networks has not been developed. In order to reduce the risks to PowerFuL-CB, confidence is required that the use of the FLCB devices on the 11 kV network will be safe and in accordance with UKPN's licence conditions and UK legislation.

This document is a report on the safety case feasibility assessment, conducted by Fraser-Nash Consultancy (Frazer-Nash) for UKPN. The assessment was underway before AMAT joined the project, and therefore only examined the ABB FLCB. Frazer-Nash understand the two devices to be similar; however, they are intended operate in slightly different locations in the 11 kV network. The ABB FLCB, which is currently at Technology Readiness Level (TRL) 4, has a higher current rating and hence has a novel type of mechanical switch that can handle this. Otherwise, Frazer-Nash understand that the function of the devices is equivalent.

As well as providing a useful starting point for developing a future safety case, the key aim of the assessment was to provide confidence that developing a safety case is an achievable task. This will help to satisfy the Network Innovation Competition (NIC) successful award criteria for the submission of PowerFuL-CB, and reduces project risk.

The assessment has identified no issues that would prevent the successful development of a safety case. However, some potential challenges, most of them already well known to the industry, have been identified and discussed in this report.

This report first addresses how a safety case approach can be used to thoroughly demonstrate that a system does not operate, or fail to operate, in such a way that may give rise to danger.

The key safety issues associated with the PowerFuL-CB approach are identified as follows:

- The potential to introduce new network faults; and
- An increased likelihood for existing network equipment to be exposed to a fault current higher than its rating as a result of the FLCB failing to operate on demand in the event of a downstream network fault.

A review of the regulatory requirements indicated that there are no insurmountable regulatory or legislative challenges outside of the need to ensure sufficiently safe, reliable operation. However, a key barrier is associated with the approval and regulatory acceptance of safety cases in the UK distribution industry. There is no formal requirement for a Distribution Network Operator (DNO) to produce safety cases for the operation of its networks, meaning there is no established due process for the review, approval and regulatory acceptance of safety cases in this sector. As UKPN will need to make an adequate case for the safe use of the FLCB and PowerFuL-CB approach, this presents a significant risk to the feasibility of being able to justify the deployment of the

FLCB as business as usual on UKPN's networks. Furthermore, the acceptability of residual risk needs to be determined.

UKPN will need to establish a pragmatic safety case process that provides a level of rigour appropriate to the risks involved, and should be tailored to the distribution industry context. Establishing this process should be addressed as a priority in the PowerFuL-CB project, and consultation with relevant stakeholders (e.g. industry, device manufacturers, Ofgem, Energy Networks Association (ENA), the Health and Safety Executive (HSE)) should be sought in this process.

Initial conversations with Ofgem and the HSE have been positive, in that no 'showstoppers' were identified that would prevent the trials and eventual use of the FLCBs on the UK distribution networks. The HSE have also confirmed their willingness to have the necessary, more detailed discussions upon the successful award of funding for PowerFuL-CB.

Frazer-Nash led a workshop with UKPN and ABB, the results of which formed the basis of a preliminary safety analysis. This indicated that the highest risk was posed from the dangerous failure of:

- The downstream circuit breakers;
- An outgoing cable; or
- The existing protection system.

A high-level failure modes and effects analysis (FMEA) and hazard identification of the FLCB installed on an 11 kV substation identified some potentially non fail-safe failure modes. The measurement, communication and control aspects of the design might also be a source of common mode failure of the 11 kV protection system. In building a safety case, work will need to be done to determine if these are in fact credible failure modes and, if so, to either design them out or ensure that the associated risk is adequately mitigated.

The high-level FMEA also identified some potential design improvements and candidate prevention and protection measures that could support the safety case. Although the device is novel, its constituent parts are largely tried and tested technologies with considerable operational history. Furthermore, the FLCB can be tested thoroughly prior to installation and as repeat maintenance once in situ, which is a significant advantage over 11 kV devices that provide fast fault current breaking available on the market today.

Following this feasibility of safety case assessment, some recommendations are made for the development of future safety case for the PowerFuL-CB approach as follows:

- Collaborate with Electricity North West in the development of the safety case strategy / context for the use of fault current breaking devices.
- Review the ABB processes and procedures in place to develop a safe design.
- Ensure the full FLCB capability is extensively tested before it is used as business as usual on the networks (i.e. with increased fault current levels).
- Systematically assess the suitability of the circuit breakers either side of the FLCB if they are to be used as mitigation, and ensure all steps are taken to ensure the system is as resilient as practicable to failure.
- Consider the control and protection system design at the earliest available opportunity, as the complexity of the modified protection system to include the FLCB is a key concern.
- A detailed hazard identification and FMEA will be required to ensure all hazards and failure modes have been identified, and investigate the likelihood and severity of each failure. Because the device is still in development, this information is still evolving, but starting this process now means that safety can

be used to inform the device's design and development.

On the basis of the design information available at the time, the discussions at the workshop, the legislative review, and Frazer-Nash's experience in other high hazard industries, no significant issues have been identified that would potentially preclude the development of an adequate safety justification. It is therefore considered that in principle, assuming the potential non fail-safe failure modes can either be designed out or their potential impact mitigated, it is feasible to produce a safety case for the PowerFuL-CB approach.

10.6. Comparison of fault level current limiting solutions

Traditional Reinforcement

- Creates fault level headroom by increasing the network's fault rating
- Involves replacing 11kV switchgear, RMUs, and potentially cables.
- Average cost: £2.48m per substation.
- Requires assets to be replaced prior to the end of their useful life, i.e. in advance of load/condition drivers; or waiting for load/condition drivers to justify the investment. This also conflicts with our asset management strategies to extend our assets' useful life.

Case Study: Upgrade the entire 11kV network to fault rating of 25kA would release fault level headroom, but at a cost of £380m

90% of LPN's 11kV network is limited to a fault level of 13.1kA, mainly due to fault ratings of 11kV CBs/RMUs. We estimate that to upgrade the entire network to 25kA (by replacing all CBs/RMUs rated <25kA) would release significant fault level headroom and cost approximately £380m. Efficient allocation for our RIIO-ED1 settlement allows £31m worth of condition-based RMU/CB replacements. Although operational efficiencies may be applied during ED1, it is very unlikely that £380m worth could be delivered within a useful timeframe. Given that equipment is primarily underground, even accessing the equipment to carry out allowed replacements will take all of the 8 years of ED1. By comparison, installing a FLCB at each of LPN's 11kV busbars could release the same amount of headroom, but (assuming £500k/FLCB) could cost as little as £106m – a theoretical **saving of £274m.**

Connect new generation to a different substation or a higher voltage.

- Avoids fault level constraints by connecting elsewhere.
- Demand for DG connections in urban areas is normally tied to specific districts or developments, which means the generators can't move closer to unconstrained parts of the network.
- Connecting to a different substation at the same voltage is more expensive because of greater distance – sometimes economically feasible.
- Connecting at a higher voltage is much more expensive because the higher-voltage cables and switchgear are much more expensive – rarely economically feasible.

Case Study: CHP in a new development

We recently investigated the feasibility of connecting 40MW of CHP as part of a new development in central London. We found that, due to fault level constraints:

- **10MW connection cost ≈ £150k (£15k/MW)** – maximum possible at 11kV without reinforcement. CHP can only operate when network is running in normal arrangement.
- **16MW connection cost ≈ £300k (£19k/MW)** – maximum possible at 33kV

- **40MW connection cost ≈ £4,000k (£100k/MW)** – must be connected at 132kV

In the absence of any smart solutions, it is clear that the maximum feasible CHP size is 16MW. A FLCB installed at either UK Power Networks' substation or the customer's premises would potentially allow 40MW of CHP to connect at 11kV. A method cost of £500k equates to a per-MW cost of £12.5k/MW, which is less than all of the traditional options. Therefore, in this case, **a FLCB could enable connection of an additional 24MW of low-carbon generation and heating at this development.**

Busbar splitting

- Reduces fault levels by feeding each busbar from as few transformers as possible.
- Bus sections are run open in intact conditions and automatically closed in the event of a transformer outage.
- LPN substations have already deployed this method as much as possible without compromising security of supply (if each busbar is fed from only one transformer, there will be a brief outage before supply is restored).
- Doesn't work in a N-1 transformer outage if the remaining transformers need to be connected in parallel to share load evenly. (This is the case at the vast majority of LPN substations).

High Impedance Transformers

- Reduces fault levels by decreasing the fault level contributions from transformers
- Requires assets to be replaced prior to the end of their useful life, i.e. in advance of load/condition drivers; or waiting for load/condition drivers to justify the investment.
- High-impedance transformers are larger, more expensive, and cause more network losses than a like-for-like replacement.
- LPN substations already use relatively high-impedance transformers.

Current Limiting Reactors

- Reduces fault levels by inserting a static impedance in series with transformers, bus sections/couplers, or interconnectors.
- Requires a spare/new transformer bay at the existing substation, which is rarely feasible in LPN.
- Causes increased network losses.

Fault current limiters (FCLs)

- Reduce fault levels by inserting an "impedance on demand".
- Under normal conditions, the device has negligible impedance and therefore minimal impact on the network. When a fault occurs, the device increases its impedance to limit the fault current.
- There are several different types of FCL that use different ways of varying their impedance. Most are intrinsically fail-safe, i.e. most credible failure modes result in the device failing to a high impedance (current limiting) state.
- Unfortunately, all known FCL technologies trialled in GB to date (e.g. the pre-saturated core and superconducting FCLs being trialled in FlexDGrid) are at least the same size as a primary transformer. They would therefore require a spare/new transformer bay at the existing substation, which is rarely feasible in LPN.

Adaptive Protection and FCL Service

- Being developed and trialled in **ENWL's Respond** Project.

- Reduces fault levels by disconnecting sources of fault current:
  - **Adaptive Protection (AP)** disconnects transformers and bus sections.
  - **FCL Service** disconnects customers' motors and generators.
- Both methods operate before the feeder CB attempts to clear the fault, which reduces the "break" fault level, but has no impact on the "make" fault level.
- Requires modifications to protection settings to ensure that the feeder CB doesn't attempt to break a fault until after the AP/FCL Service method has operated.
- Both methods are activated only when needed via a **Fault Level Assessment Tool.**
- Both methods could be useful in LPN because they do not require any large equipment to be installed in substations, but they would need to be combined with a solution that can reduce "make" fault levels. (At 99% of LPN substations, the "make" constraint will be reached before the "break" constraint.)

I_s-limiter

- Reduces fault levels by disconnecting sources of fault current i.e. a transformer, bus coupler, or interconnector.
- Uses a combination of an exploding disconnector and current-limiting fuse to disconnect a fault current before the first current peak, which means it can reduce both "break" **and "make"** fault levels.
- It is a single-shot device: i.e. The "inserts" must be replaced after every operation, and the "inserts" cannot be tested without expending them.
- Commonly used by DNOs outside GB and on private networks within GB.
- Not currently used on GB DNO networks because of concerns that its failure to operate when required could put DNOs' and customers' assets at risk of catastrophic failure. **ENWL's Respond project** is aiming to prove that Is-limiters can be used safely on GB DNO networks.
- The need to visit site to replace "inserts" after a fault may compromise security of supply at LPN substations (see Section 10.3.2 for detailed explanation).

Fault Limiting Circuit Breaker

- Reduces fault levels by disconnecting sources of fault current i.e. a transformer, bus coupler, or interconnector.
- Uses power electronics to disconnect a fault current before the first current peak, which means it can reduce both "break" **and "make"** fault levels.
- It is a multiple-shot device: i.e. it can reclose after the fault has been cleared from the network, and can be routinely tested to identify hidden failures.
- The **Active Fault De-coupler** that WPD is trialling in their **FlexDGrid** Project is a type of FLCB. Unfortunately, it requires too much physical space to be feasible for use in LPN.

