WPD INNOVATION
Transforming the electricity network

EDGE-FCLi

Closedown Report

June 2022

WESTERN POWER DISTRIBUTION
Serving the Midlands, South West and Wales

Version Control

Issue	Date
D02	19/04/2022
V00	16/05/2022
V01	27/06/2022

Publication Control

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1. Executive Summary

The Embedded Distributed Generation Electronic Fault Current Limiting interrupter (EDGE-FCLi) is a novel power electronic fault current limiter designed and manufactured by GridON. It is an 11kV three-phase unit that has a 6.2MVA rating and is designed to connect in series with Distributed Generation (DG) on the 11kV distribution network.

The EDGE-FCLi can limit the fault current contribution from DG by quickly disconnecting the generator from the network upon detection of a fault condition. The aim of the device is to facilitate increased capacity for DG on fault level constrained networks and avoid the need for expensive network reinforcement or other methods to resolve fault level issues.

The project was a joint Network Innovation Allowance (NIA) project between Western Power Distribution (WPD) and UK Power Networks (UKPN), with both parties working collaboratively to build, design, test, and trial a device on their respective 11kV networks. This approach was taken to ensure that the technology was safe to connect to the 11kV network and was also replicable across Great Britain (GB).

The WPD device was successfully installed and trialled in series with three 1.4MW Combined Heat and Power (CHP) units connected to the 11kV network supplied from the University of Warwick (UoW) 33/11kV primary substation.

The EDGE-FCLi has demonstrated that it can successfully limit short circuit currents in a controlled test laboratory environment. The device was able to interrupt short circuit current in less than 10ms for a range of prospective peak currents applied during short circuit tests at KEMA, Prague. The device, however, has not experienced any real-world fault conditions since it has been connected to the live network at the UoW and therefore the fault detection and limiting performance of the device is yet to be proven in the field.

The EDGE-FCLi has shown that it is capable of sustained operation under load current. This was tested in the temperature rise test at full rated current in the GridON factory, and for longer durations in a Long Duration Performance Test (LDPT) or ‘soak test’ prior to the connection on the live network supplied by UoW. However, the device has only been connected in series with the CHP machines at UoW for a short duration over the field trial.

The WPD EDGE-FCLi experienced issues with its Built In Test (BIT) protection mechanism during the field trial. This mechanism is initiated at regular intervals to check that the power electronics in the device are working correctly. There were two instances where the BIT function spuriously tripped the EDGE-FCLi even though the power electronics were healthy. This caused prolonged outage periods of the device as investigations were instigated to understand the cause of the BIT failures, confirm the defects and test and deploy the solutions to remedy the problems. This ultimately limited the time the device spent connected in series with the CHP generators at UoW substation. The WPD EDGE-FCLi was successfully reconnected to the 11kV network after the BIT issues were resolved and the device remains in operation at the time of writing this closedown report.

Overall, the EDGE-FCLi performed well in testing and has demonstrated that the technology and basic design philosophy is able to carry rated load current, is safe to connect to the 11kV network and is able to successfully limit short circuit current. The performance of the EDGE-FCLi in the field trial appears to align with the positive outcomes witnessed during the testing, based on the relatively short duration it has been connected to the 11kV network. The project team will continue to analyse the performance of the EDGE-FCLi over a longer duration with the goal of seeing the device respond to a real-world network fault on the 11kV network.

2. Project Background

2.1. Overview

The growth of connected Distributed Generation (DG) has caused an increase fault level across the 11kV network. This is particularly an issue in urban areas, where the fault level is more likely to exceed the capability of the switchgear to safely disconnect a network fault.

The Embedded Distributed Generation Electronic Fault Current Limiting interrupter (EDGE-FCLi) is a prototype solid-state fault current limiter that has been developed and trialled as part of the EDGE-FCLi Network Innovation Allowance (NIA) project. The device is manufactured by GridON in Israel and is designed to connect in series with DG on the 11kV network. The device can quickly disconnect the DG from the network upon detection of a fault condition. Therefore, it can limit the fault current contribution from DG and overcome fault level issues that can limit network capacity and prevent future DG connections without the need for network reinforcement or other methods to resolve fault level issues.

The project was a joint NIA project between Western Power Distribution (WPD) and UK Power Networks (UKPN) to ensure that a device is developed that is safe to connect to the 11kV network and is also replicable so that it can be deployed throughout Great Britain (GB).

The EDGE-FCLi was installed at the University of Warwick (UoW) primary substation. The device is a three phase 11kV power electronic fault interrupting device that is designed to operate in series with distributed generators up to 5MW in size. Figure 2-1 shows a simplified diagram of a generic EDGE-FCLi connection to the 11kV distribution network.

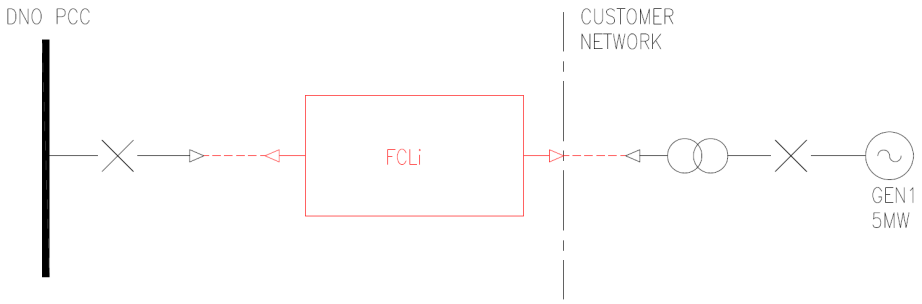

Figure 2-1 Generic EDGE-FCLi connection to the distribution network

2.2. Operation

The EDGE-FCLi uses in-built electronics to detect external network faults and quickly disconnect the generator from the network if the measured fault current exceeds pre-configured fault detection thresholds. The device limits fault current infeed by interrupting the generator current flow before it reaches the first prospective peak (approximately 10ms after fault initiation). This is shown graphically in Figure 2-2 for a 3-phase fault. The solid lines show the short circuit current being interrupted before the prospective current has a chance to reach the peak value (shown by the dashed lines).

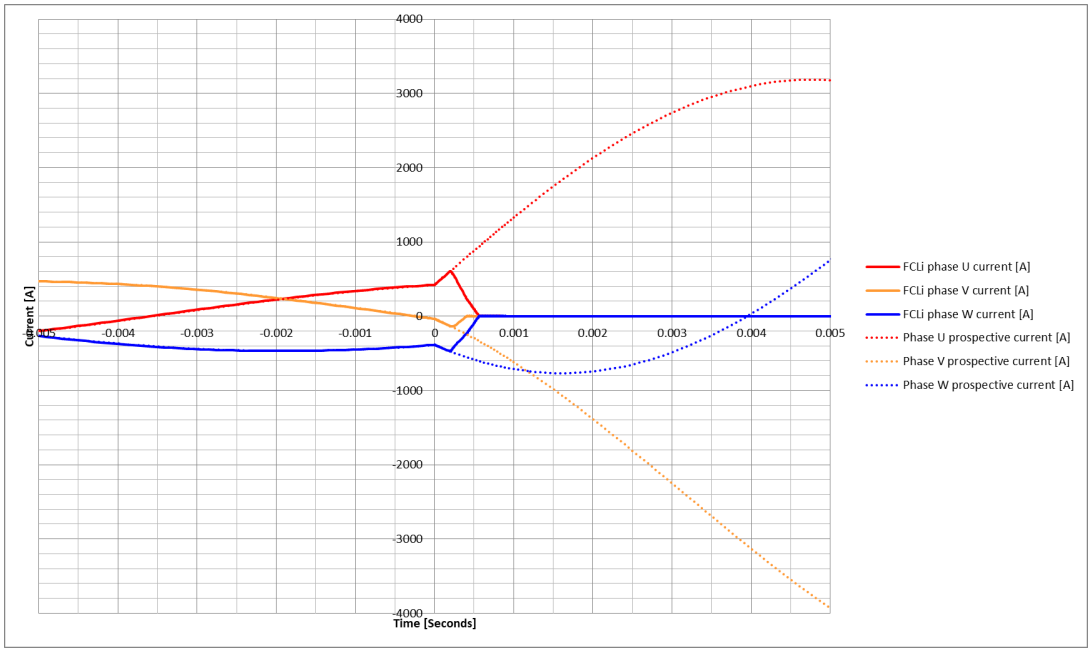

Figure 2-2 Graph of EDGE-FCLi interrupting short circuit current (3-phase fault)

The purpose of the device is to limit generator fault level contribution at locations on the network that are close to their switchgear short circuit ratings. This will allow the connection of additional generation in these areas without triggering replacement of the switchgear with higher short circuit rated units.

3. Scope and Objectives

The project has met the objectives set out when the project was registered as given in Table 3-1 below.

Table 3-1 Status of project objectives

Objective	Status	Comment
Design an 11kV FCLi for a <= 5MW generator	✓	Complete. The WPD EDGE-FCLi was installed in series with three 1.4MW Combined Heat and Power (CHP) machines supplied from the 33/11kV UoW primary substation.
Manufacture the FCLi	✓	Complete. The WPD EDGE-FCLi was manufactured and successfully passed its Factory Acceptance Test (FAT) on 1 June 2020.
Perform detailed testing on the manufactured FCLi including Factory Acceptance Testing, external lab testing and 'soak' testing	✓	Complete. The WPD EDGE-FCLi successfully passed its FAT on 1 June 2020. The EDGE-FCLi then successfully passed all short circuit tests carried out at the KEMA third party laboratory Prague, Czech Republic on 29-30 June 2020. A Long Duration Performance Test (LDPT) was then initiated on the 15 February 2021 and ran for four calendar weeks, concluding on the 15 March 2021. The EDGE-FCLi successfully passed this 'soak test'.
Complete Internal Arc Testing of a prototype device	✓	Complete. The UKPN EDGE-FCLi device successfully passed an Internal Arc Classification (IAC) test carried out on a dummy device at KEMA's laboratory in Prague, Czech Republic on 16 December 2019.
Provide learning and recommendations for the suitability of such a device for implementation in the distribution network	✓	Complete. A performance report on the EDGE-FCLi has been produced. In addition, the project team has delivered several presentations to the industry detailing the operation and performance of the EDGE-FCLi.