Table 31 - Technical comparison of solutions that reduce fault levels

Solution	ABB FLCB	AMAT FLCB	Active Fault De-coupler	I_s-limiter	Current limiting reactor / High-Z Tx	Saturated/Shielded Core FCL	Resistive Superconducting FCL	Hybrid Power Electronic FCL	RESPOND FCL Service	RESPOND Adaptive Protection	Busbar Splitting
Principle	Disconnect sources of fault current	Disconnect sources of fault current	Disconnect sources of fault current	Disconnect sources of fault current	Constant impedance	Non-linear impedance	Non-linear impedance	Switched impedance	Disconnect sources of fault current	Disconnect sources of fault current	Disconnect sources of fault current
Load current carried by	Mechanical fast commutating switch (FCS)	IGBTs	IGBTs	Explosive disconnector (tubular busbar filled with explosive)	Air-cored reactor / high impedance transformer winding	Iron-cored reactor – reactance kept low by saturating the iron core with a DC bias coil, permanent magnets, or a short-circuited superconducting secondary winding	Superconductor – resistance kept close to zero by cryogenic cooling	IGBTs	N/A	N/A	N/A – bus coupler run normally open;[20]
Fault current limited by	IGBTs – normally bypassed by FCS	IGBTs	IGBTs	Current-limiting fuse – normally bypassed by explosive disconnector	Air-cored reactor / high impedance transformer winding	Current over a certain threshold causes desaturation of the iron core and significant increase in reactance	Current over a certain threshold causes quench in the superconductor and significant increase in resistance.	Current-limiting reactor – normally bypassed by IGBTs	Rapid disconnection of customers' generators/motors	Rapid disconnection of transformers and/or bus couplers	Permanent segregation of busbars and transformers
Triggered by	Triggering circuit	Triggering circuit	Triggering circuit	Triggering circuit	Fault current (self-triggering)	Fault current (self-triggering)	Fault current (self-triggering)	Triggering circuit	Protection relays at the customers' premises	Protection relays at the substation	N/A
Known manufacturers	ABB	AMAT	GE/Alstom	ABB	Numerous	GridON, Fault Current Ltd, ASG	Nexans, AMAT, Superpower, AMSC	AMAT	N/A	N/A	N/A
TRL	TRL4	TRL5-6	TRL5-6	TRL9[21]	TRL9	TRL7	TRL7	TRL7	TRL7	TRL7	TRL9
Relevant Innovation Projects / Trial Sites	PowerFuL-CB (UKPN)	PowerFuL-CB (UKPN)	FlexDGrid (WPD)	Respond (ENWL)	N/A	FlexDGrid (WPD), Newhaven (UKPN/ETI), Scunthorpe & Jordanthorpe (NPG)	FlexDGrid (WPD), Bamber Bridge (ENWL), Ainsworth Rd (SPEN)	-	Respond (ENWL)	Respond (ENWL)	N/A

[20] Bus coupler is closed by auto-switching scheme in event of an unplanned transformer outage, which results in a short interruption. Doesn't work for substations with more than two transformers.

[21] but not used on GB DNO networks to date because of safety/reliability concerns

Table 32 - Performance comparison of solutions to reduce fault levels

Solution	ABB FLCB	AMAT FLCB	Active Fault De-coupler	I_s-limiter	Current limiting reactor / high impedance transformer	Saturated/Shielded Core FCL	Resistive Superconducting FCL	Hybrid Power Electronic FCL	RESPOND FCL Service	RESPOND Adaptive Protection	Busbar Splitting
"break" fault level reduction	High	High	High	High	Moderate	Moderate	Moderate	Moderate	High	High	High
"make" fault level reduction[22]	High	High	High	High	Moderate	Moderate	Moderate	Moderate	None[23]	None[23]	High
Impact on customers	No[24]	Yes[25]	No	No	No	No	No	No	Yes[26]	No	Yes
Time to restore to secure running arrangement	Can reclose as soon as fault is cleared	Can reclose as soon as fault is cleared	Can reclose as soon as fault is cleared	> 1 hour[27]	Instantaneous	Instantaneous	< 3 min	Can reclose as soon as fault is cleared	Can reclose as soon as fault is cleared	Can reclose as soon as fault is cleared	Requires permanent running in insecure arrangement
Operation and maintenance impact	Low	Low	Low – Medium	High	Low – Medium	Low – Medium	Low – Medium	Low – Medium	Low	Low	Low
Physical space required	Medium	Medium	Large	Medium	Large	Large	Large	Large	Negligible	Negligible	Nil
Losses / quiescent power consumption	Negligible	Low	Significant	Nil	Significant	Significant[28]	Significant	Significant	Nil	Nil	Nil
Requires delayed fault clearance times	No	No	No	No	No	No	No	No	Yes	Yes	No
Showstoppers for use in Central London	None	None	Too big	Compromises security of supply	Too big	Too big	Too big	Too big	Doesn't reduce "make" FLs	Doesn't reduce "make" FLs	Compromises security of supply

[22] i.e. achieves fault level reduction before first current peak
[23] Requires transformers / bus couplers / customers to be disconnected before any circuit breaker or RMU can be operated, which is considered impractical
[24] No impact on customers if installed at the substation; but will affect any customers who choose to have the device installed at their premises to enable them to connect more generation to the network.
[25] For customers who choose to use this solution
[26] For customers who choose to use this solution
[27] I_s-limiter modules need to be replaced after every fault-limiting operation
[28] Except for Fault Current Ltd's permanent magnet design, which has very low losses

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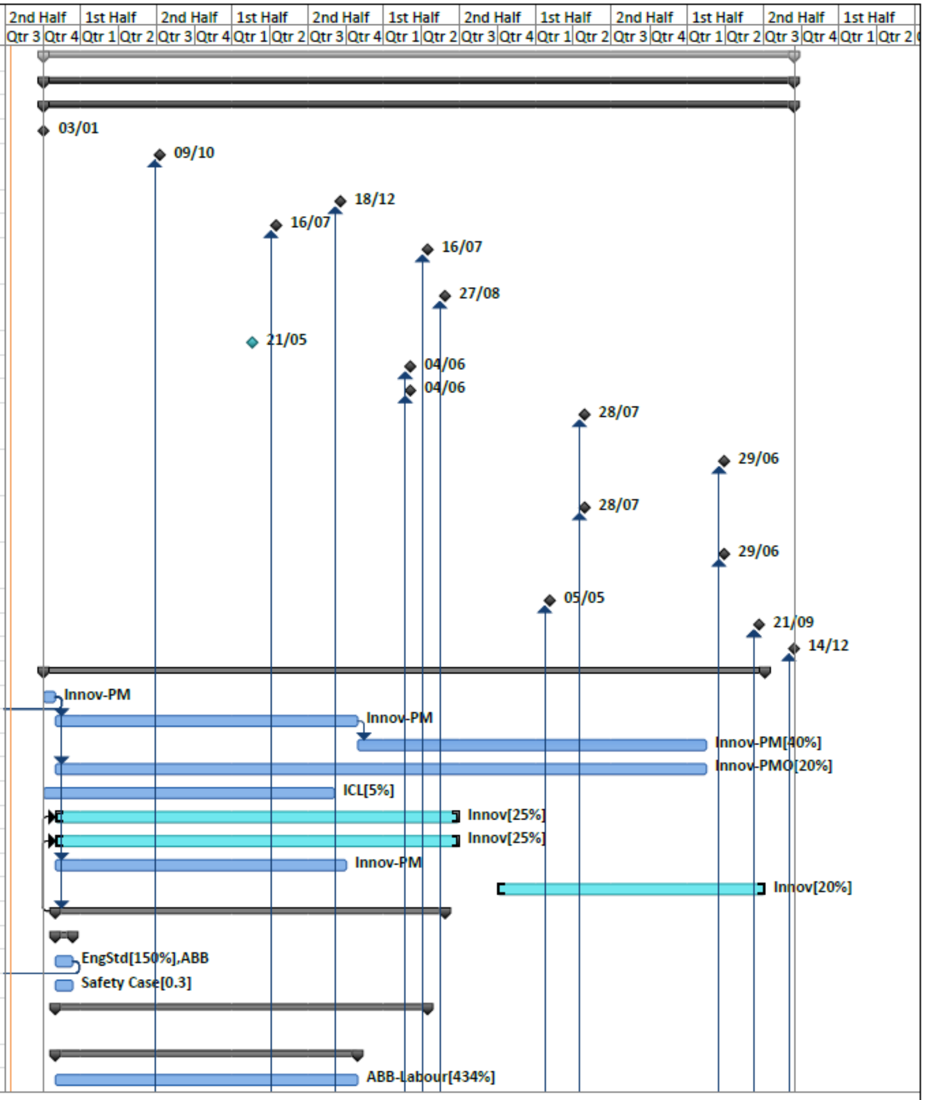
RIIO NIC NETWORK INNOVATION COMPETITION

10.7. Detailed Project plan

ID	Indicators	Task Mode	Task Name	Duration	Start	Finish
0			**POWERFL-CB Project Plan**	**1291 days**	**Tue 03/01/17**	**Tue 14/12/21**
1			**Project Plan**	**1291 days**	**Tue 03/01/17**	**Tue 14/12/21**
2			**Project Milestones**	**1291 days**	**Tue 03/01/17**	**Tue 14/12/21**
3			Project start	0 days	Tue 03/01/17	Tue 03/01/17
4			SDRC 9.3.1: Understanding customer requirements	0 days	Mon 09/10/17	Mon 09/10/17
5			Method 1 prototype complete	0 days	Tue 18/12/18	Tue 18/12/18
6			Method 2 prototype complete	0 days	Mon 16/07/18	Mon 16/07/18
7			SDRC 9.1.1 - Learning from Method 1 Prototyping	0 days	Tue 16/07/19	Tue 16/07/19
8			SDRC 9.1.2 - Learning from Method 2 Prototyping	0 days	Tue 27/08/19	Tue 27/08/19
9			SDRC 9.1.3 - Preliminary Safety Case	0 days	Mon 21/05/18	Mon 21/05/18
10			Method 1 commissioned	0 days	Tue 04/06/19	Tue 04/06/19
11			Method 2 commissioned	0 days	Tue 04/06/19	Tue 04/06/19
12			SDRC 9.2.1 - Learning from Method 1 Demonstration	0 days	Tue 28/07/20	Tue 28/07/20
13			SDRC 9.2.2 - Learning from Method 2 Demonstration	0 days	Tue 29/06/21	Tue 29/06/21
14			SDRC 9.2.3 - Learning from Method 1 Demonstration	0 days	Tue 28/07/20	Tue 28/07/20
15			SDRC 9.2.4 - Learning from Method 2 Demonstration	0 days	Tue 29/06/21	Tue 29/06/21
16			SDRC 9.3.2: Suitability of FLCBs	0 days	Tue 05/05/20	Tue 05/05/20
17			SDRC 9.4.1 - Final Learning Report	0 days	Tue 21/09/21	Tue 21/09/21
18			Closedown report	0 days	Tue 14/12/21	Tue 14/12/21
19			**Project Management**	**1241 days**	**Tue 03/01/17**	**Tue 05/10/21**
20			Mobilisation	4 wks	Tue 03/01/17	Mon 30/01/17
21			UKPN Project Manager - Full Time	104 wks	Tue 31/01/17	Mon 28/01/19
22			UKPN Project Manager - 2d/wk	120 wks	Tue 29/01/19	Mon 17/05/21
23			UKPN PMO - 1d/wk	224 wks	Tue 31/01/17	Mon 17/05/21
24			Power Electronics Expert Support	500 days	Tue 03/01/17	Mon 03/12/18
25			UKPN WS1 Lead	695 days	Tue 31/01/17	Mon 30/09/19
26			UKPN WS2 Lead	695 days	Tue 31/01/17	Mon 30/09/19
27			UKPN WS3 Lead	501 days	Tue 31/01/17	Tue 01/01/19
28			UKPN WS4 Lead	460 days	Wed 01/01/20	Tue 05/10/21
29			**WS1: Prototype and validation testing**	**671 days**	**Tue 31/01/17**	**Tue 27/08/19**
30			**Engineering Standards**	**30 days**	**Tue 31/01/17**	**Mon 13/03/17**
31			FLCB Specification (UKPN EDS)	6 wks	Tue 31/01/17	Mon 13/03/17
32			Safety Case Development	6 wks	Tue 31/01/17	Mon 13/03/17
33			**Method 1a: ABB Prototyping and validation testing for substation**	**641 days**	**Tue 31/01/17**	**Tue 16/07/19**
34			**ABB Costs**	**520 days**	**Tue 31/01/17**	**Mon 28/01/19**
35			Labour & Admin	520 days	Tue 31/01/17	Mon 28/01/19