4. Success Criteria

The project has met the success criteria set out when the project was registered as given in Table 4-1 below.

Table 4-1 Status of project success criteria

Criterion	Status	Comment
The EDGE-FCLi limits and reduces to zero before the first peak the fault current contribution of the generator during a network fault	✓	Complete. The WPD EDGE-FCLi successfully passed all short circuit tests carried out at the KEMA third party laboratory Prague, Czech Republic on 29-30 June 2020.
The EDGE-FCLi introduces minimal disturbance to the network and the generator during normal operation	✓	Complete. The WPD EDGE-FCLi was installed with a bypass circuit breaker for the field trial. This ensured that the generator could be reconnected to the network without the EDGE-FCLi in the circuit, thus avoiding prolonged outages of the CHP generators.
The EDGE-FCLi remains in normal conduction mode for transient non-fault related events and for faults outside the 11kV network on to which it is connected	✓	Complete. The WPD EDGE-FCLi successfully passed all short circuit tests carried out at the KEMA third party laboratory Prague, Czech Republic on 29-30 June 2020. These tests also included short circuit prospective currents that were below the detection thresholds. The WPD EDGE-FCLi is currently energised and conducting on the 11kV network fed from the UoW substation.
Any device failures are minor and do not render the plant unavailable for more than a few hours.	✓	Complete. The WPD EDGE-FCLi was installed with a bypass circuit breaker for the field trial. This ensured that the generator could be reconnected to the network without the EDGE-FCLi in the circuit, thus avoiding prolonged outages of the CHP generators. There have been some minor updates to the WPD EDGE-FCLi Built In Test (BIT) operation to improve the performance of the device.

5. Details of the Work Carried Out

5.1. Overview

The project has successfully completed the design, build, test, installation, and trial of the EDGE-FCLi device. The trial site was the 33/11kV UoW primary substation. The site was selected due to its proximity to three 1.4MW CHP machines that supply electricity and heat to the local university campus. The device was connected in series with the UoW CHP generators fed from 11kV circuit breaker “CB26”. A new four panel 11kV switchboard extension was installed to provide control, protection and bypassing of the EDGE-FCLi. Figure 5-1 below shows the single line diagram of the connection with the new equipment shown in red.

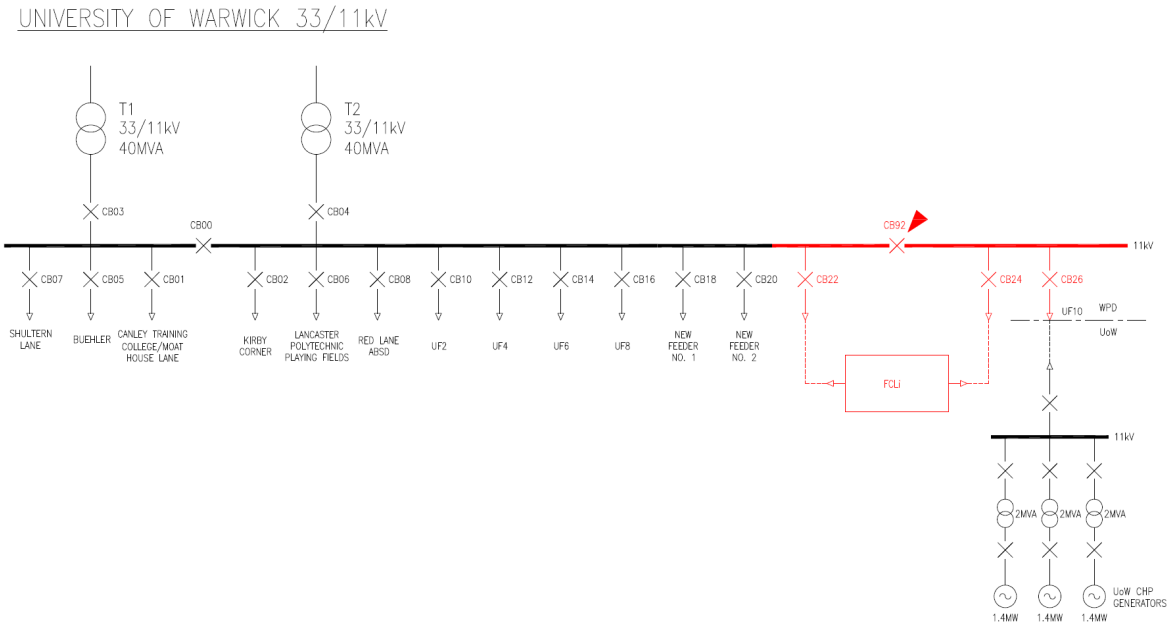

Figure 5-1 Final single line diagram of 33/11kV UoW substation

The bus section circuit breaker CB92 was included in the design to allow the EDGE-FCLi to be bypassed and keep the CHP machines connected under an EDGE-FCLi outage. This configuration is acceptable at the UoW as the site does not have a fault level limitation and a bypass was decided as prudent measure for the innovation trial. However, at locations where the fault level is a concern, the use of a bypass circuit breaker should be reviewed on a case-by-case basis.

A protection trip signal received from the EDGE-FCLi, either due to an internal device fault or a fault detection operation, will automatically initiate opening of CB22, CB24 and CB26 11kV circuit breakers.

Figure 5-2 and Figure 5-3 show the EDGE-FCLi at various stages of the project to give the reader some context to the device and the installation. Figure 5-2 shows the device during the factory tests prior to shipment to the UK. Figure 5-3 shows the device contained within its GRP housing at the UoW trial site.

Figure 5-2 EDGE-FCLi during FAT test in Israel

Figure 5-3 EDGE-FCLi in its GRP housing at UoW 33/11kV substation

5.2. Design

The EDGE-FCLi project has successfully delivered the detailed design of a novel power electronic fault current limiter and moved the associated Technology Readiness Level (TRL) from TRL4 “Bench Scale Research” to TRL6 “Large Scale Deployment”. A detailed account of the conceptual and detailed design can be found in the Oct 2018 – Mar 2019 and Apr 2019 – Sept 2019 six-monthly progress reports.

5.3. Testing

The EDGE-FCLi was subjected to a rigorous test regime that incorporated the following three test phases:

- Factory Acceptance Test (FAT) carried out at GridON’s test facilities in Israel on 1 June 2020.
- Short circuit testing carried out at the KEMA laboratory in Prague, Czech Republic on 29-30 June 2020.
- Long Duration Performance Testing (LDPT) carried out at the 33/11kV UoW substation trial site prior to energisation at 11kV. The test was initiated on 15 February 2021 and concluded on the 15 March 2021.

The device successfully passed all test requirements in each phase. Specific details on the test methodologies and test results of all testing phases can be found in the associated six-monthly reports. The FAT and short circuit testing is documented in the Apr 2020 – Sept 2020 six-monthly report. The LDPT is documented in the Oct 2020 – Mar 2021 six-monthly report.

5.4. Trial

The EDGE-FCLi was successfully connected and energised on the 11kV network at the UoW 33/11kV primary substation on 13 May 2021. Unfortunately, the EDGE-FCLi experienced several unplanned outages during the field trial due to failure of the device’s BIT system. However, the project team were able to resolve the issues that led to the outages and reconnect the device to complete the field trial on 25 March 2022. The BIT issues that caused the outages are described in detail in the Apr 2021 – Sept 2021 and Oct 2021 – Mar 2022 six-monthly reports as well as the EDGE-FCLi Performance Report.

6. Performance Compared to the Original Aims, Objectives and Success Criteria

6.1. General

The EDGE-FCLi project has met the original aims and objectives, and success criteria that were set out in the NIA Project Registration and PEA Document. The evidence indicating that the original scope and objectives have been carried out is provided in Table 3-1 in Section 3. The evidence to demonstrate that the original success criteria have been achieved is provided in Table 4-1 in Section 4.

6.2. Network Fault

The EDGE-FCLi has demonstrated that it can successfully limit short circuit currents in a controlled test laboratory environment. The device was able to interrupt the short circuit current in less than 10ms for a range of prospective peak currents and therefore met the short circuit test pass criteria. However, the device has not experienced any fault conditions since it has been connected to the trial network at the UoW (May 2021 – March 2022) and therefore the fault detection and limiting performance of the device in the field is inconclusive.

6.3. Built-In-Test (BIT) Trips

The EDGE-FCLi experienced prolonged outage periods during the field trial as investigations were carried out into the cause of the BIT failures and solutions were developed to remedy the problems. This ultimately limited the time the device spent connected in series with the CHP generators at UoW substation.

One of the initial success criteria was to ensure that any device failures do not render the generating plant unavailable for more than a few hours. The design of the EDGE-FCLi integration at UoW considered the possibility that there could be sustained outages and implemented a bypass circuit breaker on the 11kV switchboard extension. This ensured that the device could be bypassed, and the CHP generators reconnected to the 11kV primary busbar very quickly after a trip command from the EDGE-FCLi. The bypass configuration was acceptable at the UoW trial site as it does not have a fault level limitation. However, it is imperative at locations where the fault level is a concern, the use of a bypass circuit breaker should be reviewed on a case-by-case basis to avoid fault level exceeding equipment ratings.

7. Required Modifications to the Planned Approach during the Project

7.1. Overview

The EDGE-FCLi project has gone through some scope modifications when compared to the original planned approach. The WPD internal change request management procedures were always followed to address these modifications. There was a re-baselining of the project in late 2019 to allow for greater collaboration with UKPN and to incorporate more testing phases into the project scope. The project also had to adapt to the onset of the COVID-19 pandemic, which significantly affected UKPN's programme. The following sections describe these modifications to the planned approach in more detail.

7.2. Project Re-baseline

The EDGE-FCLi project plan was re-baselined in December 2019 to allow for greater collaboration with UKPN, and to further ensure that the device is replicable and deployable throughout GB. The adapted plan facilitated a more integrated and joined up approach to the design, factory testing, and laboratory testing of the EDGE-FCLi to ensure that it was suitable for longer-term testing and site trials. The re-baselined plan included greater testing requirements to ensure the device was safe to connect and operate on the 11kV network. This involved UKPN carrying out an Internal Arc Classification (IAC) test and WPD completing the LDPT, a long term 'soak' test.