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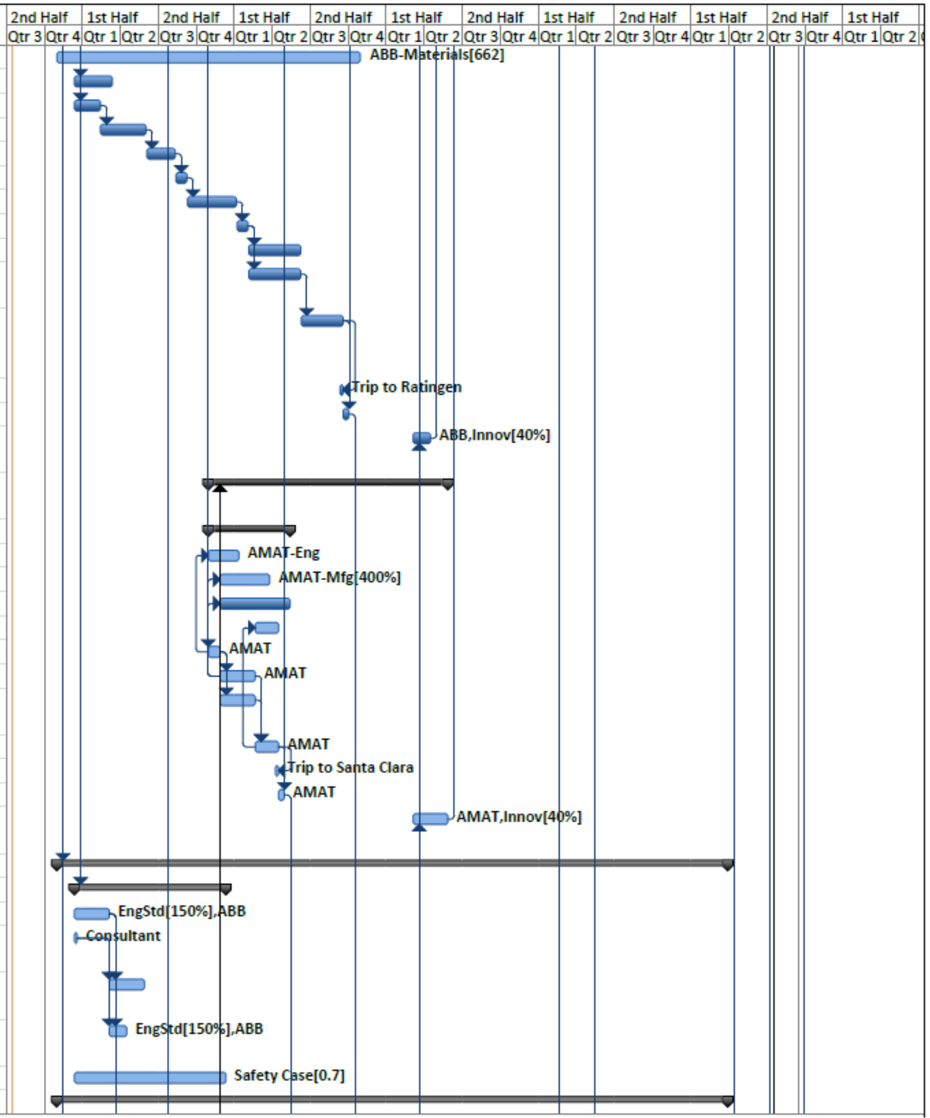
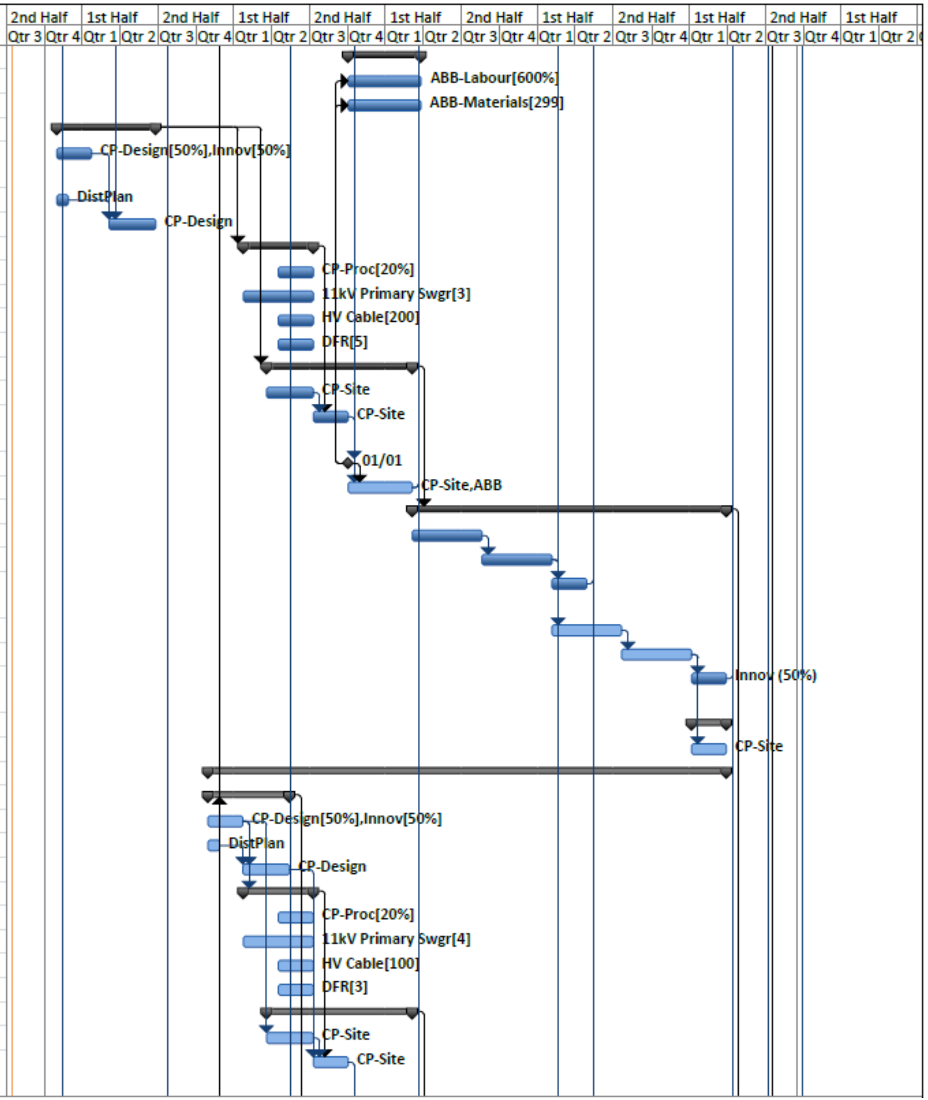
RIIO NIC NETWORK INNOVATION COMPETITION

ID		Task Mode	Task Name	Duration	Start	Finish
36			Materials	520 days	Tue 31/01/17	Mon 28/01/19
37			Order Parts	65 days	Tue 14/03/17	Mon 12/06/17
38			Gate Drive Unit (GDU)	45 days	Tue 14/03/17	Mon 15/05/17
39			Fast Commutating Switch (FCS)	79 days	Tue 16/05/17	Fri 01/09/17
40			Control and protection	50 days	Mon 04/09/17	Fri 10/11/17
41			Prototype assembly	20 days	Mon 13/11/17	Fri 08/12/17
42			Validation testing at SECRC	85 days	Mon 11/12/17	Fri 06/04/18
43			Design Improvements	20 days	Mon 09/04/18	Fri 04/05/18
44			Integration in switchgear cubicle	90 days	Mon 07/05/18	Fri 07/09/18
45			Prototyping of three units (two for tests and one for pilot)	90 days	Mon 07/05/18	Fri 07/09/18
46			Testing and validation on complete unit in switchgear cubicle (including short circuit test)	72 days	Mon 10/09/18	Tue 18/12/18
47			Witness testing	1 wk	Wed 12/12/18	Tue 18/12/18
48			Deliver protypes to sites	10 days	Wed 19/12/18	Tue 01/01/19
49			SDRC 9.1.1: Deliver substation development learning report	6 wks	Wed 05/06/19	Tue 16/07/19
50			**Method 1b: AMAT Technology Development for customer**	**411 days**	**Tue 30/01/18**	**Tue 27/08/19**
51			**AMAT Costs**	**140 days**	**Tue 30/01/18**	**Mon 13/08/18**
52			Engineering Effort	53 days	Tue 30/01/18	Thu 12/04/18
53			AMAT Manufacturing Effort	85 days	Tue 27/02/18	Mon 25/06/18
54			Materials	6 mons	Tue 27/02/18	Mon 13/08/18
55			Testing	8 wks	Tue 22/05/18	Mon 16/07/18
56			Design	4 wks	Tue 30/01/18	Mon 26/02/18
57			Build FLCB	12 wks	Tue 27/02/18	Mon 21/05/18
58			Build Mutual Reactor (AMAT to confirm costs)	12 wks	Tue 27/02/18	Mon 21/05/18
59			Test	8 wks	Tue 22/05/18	Mon 16/07/18
60			Witness testing	1 wk	Tue 10/07/18	Mon 16/07/18
61			Deliver protypes to sites	2 wks	Tue 17/07/18	Mon 30/07/18
62			SDRC 9.1.2: Deliver customer development learning report	12 wks	Wed 05/06/19	Tue 27/08/19
63			**WS2: Demonstration on the network**	**1151 days**	**Tue 31/01/17**	**Tue 29/06/21**
64			**Engineering Standards**	**260 days**	**Tue 14/03/17**	**Mon 12/03/18**
65			FLCB Network Design Standard (UKPN EDS)	12 wks	Tue 14/03/17	Mon 05/06/17
66			Method for modelling FLCB in power system studies	1 wk	Tue 14/03/17	Mon 20/03/17
67			Feasibility study on sample of UKPN-wide sites	12 wks	Tue 06/06/17	Mon 28/08/17
68			FLCB Operating and Maintenance procedures (UKPN EOS)	6 wks	Tue 06/06/17	Mon 17/07/17
69			Safety Case Development	52 wks	Tue 14/03/17	Mon 12/03/18
70			**Method 1: Substation Trial Site**	**1151 days**	**Tue 31/01/17**	**Tue 29/06/21**