The project work packages in the NIA Project Registration and Project Eligibility Assessment (PEA) were subsequently adjusted to meet the new project requirements. Table 7-1 gives the new work package structure that was developed. An updated PEA was subsequently submitted to the ENA on 3 January 2020 after agreement was made with UKPN on their more integrated role in the project.

Table 7-1 Adjusted work packages following project re-baseline in late 2019

Work Package No.	Work Package Description
1	Device specifications – Specifications will be defined to cover all the device requirements.
2	Preliminary EDGE-FCLi design and review – This includes the identification of key components, high level electrical, thermal and control design, and detailed test plan preparation.
3	Detailed EDGE-FCLi design and review – This involves full design of all parts including power modules, insulation, control system and operator interface, fault detection system, enclosures, thermal and ventilation detailed design.
4	EDGE-FCLi device manufacture.
5	Performance testing – The EDGE-FCLi will undergo several rigorous tests including Factory Testing, Laboratory/Type Testing, and Internal Arc Testing.
6a*	LDPT (conditional on successful completion of work packages 1-5).
6b*	Installation and operation of the UKPN FCLi on their 11kV network.
7*	Trial of the WPD EDGE-FCLi on 11kV network (conditional on successful completion of work packages 6a and 6b for six months).
Asterisk (*) indicates the updated/new work packages	

The updates to the plan meant that the installation and trial of the WPD device at the selected trial site location was now dependent on successful completion of the LDPT and successful operation of the UKPN device on their 11kV network

for a period of six months. This approach allowed the project to maximise the learning generated whilst also ensuring customers receive continuing value for money.

7.3. COVID-19 and UKPN Programme

The COVID-19 pandemic has had a significant impact on certain aspects of the project delivery. National governments across the globe were beginning to implement severe travel restrictions and public health measures to curb the spread of the disease at the time when the FAT and short circuit testing for the WPD device were being planned (17-18 March 2020 and 23-24 April 2020 respectively). The escalating COVID-19 situation eventually led to the postponement of the FAT and short circuit testing as the Israeli and Czech governments enforced a ban for all foreign nationals aiming to enter their countries on w/c 9 March 2020.

The FAT and short circuit testing were subsequently rescheduled after it was agreed to employ a system of remote witnessing. This was a significant departure from WPD policy where witness testing of this nature is normally attended in person. However, after careful planning, the remote testing proved successful with GridON providing WPD witnessing engineers with the appropriate viewpoints and detailed walkthroughs of the test equipment and procedures. GridON used Zoom to provide the videoconferencing system. The learning generated from the remote witnessing is documented and described in more detail in the Apr 2020 – Sep 2020 six monthly report.

Unfortunately, the COVID-19 situation had a more significant impact on the UKPN programme. Their EDGE-FCLi was originally selected to be connected in series with CHP generators located within a hospital facility. The UKPN customer was therefore acutely affected by the COVID-19 pandemic, and this had an impact on the perception of risk associated with the first-of-a-kind installation of an EDGE-FCLi. UKPN have encountered considerable difficulty coming to agreement with the customer at the proposed trial site, and this was further compounded by reliability concerns due to the spurious BIT trips experienced in the WPD field trial.

The delays on the UKPN installation meant that a further refinement of the project direction had to take place to ensure that the project could continue and provide learning to the wider industry. The WPD installation was initially conditional on a successful six-month trial of the EDGE-FCLi device at UKPN's trial site, however, this dependency could not be achieved due to the COVID-19 delays previously mentioned. Therefore, to maintain progress and project learning, we continued with our EDGE-FCLi connection independently of UKPN. The project work packages in the PEA were modified accordingly and submitted to the ENA on 20 January 2022 and are shown in Table 7-2.

Table 7-2 Adjusted work packages following UKPN COVID-19 delays

Work Package No.	Work Package Description
1	Device specifications – Specifications will be defined to cover all the device requirements.
2	Preliminary EDGE-FCLi design and review – This includes the identification of key components, high level electrical, thermal and control design, and detailed test plan preparation.
3	Detailed EDGE-FCLi design and review – This involves full design of all parts including power modules, insulation, control system and operator interface, fault detection system, enclosures, thermal and ventilation detailed design.
4	EDGE-FCLi device manufacture.
5	Performance testing – The EDGE-FCLi will undergo several rigorous tests including Factory Testing, Laboratory/Type Testing, and Internal Arc Testing.
6*	LDPT (conditional on successful completion of work packages 1-5).
7*	Trial of the WPD FCLi on the 11kV network where 6 is successful
Asterisk (*) indicates the updated/new work packages	

The UKPN EDGE-FCLi has been fully manufactured and tested and is currently in storage awaiting deployment to their trial site. After continuing discussions with WPD throughout the closedown activities, we understand UKPN have been evaluating the merits of different options for continuing with a separate NIA project, including selecting a different trial site for EDGE-FCLi. However, at the time of this process is still underway and a separate NIA project has not yet been finalised.