ID		Task Mode	Task Name	Duration	Start	Finish
71			**ABB Costs**	**125 days**	**Wed 02/01/19**	**Tue 25/06/19**
72			ABB Labour & Admin	125 days	Wed 02/01/19	Tue 25/06/19
73			ABB Materials and Equipment	125 days	Wed 02/01/19	Tue 25/06/19
74			**Design & Planning**	**170 days**	**Tue 31/01/17**	**Mon 25/09/17**
75			Site Selection & Preliminary Design (Gate B)	12 wks	Tue 31/01/17	Mon 24/04/17
76			Power Systems Studies	4 wks	Tue 31/01/17	Mon 27/02/17
77			Detailed Design (Gate C)	16 wks	Tue 06/06/17	Mon 25/09/17
78			**Procurement**	**120 days**	**Wed 25/04/18**	**Tue 09/10/18**
79			Tendering overhead	12 wks	Wed 18/07/18	Tue 09/10/18
80			Switchgear	24 wks	Wed 25/04/18	Tue 09/10/18
81			Cables	12 wks	Wed 18/07/18	Tue 09/10/18
82			Digital Fault Recorders	12 wks	Wed 18/07/18	Tue 09/10/18
83			**Site works**	**250 days**	**Wed 20/06/18**	**Tue 04/06/19**
84			Civil enabling works	16 wks	Wed 20/06/18	Tue 09/10/18
85			Electrical/protection/control/SCADA enabling works	12 wks	Wed 10/10/18	Tue 01/01/19
86			FLCB Prototype Delivered to Site	0 days	Tue 01/01/19	Tue 01/01/19
87			FLCB Installation and commissioning	22 wks	Wed 02/01/19	Tue 04/06/19
88			**Trial Period**	**540 days**	**Wed 05/06/19**	**Tue 29/06/21**
89			Trial Period Month 0-6	24 wks	Wed 05/06/19	Tue 19/11/19
90			Trial Period Month 6-12	24 wks	Wed 20/11/19	Tue 05/05/20
91			SDRC 9.2.1: Interim Learning Report - Method 1 Demonstration	12 wks	Wed 06/05/20	Tue 28/07/20
92			Trial Period Month 12-18	24 wks	Wed 06/05/20	Tue 20/10/20
93			Trial Period Month 18-24	24 wks	Wed 21/10/20	Tue 06/04/21
94			SDRC 9.2.3: Final Learning Report - Method 1 Demonstration	12 wks	Wed 07/04/21	Tue 29/06/21
95			**Trial End**	**60 days**	**Wed 07/04/21**	**Tue 29/06/21**
96			Decommissioning OR Handover to BAU	12 wks	Wed 07/04/21	Tue 29/06/21
97			**Method 2: Customer Trial Site**	**891 days**	**Tue 30/01/18**	**Tue 29/06/21**
98			**Design & Planning**	**140 days**	**Tue 30/01/18**	**Mon 13/08/18**
99			Preliminary Design (Gate B)	12 wks	Tue 30/01/18	Mon 23/04/18
100			Power Systems Studies	4 wks	Tue 30/01/18	Mon 26/02/18
101			Detailed Design (Gate C)	16 wks	Tue 24/04/18	Mon 13/08/18
102			**Procurement**	**120 days**	**Wed 25/04/18**	**Tue 09/10/18**
103			Tendering overhead	12 wks	Wed 18/07/18	Tue 09/10/18
104			Switchgear	24 wks	Wed 25/04/18	Tue 09/10/18
105			Cables	12 wks	Wed 18/07/18	Tue 09/10/18
106			Digital Fault Recorders	12 wks	Wed 18/07/18	Tue 09/10/18
107			**Site Works**	**250 days**	**Wed 20/06/18**	**Tue 04/06/19**
108			Civil enabling works	16 wks	Wed 20/06/18	Tue 09/10/18
109			Electrical/protection/control/SCADA enabling works	12 wks	Wed 10/10/18	Tue 01/01/19



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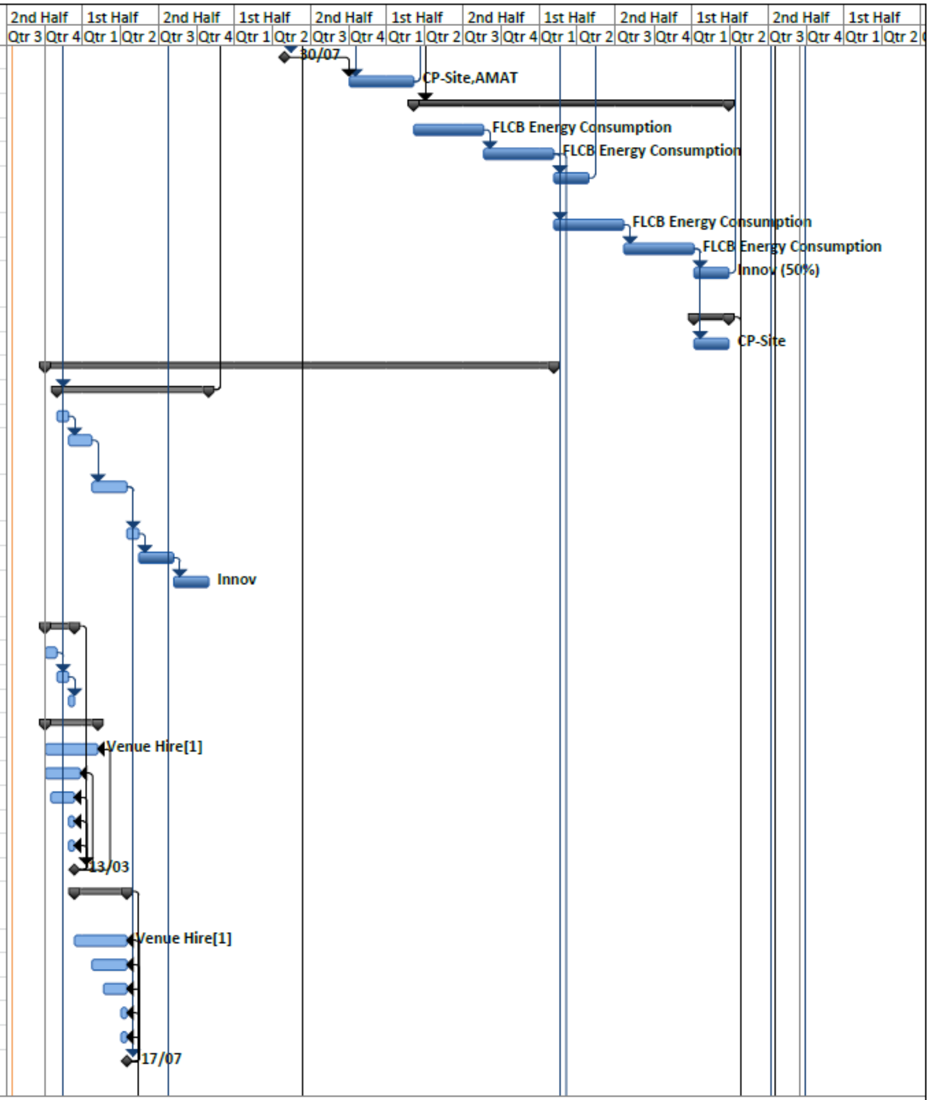
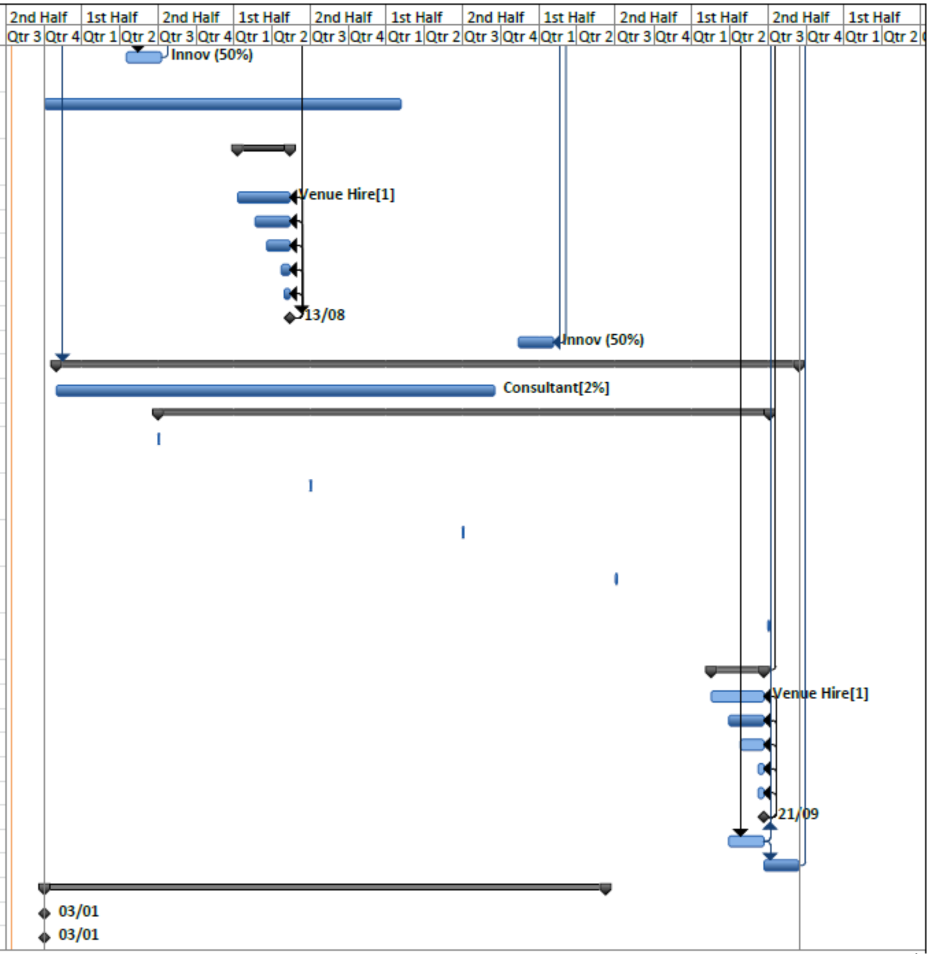
ID		Task Mode	Task Name	Duration	Start	Finish
110			FLCB Prototype Delivered to Site	0 days	Mon 30/07/18	Mon 30/07/18
111			FLCB Installation and commissioning	22 wks	Wed 02/01/19	Tue 04/06/19
112			**Trial Period**	**540 days**	**Wed 05/06/19**	**Tue 29/06/21**
113			Trial Period Month 0-6	24 wks	Wed 05/06/19	Tue 19/11/19
114			Trial Period Month 6-12	24 wks	Wed 20/11/19	Tue 05/05/20
115			SDRC 9.2.2: Interim Learning Report - Method 2 Demonstration	12 wks	Wed 06/05/20	Tue 28/07/20
116			Trial Period Month 12-18	24 wks	Wed 06/05/20	Tue 20/10/20
117			Trial Period Month 18-24	24 wks	Wed 21/10/20	Tue 06/04/21
118			SDRC 9.2.4: Final Learning Report - Method 2 Demonstration	12 wks	Wed 07/04/21	Tue 29/06/21
119			**Trial end**	**60 days**	**Wed 07/04/21**	**Tue 29/06/21**
120			Decommissioning OR Handover to BAU	12 wks	Wed 07/04/21	Tue 29/06/21
121			**WS3: Understand customers' requirements**	**871 days**	**Tue 03/01/17**	**Tue 05/05/20**
122			**Customer Recruitment**	**260 days**	**Tue 31/01/17**	**Mon 29/01/18**
123			Develop Customer Engagement Plan	4 wks	Tue 31/01/17	Mon 27/02/17
124			Ofgem Approval of Customer Engagement Plan	8 wks	Tue 28/02/17	Mon 24/04/17
125			Discussions with customers to confirm requirements/interest	12 wks	Tue 25/04/17	Mon 17/07/17
126			Make offers to customers	4 wks	Tue 18/07/17	Mon 14/08/17
127			Wait for responses	12 wks	Tue 15/08/17	Mon 06/11/17
128			Technical/commercial/legal negotiations with a single customer	12 wks	Tue 07/11/17	Mon 29/01/18
129			**Specify customer offering**	**50 days**	**Tue 03/01/17**	**Mon 13/03/17**
130			Define use cases and technical proposals	4 wks	Tue 03/01/17	Mon 30/01/17
131			Develop CBA for use cases	4 wks	Tue 31/01/17	Mon 27/02/17
132			Develop business case	10 days	Tue 28/02/17	Mon 13/03/17
133			**First user dialogue event - describe offering**	**90 days**	**Tue 03/01/17**	**Mon 08/05/17**
134			Book venue	18 wks	Tue 03/01/17	Mon 08/05/17
135			Send "save the date"	12 wks	Tue 03/01/17	Mon 27/03/17
136			Send invitations	8 wks	Tue 17/01/17	Mon 13/03/17
137			Prepare materials	2 wks	Tue 28/02/17	Mon 13/03/17
138			Send reminders	2 wks	Tue 28/02/17	Mon 13/03/17
139			**First user dialogue event - describe offering**	**0 days**	**Mon 13/03/17**	**Mon 13/03/17**
140			**Second user dialogue event - recruitment process**	**90 days**	**Tue 14/03/17**	**Mon 17/07/17**
141			Book venue	18 wks	Tue 14/03/17	Mon 17/07/17
142			Send "save the date"	12 wks	Tue 25/04/17	Mon 17/07/17
143			Send invitations	8 wks	Tue 23/05/17	Mon 17/07/17
144			Prepare materials	2 wks	Tue 04/07/17	Mon 17/07/17
145			Send reminders	2 wks	Tue 04/07/17	Mon 17/07/17
146			**Second user dialogue event - recruitment process**	**0 days**	**Mon 17/07/17**	**Mon 17/07/17**

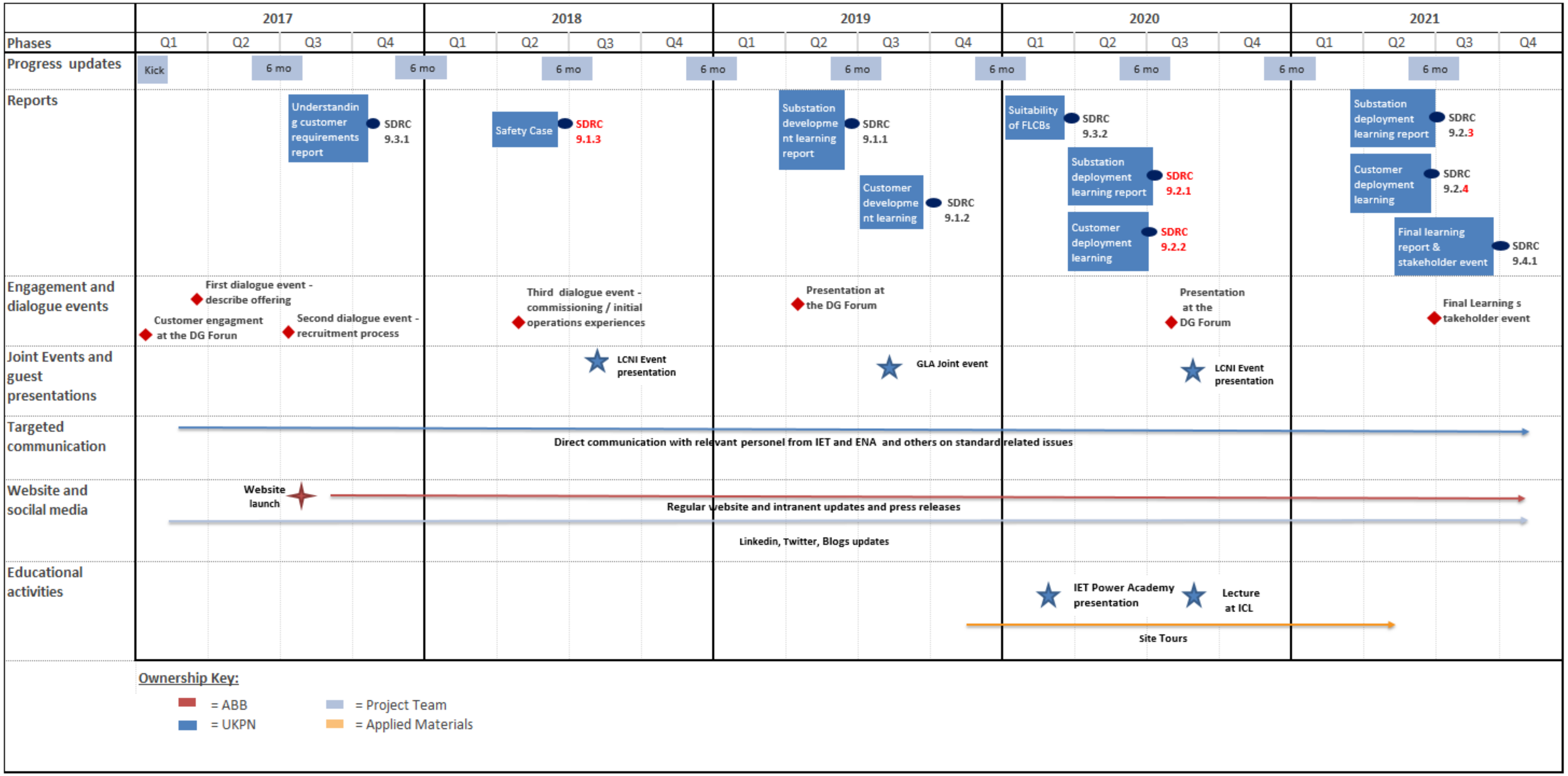


ID		Task Mode	Task Name	Duration	Start	Finish
147			SDRC 9.3.1: Understanding customer requirements report	12 wks	Tue 18/07/17	Mon 09/10/17
148			Continuous engagement via focus groups and open dialogue	122 wks	Tue 03/01/17	Mon 06/05/19
149			**Third user dialogue - commissioning / initial operations experiences**	**90 days**	**Tue 10/04/18**	**Mon 13/08/18**
150			Book venue	18 wks	Tue 10/04/18	Mon 13/08/18
151			Send "save the date"	12 wks	Tue 22/05/18	Mon 13/08/18
152			Send invitations	8 wks	Tue 19/06/18	Mon 13/08/18
153			Prepare materials	3 wks	Tue 24/07/18	Mon 13/08/18
154			Send reminders	2 wks	Tue 31/07/18	Mon 13/08/18
155			**Event**	**0 days**	**Mon 13/08/18**	**Mon 13/08/18**
156			SDRC 9.3.2: Suitability of FLCBs	12 wks	Wed 12/02/20	Tue 05/05/20
157			**WS4: Knowledge Dissemination**	**1271 days**	**Tue 31/01/17**	**Tue 14/12/21**
158			External Comms & publishing	750 days	Tue 31/01/17	Mon 16/12/19
159			**LCNI Conference**	**1047 days**	**Mon 02/10/17**	**Tue 05/10/21**
160			2017 - Conference attendence and materials	3 days	Mon 02/10/17	Wed 04/10/17
161			2018 - Conference attendence and materials	3 days	Mon 01/10/18	Wed 03/10/18
162			2019 - Conference attendence and materials	3 days	Tue 01/10/19	Thu 03/10/19
163			2020 - Conference attendence and materials	3 days	Thu 01/10/20	Mon 05/10/20
164			2021 - Conference attendence and materials	3 days	Fri 01/10/21	Tue 05/10/21
165			**SDRC 9.4.1: Final learning stakeholder event**	**90 days**	**Wed 19/05/21**	**Tue 21/09/21**
166			Book venue	18 wks	Wed 19/05/21	Tue 21/09/21
167			Send "save the date"	12 wks	Wed 30/06/21	Tue 21/09/21
168			Send invitations	8 wks	Wed 28/07/21	Tue 21/09/21
169			Prepare materials	2 wks	Wed 08/09/21	Tue 21/09/21
170			Send reminders	2 wks	Wed 08/09/21	Tue 21/09/21
171			**Event**	**0 days**	**Tue 21/09/21**	**Tue 21/09/21**
172			SDRC 9.4.1: Deliver Final Learning Report	12 wks	Wed 30/06/21	Tue 21/09/21
173			Deliver Close Down Report	12 wks	Wed 22/09/21	Tue 14/12/21
174			**Contingencies**	**960 days**	**Tue 03/01/17**	**Mon 07/09/20**
178			**Partner Contributions**	**0 days**	**Tue 03/01/17**	**Tue 03/01/17**
181			**UKPN Contributions**	**0 days**	**Tue 03/01/17**	**Tue 03/01/17**

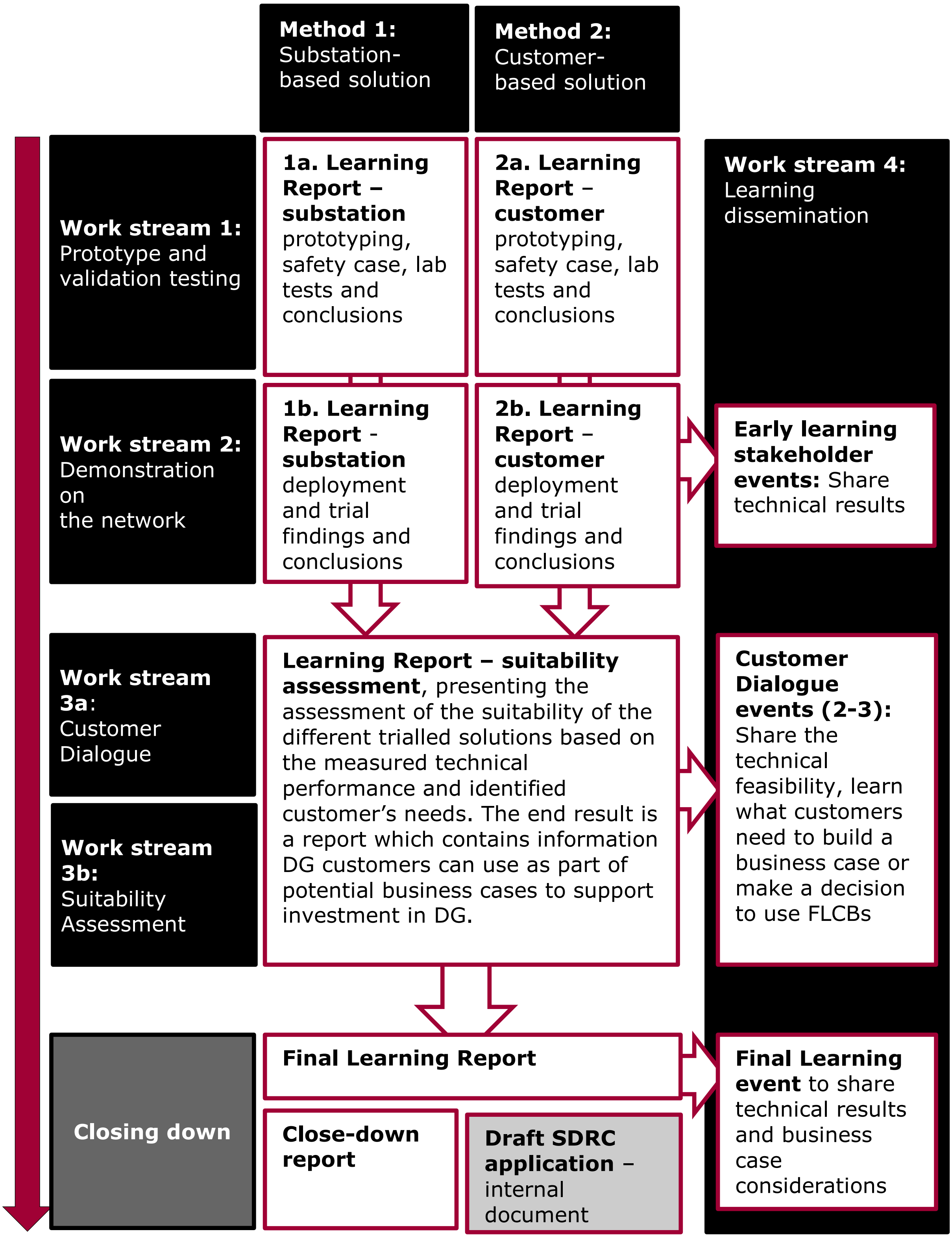


Project: POWERFL-CB Project Plan Date: Fri 05/08/16	Task		Project Summary		Inactive Milestone		Manual Summary Rollup		Deadline
	Split		External Tasks		Inactive Summary		Manual Summary		Progress
	Milestone		External Milestone		Manual Task		Start-only		
	Summary		Inactive Task		Duration-only		Finish-only		