8. Project Costs

Table 8-1 Project spend

Budget Item No.	Activity	Budget (£k)	Actual	Variance (%)
1	GridON EDGE-FCLi	1,250.0	1,249.7	-0.02
2	Contractor Costs	367.6	360.5	-1.93
3	WPD Project Management	122.1	67.1	-45.0
4	Equipment and Labour	258.9	246.5	-4.79
5	Schneider Switchgear	105.2	105.2	0.00
6	Long Term Performance Test	108.0	0.0	-100
-	**Totals**	**2,211.8**	**2,137.4**	**-3.36**

The LDPT budget item (no. 6) was originally set up to account for the costs of testing the EDGE-FCLi at a third-party external laboratory. As explained in the Apr 2020 – Sept 2020 six monthly progress report, an alternative method of performing the test at the University of Warwick (UoW) substation was explored and found to be the optimal solution from a cost and time perspective. The cost for the alternative LDPT solution was significantly lower than the original solution and was able to be absorbed into the budget for the site commissioning activities, hence the reason for zero spend on the associated line item in Table 8-1.

There is also a negative variance in WPD project management costs as the project management activities were largely delivered by GHD on behalf of WPD. GHD were contracted by WPD to support the project management and technical integration of the EDGE-FCLi in late December 2019 when the project was re-baselined, and the previous consultant ended their involvement with the project.

9. Lessons Learnt for Future Projects

The learning from the project has been captured and presented to stakeholders in various reports and documents, namely:

- The suite of six-monthly progress reports; and
- EDGE-FCLi Performance report.

The key learning points have been summarised in Table 9-1.

Table 9-1 Project learning summary

Area	Learning Detail	Comment
Design	The existing EDGE-FCLi design does not have directional fault detection capability i.e., the device is not able to distinguish the difference between the direction of current flowing from the network towards the generator and vice versa.	This requirement was not specified in the technical specification and hence was not included in the design. The lack of directional capability was not something that caused major issues at the UoW as the trial substation did not have a fault level limitation, and therefore the EDGE-FCLi could be energised with the bypass closed and the generator connected to the 11kV network. This may not be the case for future constrained sites and therefore any future design iteration should look to include directional capability.
Design	The cooling system fans that extract heat losses from the EDGE-FCLi power electronics have two speed settings medium and high speed. The speed is determined by the ambient air temperature and pressure drop in system.	The EDGE-FCLi successfully passed the temperature rise test during the FAT carried out at GridON's test facilities in Israel on 1 June 2020. This confirmed that the fan speed settings and control methodology was acceptable. However, for future design iterations it may be useful to link the fan speed to the load current magnitude flowing through the device. This may optimise the loading on the fans, increasing their lifespan and reducing fan noise, although, this would need to be subject to further investigation.
Design	The fault detection settings are critical to ensuring that the EDGE-FCLi operates in response to network faults and does not operate for transient events, such as switching impulses or transformer magnetic inrush	For future installations of the EDGE-FCLi, it is important that an in-depth study is carried out to produce an optimised set of fault detection settings. This can be achieved by modelling the local network and applying three phase faults in an iterative fashion at increasing distances away from the 11kV primary busbar.
Design	It is a manual process to change the fault detection settings on the EDGE-FCLi.	The fault detection control circuity includes two factory pre-set detection thresholds. In addition, a fully adjustable selection is available using trimmer-potentiometers for both criteria. In future designs it would be recommended to update this manual system to make it easier to select and configure the detection thresholds i.e., a basic HMI could be used to allow simple user input of new settings.

Testing	GridON demonstrated that the rated current operation of the EDGE-FCLi with N-1 fans (11 out of 12 fans running) at an ambient temp of 40°C is thermally more onerous than the condition where all the fans are at medium speed with ambient temperature just below the threshold for the high-speed fan setting.	It was important to clarify that the N-1 scenario was the most onerous in terms of the thermal demands on the cooling system so that the temperature rise test developed in the FAT was appropriately specified. A robust and well-defined test specification is required to ensure that a new device such as the EDGE-FCLi is safe to connect and operate on the network.
Testing	The EDGE-FCLi did not initially pass the preliminary 28kV withstand test and 95kV lightning impulse tests that were carried out prior to the FAT. Further detail can be found in the October 2019 – March 2020 six monthly report.	GridON investigated the root cause of the insulation breakdown and determined that additional solid insulation was required in the EDGE-FCLi phase compartments. Furthermore, the low voltage dc supplies for the power electronic modules were required to be relocated in the phase cabinets. The device subsequently passed the preliminary and FAT tests. This learning item demonstrates the effectiveness of a rigorous test regime to identify and remedy issues at an early stage.
Testing	The FAT was witnessed remotely over video conference due to the Covid-19 travel restrictions that were in place at the time of testing.	This proved to be an effective way of progressing the project programme under the travel restrictions that were in place. There are, however, some learning points for future remote tests: • Ensure the cameras are modern and high quality this will help the engineers to have a clear view of the test. In addition, make sure they have a good support (i.e., tripods) to minimise jitter. • A plan is required for the positioning of the cameras for each test so that the witnessing engineer can see all relevant parts of the device/setup. • It is advisable to have two witnessing engineers present on the video conference as witnessing the more complex tests (such as functional tests) where multiple views are required can be shared between the witnessing engineers.
Testing	The device performed well in the short circuit testing and passed all required performance tests in the test specification.	A notable learning point from the short circuit testing was the EDGE-FCLi operates very rapidly when it detects a short circuit current above the threshold setting value (in this case the 25kA RMS prospective current). The device operated in less than 200µs. Further detail on the short circuit test results can be found in the Apr 2020 – Sept 2020 six-monthly report.
Testing	The project team identified that the UoW trial substation had spare ways on the local substation LVAC distribution board that could be used to connect the EDGE-FCLi for the LDPT.	The use of the existing LVAC supplies at UoW saved the project significant cost as the device will not need to be shipped to a third-party lab for the LDPT. A detailed description of the LDPT is documented in the Oct 2020 – Mar 2021 six-monthly report.

Testing	The EDGE-FCLi successfully passed the LDPT with no issues or observations noted.	The LDPT was initiated on the 15 February 2021 and ran for four calendar weeks, concluding on the 15 March 2021 The LDPT was a necessary part of the testing sequence prior to the connection of the EDGE-FCLi to the 11kV distribution network. The EDGE-FCLi is a 'first -of-its-kind' device and therefore it was important to ensure it was safe and reliable before energisation on the live 11kV network. A detailed description of the LDPT is documented in the Oct 2020 – Mar 2021 six-monthly report.
Delivery and Offloading	During delivery and offloading the EDGE-FCLi had to be unpacked and rebuilt at the temporary storage location to ensure that the internal components were protected from rain during transport and offloading to the site.	It is a learning point that the design of future devices is improved to ensure that they can be offloaded more efficiently even in inclement weather. An improved solution would be for the manufacturer to supply the EDGE-FCLi and its associated protective enclosure as a single unit under one contract, or to install the device indoors therefore avoiding issues with the external environment.
Commissioning	The 11kV cables were not able to be pressure tested (using the VLF test kit) with the cables terminated in the EDGE-FCLi HV cable box.	The 11kV cable terminations at the EDGE-FCLi were disconnected to allow the pressure test to take place. It was carried out like this on the manufacturer's request, to avoid any damage to the internal power electronic circuitry.
Commissioning	During the commissioning, the project team gained a deeper insight into how Control Engineers manage alarms in the Network Management System (NMS).	The Control Engineers have two main alarm screens. The primary screen "CAD" displays all alarms that are set to be 'acknowledgeable' i.e., the engineer has to manually accept the alarm remove it from the CAD. The CAD is typically used for high priority alarms that require control actions. The second screen is the "HAD" and displays manual or auto-acknowledged alarms. It is used as an event viewer. Auto-acknowledge alarms are typically low priority alarms that go straight to the HAD to avoid large numbers of alarms being presented to the engineer at any one time.
Commissioning	During the final stages of the commissioning, it was observed that the IDLE and RECOVERY commands were reversed in the HMI panel wiring. This was quickly resolved during the end-to-end signal testing and subsequent device energisation	It is critical that end-to-end signal testing is carried out for all innovation equipment to ensure that the analogues and binaries are correctly linked back to the NMS.
Commissioning	During the first energisation of the device, it was noted by the network specialist that the EDGE-FCLi LV supply is fed from the auxiliary transformer on GT1. If there is maintenance on GT1, the substation auxiliary supply will be manually swapped onto GT2, possibly causing a temporary loss of supply to the EDGE-FCLi. This will cause the FCLi to shut down.	This issue was recorded during the commissioning activites, and it is recommended to place a note on the auxiliary supply switch that a site operative is to bypass the EDGE-FCLi if the LV auxiliary supply is being switched across to the GT2 auxiliary transformer.

Trial	The EDGE-FCLi tripped itself off the network in response to a BIT Trip failure “BIT Trip 1” that occurred on 19 May 2021.	BIT Trip 1 was erroneously triggered as the load current setting for BIT activation was set too low and noise in the measurements caused the BIT protection to operate when it should have been blocked. GridON carried out an investigation and updated the control system software to resolve the issue. In the future it would be recommended to revisit the BIT design so that the system takes multiple load current measurements and averages the results, rather than taking a single load current measurement that is susceptible to signal noise. Further detail on the BIT Trip 1 issue can be found in the EDGE-FCLi Performance report and the April 2021 – September 2021 six monthly report.
Trial	During the software update to fix the BIT Trip 1 trigger current level, the air intake filters on the EDGE-FCLi were removed. It was found that the filters were heavily saturated with dust.	The filters should be replaced on the EDGE-FCLi regularly to avoid the build-up of dust and debris and therefore a reduction in air flow through the cooling system. The maintenance intervals for filter replacement are specified in the EDGE-FCLi Installation and Maintenance policy.
Trial	The EDGE-FCLi tripped itself off the network in response to another BIT Trip failure “BIT Trip 2” that occurred on 28 July 2021.	GridON carried out a detailed investigation into the cause of the second BIT trip failure. The investigation found a metal filing lodged between two digital output pins on the EDGE-FCLi Master Control Unit (MCU) PCB board. This was found to be the root cause of the BIT trip failure. Further detail on the BIT Trip 2 issue can be found in the EDGE-FCLi Performance report and the April 2021 – September 2021 six monthly report.
Trial	Telecontrol modifications had to be made due to feedback from control engineers through the trial period.	The telecontrol design was significantly simplified from the original design based on the control engineer feedback. The IDLE and RECOVERY commands were relabelled as IN and OUT respectively. This aligns with the way existing protection equipment is configured in the NMS. The learning point would be to engage with the control engineers in the detailed design phase. In that way, there is greater visibility of the telecontrol aspects earlier in the project delivery and this will reduce the likelihood of changes to the telecontrol configuration after device energisation. Further detail on the telecontrol changes can be found in the October 2021 – March 2022 six monthly report.