10.8. Knowledge Dissemination Roadmap



10.9. Summary of Project Design



10.10. Project Team

10.10.1. Organogram

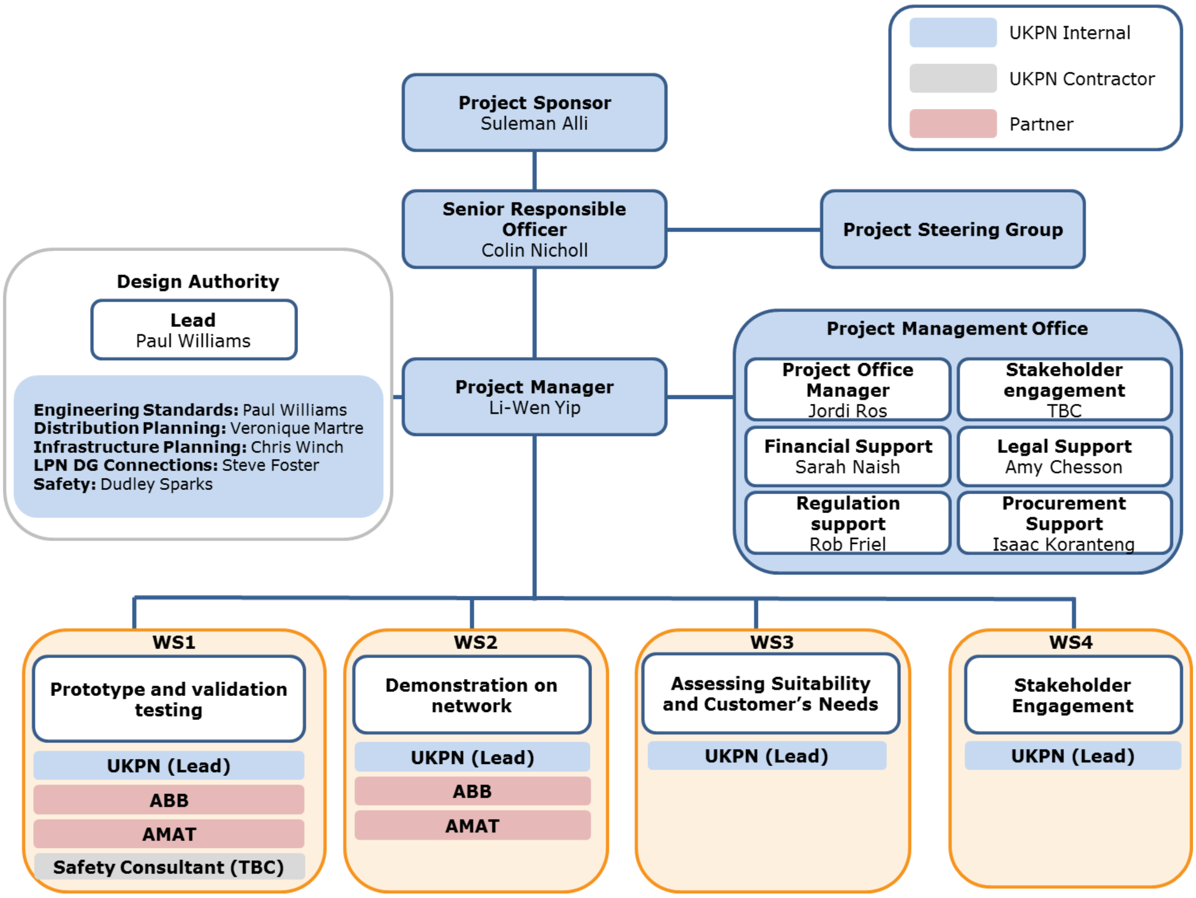


Figure 19 Project management and governance structure

10.10.2. Key UK Power Networks Staff

Li-Wen Yip BEng(Hons) CEng MIET will act as the Project Manager. He has over 10 years' experience in design, construction, operation, and maintenance of public and industrial electricity distribution networks in Australia and the UK, and has previously held engineering and project delivery roles at AECOM and Mount Isa Mines. He holds a Bachelor of Engineering with Honours in Computer Systems Engineering from James Cook University.

Colin Nicholl BEng MSc MBA MIET will act as the Project's Senior Responsible Officer. He brings to the role 25 years of experience within the electricity industry and substantial industry knowledge from a range of technical, commercial, and strategic roles. These have included: network planning, outage planning, protection commissioning, asset management, business planning. He is currently a member of UK Power Networks Senior Management Team as the Head of Innovation and Business Planning.

Paul Williams BSc (Hons) MIET will lead the Project Design Authority. He brings to the role 35 years of experience in the electricity industry and a depth of knowledge of working on the UK distribution network specifically regarding the specification, testing, and standardisation of electricity distribution assets. He has a proven track record of proving and promoting innovation. Paul is currently the Technical Sourcing and Standards Manager and is a key technical expert on UK Power Networks Senior Management Team.

Jordi Ros MSc, APMP, PRINCE2, PPM will act as the Project Management Officer as a key part of UK Power Networks innovation portfolio. He brings to the project over 10 years of experience in project management and the project office function: creating robust project management solutions across private and public sector organisations and delivering benefits while increasing project performance and efficiency.

10.10.3. About ABB

ABB is a global leader in power and automation technologies with a long tradition in developing state of the art technologies and products. ABB's Corporate Research is a global research and development function within ABB and develops new technologies and methods that are used within all ABB business units.

ABB Sweden will be the main organization within ABB participating in the project. We have about 8,800 employees and reside on more than 30 locations in Sweden. ABB Sweden is represented primarily by ABB Corporate Research (SECRC). Located in Västerås, Sweden, SECRC has more than 250 employees, of whom more than 60% have a PhD degree and who have extensive experience in running research projects, both internal and with public funding. The research centre focuses on research in both power and automation. The leading research group will be the Switching Technologies group, which employs experts within the area of electro-technology, arc physics, and physics and materials technologies.

Our parent group ABB is a leading manufacturer of low voltage and high voltage equipment. We have an extensive research and development activity, with experience in development of various switching apparatus in both AC and DC technologies. This also includes advanced laboratory infrastructure able to validate new products. Additionally, ABB is a leading supplier of products and systems for power and automation applications globally. ABB has a wide co-operation network with different universities and research institutes at the international level.

ABB Corporate Research (SECRC) Role in the project

In the project, SECRC will take the lead in the **development, testing and contribute in the pilot installation of FLCBs**. We will constantly be involved in the research and innovation aspects and will also contribute with application knowledge and insight into technical aspects of the circuit breaker and its system interaction with the overall distribution system.

Relative Expertise / Experience and how it matches the tasks in the proposal

SECRC has considerable previous experience in breaker development. ABB has participated in several relevant EC funded projects such as EIT InnoEnergy; CiPower and ESPE projects to mention a few. SECRC has extensive experience in the area of DC circuit breakers including semiconductor based technologies. SECRC is expected to provide technical expertise, lab facilities, prototype development as well as insight in possible business cases based on project results.

Key personnel

Lars Liljestrand, Corporate Research Fellow. Lars Liljestrand has 30 years at ABB's Corporate Research Center working with various switching apparatus (AC and DC) and key contributor in the Hybrid HVDC Breaker development. Competence in electrical apparatus and its high frequency interaction in the power system. Has contributed to more than 30 patents or patent applications. Has a Licentiate degree (pre-doctoral) from Uppsala University in High Voltage Physics 1986.

Magnus Backman, R&D Team Manager. Magnus Backman has spent over 21 years at ABB, working with semiconductor hybrid switches and breakers. Has contributed to more than 20 patents or patent applications. Has a Master of Science degree in Engineering Physics from Uppsala University 1994.

Ara Bissal, Scientist & Development Engineer. Ara Bissal has spent 5 years at ABB working with DC breakers for HVDC applications and ultra-fast actuators. Has a PhD degree from Royal Institute of Technology, Stockholm, 2015 on Modeling and Verification of Ultra-Fast Electro-Mechanical Actuators for HVDC Breakers. Currently working in the EU funded EIT KIC InnoEnergy project ESPE: Load Current Commutation and Interruption by Electromechanical Switches and Power Electronics.

Elisabeth Lindell, Principle Scientist. Elisabeth Lindell is a Development Engineer at ABB's Corporate Research Center. He has spent 5 years at ABB working with medium voltage breakers and their interaction in the system. Has a PhD degree from Chalmers University of Technology, Gothenburg, 2009.

Lars Jonsson, Principle Scientist. Lars Jonsson is a Development Engineer at ABB's Corporate Research Center. He has 26 years at ABB working with switching technologies such as diode based circuit breakers, vacuum based on load tap changers and ultra-fast actuators. Has a Master of Science degree in Engineering Physics.

Relevant previous projects or activities, connected to the subject of the proposal and Publications and/or products, services or other achievements

We have performed several projects related to switching devices like circuit breakers for medium voltage or DC applications. In most cases the project was initiated by the Research Center and developed to prototype until taken over by our Product Development team. Examples of development projects are listed below with reference to either published papers or patent applications.

1. Mechanical medium voltage DC circuit breaker. Pending patent application, WO2015062644
2. Novel mechanical & electrical hybrid medium voltage AC circuit breaker/capacitor switch. Conference paper. "A diode based capacitor switch – A novel solution for power quality improvement", Paper 839, Cired 2011.
3. Medium voltage AC fault current limiter. Granted patent "An electric device, a current limiter and an electric power network", number EP1377995-A1
4. Mechanical & power electronic hybrid high voltage DC circuit breaker. Conference paper. "Hybrid HVDC breaker – A solution for future HVDC systems", B4-304, Cigré 2014.
5. Mechanical high voltage DC circuit breaker. Conference paper. "A low loss mechanical HVDC breaker for HVDC Grid applications", B4-303, Cigré 2014.
6. Metallic return transfer breaker for high voltage DC applications. Granted patent "DC current breaker", number: US20110175460-A1
7. Mechanical medium voltage DC circuit breaker. Conference paper. "Medium voltage DC vacuum circuit breaker", CP-494, ICEPE-ST 2015, Korea

10.10.4. About Applied Materials (AMAT)

Dr. Paul J. Murphy, Managing Director of Engineering, Varian Semiconductor and G.M. Varian Power Systems of Applied Materials, USA.

Mr. Murphy obtained his Ph.D. in Physics in 1993 and has vast experience in Guidance Systems, Scientific Instruments, Space and Satellite Design and High Voltage Systems. Paul has held various senior level positions in Engineering with Varian since 1997 and is currently G.M. of Varian Power Systems Group

Dr. Kasegn Tekletsadik, MIEEE Director of FCL Technology Applied Materials, USA. Mr. Tekletsadik obtained his PhD from the University of Strathclyde, Dept of Electrical Eng., Glasgow, Scotland, UK in Electrical Power Engineering in 1991. He holds several patents and has published several papers in areas of high voltage, fault current limiters, Plasma and x-ray technology. Mr. Tekletsadik was also a research fellow at the University of Strathclyde, Dept of Electrical Eng., Glasgow, Scotland, UK from 1991 - 1994. He has held Engineering positions with such companies as General Electric, Rolls Royce and SuperPower.

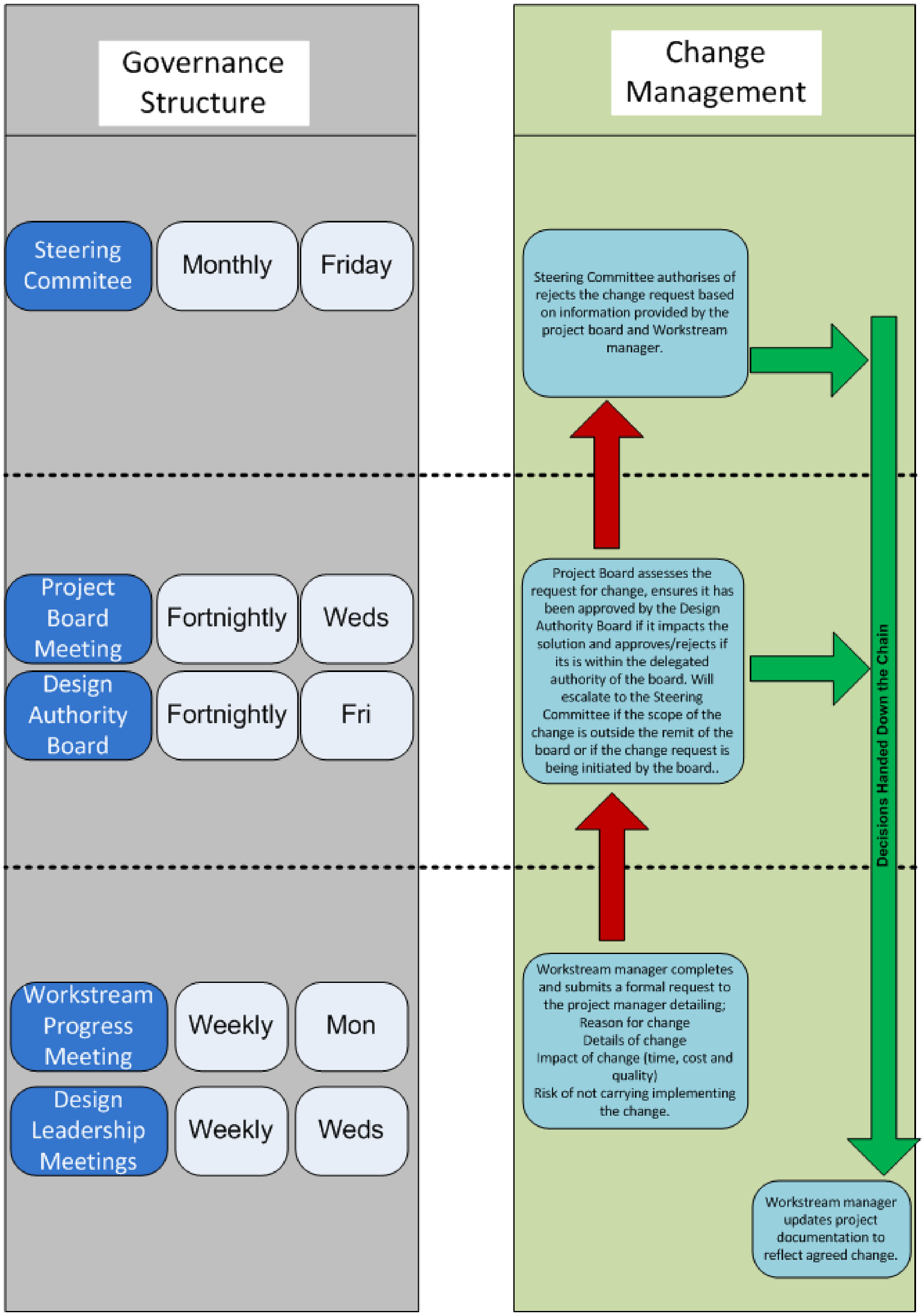
Mr John Ludlum is currently the Global Director of Business Development Varian Power

Systems of Applied Materials, USA. Mr. Ludlum has spent more than 25 years in a sales and marketing role serving the utility industry. His experience includes all of the major markets in Europe, North & South America as well as the Asia Pacific region. He has held senior management positions with such companies as Schneider Electric, Eaton Cutler Hammer and Landis & Gyr. Mr. Ludlum holds a Bachelor of Business Administration with a Marketing Major

Mr Adrian Wilson, CEng, FIET is an Electrical Engineer at Applied Materials based in the UK. He has degrees from Bradford and Warwick universities. His main area of expertise is Fault Current Limitation, an area where he has been active since 2004 and has installed several operational units into distribution network operator sites. Prior to this he had position at NaREC, engineering the integration of renewables into electrical grids and at British Steel managing maintenance, projects and HV distribution.

Mr Herbert Piereder has been working in the area of electrical power engineering since 1990 and has held senior positions in finance, marketing, business development and innovation management (at SGP Energy & Environment, ELIN , VA Tech T&D, Enovations Consulting, Applied Superconductor Ltd., Applied Materials Inc.) with a particular focus on Austria, Germany, China, the USA and the UK. Herbert holds a Masters Degree in Mechanical Engineering from the Technical University of Vienna and a Global Executive MBA from the Fuqua School of Business (Duke University, NC). Together with his industry experience he has access to a global network of customers, industry experts, suppliers and agents. He is currently Consulting Director at Applied Materials Inc., responsible for business development Fault Current Limiters in Europe.

10.10.5. Project Governance and Change Control Process



10.11. Risk Register

Ref	Status	Category	Description	Owner	Probability	Severity	Mitigation
R1		Financial risk	ABB's costs increase because of exchange rate movements due to Brexit developments	ABB	< 60%	5- Serious, >£50k	ABB has agreed to hold their quoted price in GBP until the project commences. Once the project has commenced, we will agree the ABB contract price in GBP, or agree the price in EUR and take steps to hedge the exchange rate risk.
R2		Trials Design	Unable to find a suitable site / willing customer for customer trial	UK Power Networks	< 60%	5- Serious, >£50k	We will engage with customers to understand their motivations for participating in the trial, so that we can design the trial and recruitment campaign to provide the right incentives and target the right customers. We will also consider relevant customer research and learning from ENWL's FCL Service trial.
R4		Project Delivery	Delay and/or cost overrun - prototype development	ABB, AMAT	< 30%	5- Serious, >£50k	ABB and AMAT have agreed to take all risk of cost overruns within their control. UK Power Networks will use our existing change control procedures to minimise the risk of changes that cause additional costs for ABB and AMAT.
R5		Project Delivery	Delay and/or cost overrun - safety case (due to unforeseeable requirements)	Safety Case consultant	< 30%	5- Serious, >£50k	We have allowed specific contingency for the safety case, based on Frazer-Nash's experience of required effort in the event of unforeseen requirements
R6		Equipment Design	Prototype as delivered is not fit for purpose	ABB, AMAT	< 30%	5- Serious, >£50k	UK Power Networks, ABB, AMAT, FNC to collaborate to develop the FLCB specifications; Safety consultant to develop safety case in parallel; engage with other HSE, ENA, and other DNOs.
R7		Equipment Design	Solution does not deliver the necessary reliability and/or redundancy to be able to prove the safety case	Safety Case Vendor	< 30%	5- Serious, >£50k	Safety case feasibility study completed before full submission. Safety case to be developed in close collaboration with FLCB designers and engineering standards
R8		Equipment Design	Solution is not suitable for general population of GB sites due to operational or physical space constraints	UK Power Networks	< 30%	5- Serious, >£50k	We will engage with other DNOs to understand any operational or physical space constraints that are unique to their networks.
R9		Trials Design	Trial site does not experience enough HV network faults to prove that the solution is safe and reliable	UK Power Networks	< 30%	5- Serious, >£50k	We will use history of HV network faults as a criterion when selecting trial sites. We will use the safety case to determine how much data is required to prove that the FLCB is safe.
R10		Trials Design	Trial fails to capture the data necessary to prove that the solution is safe and reliable	UK Power Networks	< 30%	5- Serious, >£50k	We will ensure that our data capture solution has adequate reliability and redundancy so that we don't miss any opportunities to capture data from real network faults.
R11		Trials Design	Solution fails to operate correctly during field trial (i.e. faults to limit fault current)	UK Power Networks	< 30%	5- Serious, >£50k	We will not allow fault levels to exceed equipment ratings until the FLCB has been proven safe and reliable.

Ref	Status	Category	Description	Owner	Probability	Severity	Mitigation
							This minimises the risk of an unsafe situation if the FLCB fails to operate correctly.
R12		Trials Design	Customer trial has adverse impacts on customer	UK Power Networks	< 30%	5- Serious, >£50k	We will identify the potential impacts on the customer and work with them to ensure the risks are well managed.
R13		Knowledge Dissemination	ABB decides not to offer a commercial product	ABB	< 30%	5- Serious, >£50k	ABB have confirmed that if they are unable to offer their foreground IPR to Licensees in the form of a commercial FLCB product, they are willing, in principle, to licence any relevant foreground/background IPR to a third party for the purpose of developing a commercial FLCB product.
R14		Knowledge Dissemination	Solution is not accepted by other DNOs	UK Power Networks	< 30%	5- Serious, >£50k	We will engage with other DNOs at key stages of the design and specification processes to ensure that their requirements and concerns are addressed.
R15		Project Delivery	Project partners unable to deliver on commitments on time because of lack of resources and/or other commitments	UK Power Networks	< 10%	5- Serious, >£50k	We will agree heads of terms and scopes for collaboration agreements with all project partners in advance of project kick-off.
R16		Project Delivery	UK Power Networks not able to deliver on commitments because project delivery team is under-resourced	UK Power Networks	< 10%	5- Serious, >£50k	We will secure resources for the core project delivery team in advance of project kick-off, and ensure adequate succession planning to manage the risk of staff movements.
R17		Project Delivery	UK Power Networks not able to deliver on commitments because other teams supporting the project are under-resourced	UK Power Networks	< 10%	5- Serious, >£50k	We have engaged the relevant business units within UK Power Networks to confirm their support of the project, and will confirm resourcing commitments during project mobilisation
R18		Project Delivery	Partner withdraws from project for financial, commercial, or technical reasons	UK Power Networks	< 10%	5- Serious, >£50k	If one technology partner withdraws from the project, we will consider using the same technology at both substation and customer sites, or if this would not provide value for customers' money, we would de-scope the project to only trial one technology at one site. If FNC withdraw from the project, we will seek an alternative partner who can provide the necessary safety case expertise.
R19		Project Delivery	Customer (trial participant) withdraws from the project because the trial is impacting their business activities	UK Power Networks	< 10%	5- Serious, >£50k	To minimise probability, We will only consider customers where the risk of adverse impact on their business activities is minimal or can be managed.
R20		Safety Risk	Breach of data protection regulations	UK Power Networks	< 10%	5- Serious, >£50k	We will ensure that all customer's details are handled and stored in accordance with our data protection procedures.
R21		Safety Risk	Solution has adverse impacts on protection grading, causing	UK Power Networks	< 10%	5- Serious, >£50k	We will complete a protection coordination study to ensure that the solution does not have any adverse effects on protection coordination.

Ref	Status	Category	Description	Owner	Probability	Severity	Mitigation
			unacceptable fault clearance times				
R22		Reputational risk	Solution fails, causing unplanned outages	UK Power Networks	< 10%	5- Serious, >£50k	We will install additional circuit breakers that enable the FLCB to be remotely bypassed and isolated to minimise the risk of unplanned outages in the event that it fails.
R23		Equipment Design	Solution is not suitable for general population of UK Power Networks sites due to operational or physical space constraints	UK Power Networks	< 10%	5- Serious, >£50k	We have already completed a preliminary feasibility study on a sample of LPN sites, and will complete a feasibility study on a sample of LPN, EPN, and SPN sites as part of the project.
R24		Equipment Design	BAU method cost is higher than expected	UK Power Networks	< 10%	5- Serious, >£50k	If we discover any issues that could increase the BAU method cost to the point where the project business case is no longer viable, we will assess whether the project should be halted or de-scoped.
R25		Equipment Design	Equipment fails to pass high power type tests	ABB, AMAT	< 10%	5- Serious, >£50k	ABB and AMAT have both allowed adequate contingency to build another prototype, in the event that the device intended for the field trials fails catastrophically during type testing and cannot be salvaged.
R26		Trials Design	Unable to find a suitable site for substation trial	UK Power Networks	< 10%	5- Serious, >£50k	If we are unable to find a suitable site in LPN (e.g. there are sites that would be suitable for a BAU deployment but not suitable for a trial for business/commercial/safety reasons), we will also consider sites in SPN or EPN that have similar operational and/or physical constraints as typical LPN sites.
R27		Knowledge Dissemination	Learning from the project is not disseminated effectively to the DNO community	UK Power Networks	< 10%	5- Serious, >£50k	We will benchmark our knowledge dissemination strategy against other projects and other DNOs to ensure its effectiveness.
R28		Knowledge Dissemination	Solution is not approved by UK Power Networks	UK Power Networks	< 10%	5- Serious, >£50k	We will involve key UK Power Networks stakeholders to champion the design and specification of the solution to ensure that it is accepted.
R29		Knowledge Dissemination	Solution is not accepted by customers	UK Power Networks	< 10%	5- Serious, >£50k	We will engage with customers to understand their requirements and motivations, and ensure the solution is designed to meet their needs.
R30		Project Delivery	Delay and/or cost overrun - civil works	UK Power Networks	< 30%	4- Significant, <£50k	We will leverage the expertise of our in-house capital delivery teams to ensure that all site works are well managed.
R31		Project Delivery	Delay and/or cost overrun - electrical installation works	UK Power Networks	< 30%	4- Significant, <£50k	We will leverage the expertise of our in-house capital delivery teams to ensure that all site works are well managed.
R32		Project Delivery	Project kick-off delayed by negotiations with project partners	UK Power Networks	< 10%	4- Significant, <£50k	We have agreed heads of terms and scopes for collaboration agreements with all project partners before full submission.

Ref	Status	Category	Description	Owner	Probability	Severity	Mitigation
R33		Project Delivery	Project delivery team lacks necessary technical expertise	UK Power Networks	< 10%	4-Significant, <£50k	We have engaged technical experts within the business to serve as the project design authority. We will also engage an expert on power electronics to provide assurance on ABB and AMAT's designs and specifications.
R34		Project Delivery	Delay and/or cost overrun - commissioning	UK Power Networks	< 30%	3-Moderate, <£20k	We will leverage the expertise of our in-house capital delivery teams to ensure that all site works are well managed.
R35		Project Delivery	Delay and/or cost overrun - customer engagement/recruitment	UK Power Networks	< 30%	3-Moderate, <£20k	We will leverage the expertise of our in-house capital delivery teams to ensure that all site works are well managed.
R36		Equipment Design	ABB-provided (conventional) circuit breakers do not comply with UK Power Network's requirements	UK Power Networks	< 30%	3-Moderate, <£20k	We have allowed adequate contingency for UK Power Networks to supply approved circuit breakers, which would be connected to the FLCB by joggle panels.

10.12. Letters of support

10.12.1. Support letter from ABB

Date: 11th October 2016

Li-Wen Yip
Innovation Engineer UKPN
PowerFuL-CB
Newington House
237 Southwark Bridge Road
London SE1 6NP

Dear Li-Wen

ABB Letter of Support

PowerFuL-CB (POWER-electronic Fault-Limiting Circuit Breaker)

ABB (www.abb.com) is a leader in power and automation technologies that enable utility, industry, transport and infrastructure customers, to improve their performance while lowering environmental impact. The ABB Group of companies operates in roughly 100 countries and employs in the order of 140,000 people.

UKPN has identified in its PowerFuL-CB submission, that CHP and other rotating Distributed Generation connections (and the associated financial and low-carbon benefits) in central London, are likely to be limited because of fault level constraints.

The pilot deployment of a Fault Limiting Circuit Breaker (FLCB) will provide Distribution Network Operators with considerable learning and the potential for an alternative tool to be utilised during the lifecycle of network design, delivery and operation.

The cost effective management of fault level within electricity distribution systems will release considerable value to customers and further allow the connection of distributed energy resources in key locations such as central London.

ABB supports the PowerFuL-CB project and if granted ABB is committed to provide in kind contribution of £500k through our R&D costs and use of our facilities. ABB welcomes the opportunity to bring its global experience to this exciting project, and to working closely with UKPN on the application of this innovative 11kV circuit breaker solution.

Yours sincerely

Mikael Dahlgren
Research Director
ABB AB, Corporate Research

Lars-Gunnar Aufrecht
Controller
ABB AB, Corporate Research

6917 0906-EN Bording

10.12.2. Support Letter from Applied Materials

APPLIED MATERIALS

3050 Bowers Avenue | P.O. Box 58039
Santa Clara, California 95054, U.S.A.
Telephone: 408 727 5555
www.appliedmaterials.com

29th July, 2016

Li-Wen Yip
Innovation Engineer UKPN
POWERFL-CB
Newington House
237 Southwark Bridge Street
London
SE1 6NP
United Kingdom

Dear Li-Wen,

Applied Materials Letter of Support
POWERFL-CB (Power electronic fault limiting circuit breaker)

Applied Materials (http://www.appliedmaterials.com/technologies/fault-current-limiters) is the technology company that drives and has driven the doubling of the number of transistors on a silicon chip for nearly the last 50years. Our highly innovative engineers have used their core skills to develop two Fault Current Limiting products and we welcome this project as a way to further develop our skills and products in a market environment.

UKPN has identified in its POWERFL-CB submission, that CHP and other rotating Distributed Generation connections (and the associated financial and low carbon benefits) in central London, are likely to be limited because of fault level constraints. It is noticeable form your LTDS statements that he level of applications/customer in the London region is between a quarter and a fourteenth of those in your other regions. Applied materials is proposing the trial of our Fault current limiter technology as a way to potentially solve some of the issues associated with this problem

Applied Materials is willing, subject to the negotiation of a final agreement, to contribute £387,668 in kind, which is projected to be over 90% or our costs associated with this project. These include but are not limited to R&D costs, use of our factory, external independent test facilities and support to your project in the installation, operation, maintenance, dissemination and customer liaison areas. We welcome the opportunity to work closely with UKPN and develop something of real value for UK Electricity customers and generator plant developers.

Yours Sincerely

Dr Paul Murphy
MD Applied Materials Power Systems

10.12.3. Support letter from ENWL

electricity north west
Bringing energy to your door

Electricity North West
Technology House, 2 Lissadel St,
Salford, M6 6APT

Direct line 08433 113944
steve.cox@enwl.co.uk

To: Li-Wen Yip

05 August 2016

Dear Sir

Letter of support for POWERFUL-CB Project

Electricity North West is pleased to provide this letter of support for your Network Innovation Competition project, POWERFL-CB.

Like UK Power Networks, we are committed to finding smart solutions to fault level constraints so that we can help accelerate the uptake of district heating and CHP in our urban networks. Work to date by Electricity North West and other GB DNOs has shown that there is no "one size fits all" solution to fault level issues, and that we need a variety of solutions to deal with the constraints and opportunities present at different sites. Indeed, our own LCNF project, **Respond**, is demonstrating how four techniques – Fault Level Assessment Tool (FLAT), Adaptive Protection, Is-limiter, and Fault Current Limiting (FCL) Service – can work together to manage fault level issues on our networks.

We understand that POWERFL-CB will aim to build on the learning outcomes of our Respond project, and as such we would be pleased to offer you any knowledge or support as appropriate that could help POWERFL-CB succeed. Of particular relevance is our insight into customers' requirements from our FCL Service trial, and our learning from deploying Is-limiters in brownfield substations.

We are particularly keen to understand how UKPN see use of the Fault Limiting Circuit Breakers (FLCBs) complementing techniques trialled as part of Respond.

We look forward to collaborating with UK Power Networks, and other DNOs pursuing fault-level related projects, to understand the full set of fault level solutions available to us and our customers.

Yours Faithfully

Steve Cox
Digitally signed by Steve Cox
DN: cn=Steve Cox, o, ou, email=steve.cox@enwl.co.uk, c=GB
Date: 2016.08.05 18:10:25 +01'00'

Head of Engineering
Electricity North West Ltd

10.12.4. Support letter from GLA

GREATERLONDONAUTHORITY

Greater London Authority
City Hall
The Queen's Walk
London, SE1 2AA

Li-Wen Yip
Innovation team
UK Power Networks

5th August 2016

Letter of support: POWERFL-CB trials

It is with great pleasure and interest that we provide this letter of support to UK Power Networks for their proposed POWERFL-CB innovation project.

The Greater London Authority (GLA) is committed to generating energy locally as it has an important role to play in developing a secure, affordable and low carbon energy system for London. We have therefore set a target to supply 25 percent of London's energy demand from local sources by 2025 and expect distributed generation connected to district heating networks to play a major role in achieving that goal. The GLA has an important role to play in enabling the deployment of embedded generation and maximising its contribution to a secure, affordable and low carbon energy system and, in the context of this project, specifically the resilience and capacity of the local electricity network. We are therefore really pleased that UK Power Networks, the main player in this space, are actively pursuing innovative new approaches to reducing the cost of connecting new or expanded existing CHP. We are also interested in understanding the financial value of embedded generation to the local electricity network through the role it can play in deferring, reducing or even eliminating the need for future reinforcement of the local electricity network. We recognise that the technologies in your trial will potentially be ready in the next 5 years during which there are likely to be many opportunities to test and ultimately benefit from the technologies being developed in this project.

We recognise the potential that the proposed two technology trials of the POWERFL-CB project could have in enabling greater integration of embedded generation into the local energy system and accelerating London's transition towards a secure, affordable and low carbon energy system. We therefore support the FLCB project and are pleased that once again, London is chosen as an innovation hub for electricity network projects.

Yours sincerely,

Simon Wyke

Principal Policy Officer – Energy

Tel: 0208 286 0954

City Hall, London, SE 2AA • london.gov.uk • 0207 983 4000

10.12.5. Support letter from Imperial College London

Imperial College London

Energy Futures Lab
Imperial College London

South Kensington Campus
London SW7 2AZ, UK
Tel: +44 20 7594 6171

t.green@imperial.ac.uk
www.imperial.ac.uk/people/t.green

Professor T C Green PhD CEng FIET SMIEEE
Professor of Power Engineering
Director, Energy Futures Lab

29th July 2016

Li-Wen Yip CEng
Innovation Engineer
UK Power Networks
Newington House
London SE1 6NP

Dear Li-Wen,

I am pleased to have this opportunity to express my strong support to UK Power Networks for their proposed POWERFL-CB innovation project. I have found the discussions with you on the topic fascinating and inspiring.

Some 15 years ago I redirected my research in power electronics to applications in power networks with topics covering HVDC and distribution network applications. In 2008, we created the Maurice Hancock Lab as a purpose built facility for validating power electronic technologies for the smart grid and were grateful that EDF Energy Networks, as UKPN's fore-runner, actively supported that initiative. In HVDC there has been huge progress over the last decade with the advent of modular multi-level converters and I am proud to have played a role in progressing that technology. Distribution networks raise somewhat different opportunities and challenges for power electronics and the technology has taken longer to progress to technical and commercial readiness. I am very pleased to be engaged with UKPN in the FUN-LV trials of power electronic devices in 400 V networks.

In the future, distribution networks will face unprecedented challenges caused by the transition to a low-carbon economy. I strongly believe the power electronics technologies have the potential to solve many of these problems. I have shared with you a draft proposal on adapting modular power converters for use as power flow devices in HV parts of distribution networks. This is an area which I think has great potential and could see the emergence of DC overlay networks. I am particularly excited that POWERFL-CB aims to accelerate the development of power-electronic fault-limiting circuit breakers, which, aside from addressing fault level issues on existing networks, are a key enabler for MVDC overlay grids. However, the pressures on foot-print, insulation systems and losses at HV in distribution networks are very different to those at EHV in transmission and for that reason there is a lot of engineering effort required to adapt technology that is relatively common now in HVDC transmission to a distribution network equivalent.

Having reviewed the design and performance of ABB's FLCB prototype, I can confirm that it uses an innovative way of greatly reducing the power losses which are so often an impediment to deploying power electronics technologies. Future advances in power electronics technology, such as the development of wide-bandgap semiconductor materials, have the potential to reduce the size and cost of FLCBs further and to the point where they could be feasible as a direct replacement for conventional circuit breakers, which could revolutionise the way we plan and operate distribution networks of the future. For these reasons I think that the POWERFL-CB project would be a huge step in defining the future use of power electronics in networks. If I might add, the effort to adapt EHV technology for HV use is a burden that manufactures will find hard to bear until the case for the equipment's use is more firmly proven. Here I think POWEFL-CB is a good use of an innovation incentive mechanism to overcome that barrier.

Yours sincerely,

T. Green

10.12.6. Support letter from WPD

WESTERN POWER DISTRIBUTION

Serving the Midlands, South West and Wales

Toll End Road
Fourth Floor
Tipton
West Midlands
DY4 0HH

Direct Dial: 0121 6239459
Email: jberry@westernpower.co.uk

Li-Wen Yip
Newington House
237 Southwark Bridge Road
London
SE1 6NP

Our ref NIC 2016 *Your ref*

Date 29 July 2016

Dear Li-Wen,

This letter is in response to the information you have recently provided regarding your NIC bid for 2016, POWERFL-CB, which is aiming to install a power-electronic fault level mitigation device.

Like UK Power Networks, we are committed to finding smart solutions to fault level constraints so that we can help accelerate the uptake of district heating and CHP in our urban networks. Our FlexDGrid project is already developing a number of solutions to this problem and we believe that the POWERFL-CB, if successful, could complement the existing fault level mitigation technology toolkit, developed as part of FlexDGrid and other key innovation projects. We see great potential for the use of power-electronic technologies on the distribution network and the POWERFL-CB could help accelerate power-electronic fault level mitigation technologies to the same technology readiness level as other, more mature, technologies.

We would be keen to further collaborate with UK Power Networks as we currently do with Electricity North West to pool the learning from our respective fault level related projects. This combined learning has the potential to help DNOs and customers understand and choose from the full set of fault level solutions available to them. In particular, we have learned a lot about deploying fault level mitigation technologies in brownfield substations; POWERFL-CB will have to deal with many similar issues, and we would be pleased to further share this learning with UK Power Networks to provide immediate benefits to the project.

We therefore take great interest in the project and should UK Power Networks be successful in their funding bid we look forward to working collaboratively to share learning and develop fault level mitigation technologies for inclusion on DNOs' networks.

Yours sincerely,

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