10. The Outcomes of the Project

The main outcomes of the project are:

- The successful design, development and testing of an EDGE-FCLi, a novel prototype solid-state fault current limiter. The device has been developed from TRL4 “Bench Scale Research” to TRL6 “Large Scale Deployment to a commercial scale device” as per the original aims of the project.
- The selection of the University of Warwick 33/11kV primary substation as an optimal location for the installation of the EDGE-FCLi. The EDGE-FCLi was connected in series with the university’s three existing 1.4MW CHP generators fed directly onto the 11kV primary busbar.
- The successful installation, commissioning, energisation, and trial of the EDGE-FCLi on the 11kV network at the trial site.
- The production of policy documentation that capture how to operate, control, inspect and maintain the EDGE-FCLi:
    - STANDARD TECHNIQUE: OC1Z Operation and Control of GridON 11kV Embedded Distributed Generation Electronic Fault Current Limiting Interrupter (EDGE-FCLi)
    - STANDARD TECHNIQUE: SP2CAE Inspection and Maintenance of GridON 11kV Embedded Distributed Generation Electronic Fault Current Limiting Interrupter (EDGE-FCLi)
- The dissemination of learning from the project through regular six-monthly reports and several presentations to the electricity distribution industry. Refer to Table 10-1 and Table 10-2 for a respective summary list of all six-monthly reports and industry presentations given for the EDGE-FCLi.
- The production of an EDGE-FCLi Performance report that summarises the performance of the EDGE-FCLi through the testing and trial phases of the project.
- The production of this closedown report to summarise and capture the learning items generated throughout the project along with all associated closedown activities.

Table 10-1 Six monthly reports

Six Monthly Report	Date of Issue
Oct 2018 – Mar 2019	12 April 2019
Apr 2019 – Sep 2019	07 October 2019
Oct 2019 – Mar 2020	17 April 2020
Apr 2020 – Sep 2020	02 November 2020
Oct 2020 – Mar 2021	13 April 2021

Apr 2021 – Sep 2021	24 September 2021
Oct 2021 – Mar 2022	14 March 2022

Table 10-2 Project dissemination

Event	Date	WPD PM	Location
Energy Networks Innovation Conference 2021	12 October 2021	D Hardman	Virtual
Energy Networks Innovation Conference 2020	8 December 2020	D. Hardman	Virtual
Low Carbon Network Fund Conference	16 October 2018	F. Chanda	Telford, UK
Electricity Innovation Forum on New Technology and Commercial Evolution, ENA	28 September 2018	F. Chanda	London, UK

11. Data Access Details

No additional data beyond the documentation referenced in this report has been gathered during this project.

Reference is made to our Energy Data Hub, which is our central data store for easy access to all of the existing data that WPD currently share with the industry, regulator and customers.

Detailed network plans are also available via our Data Portal.

12. Foreground IPR

Default IPR arrangements apply to the project. There has been no foreground IPR created in this project. However, a complete list of all background IPR from all project partners was compiled at the beginning of the project. GridON entered this project with two relevant background IPR patent applications:

1. Patent application “DC Power Supply Arrangement” - filed on 24 January 2017
2. Patent application “AC Switching Arrangement” - filed on 21 March 2017

13. Planned Implementation

The project has demonstrated the successful design, development, and trial of the EDGE-FCLi, a novel prototype solid-state fault current limiter. The device has been developed from TRL4 “Bench Scale Research” to TRL6 “Large Scale Deployment to a commercial scale device” as per the original aims of the project. Nevertheless, there are design and operational learning points that should be addressed before a wider deployment of the technology, and these are summarised in Table 9-1 in Section 9.

The EDGE-FCLi is now a device that can be used as an alternative method for DNOs to connect generation at fault level constrained sites without having to use expensive traditional reinforcement. The deployment of the EDGE-FCLi at new locations on the 11kV network, however, should be carefully analysed with reference to the learning points captured in this document; the specific customer and site requirements that will differ from the trial site in this project; and any future learning or data generated by the ongoing monitoring of the EDGE-FCLi installed at the UoW trial site.

Whilst the EDGE-FCLi has shown good technical performance in the testing phases, there were instances where it had to be disconnected from the UoW 11kV network for significant periods of time due to technical difficulties with elements of the EDGE-FCLi control system as described in Section 6.3. These issues have now been resolved; however, they have led to a lack of uninterrupted operation and the device has yet to experience a real-world network fault. It would be prudent to monitor the device at UoW for a further nominal time period (e.g., 12 months) before beginning to consider the EDGE-FCLi as an BaU alternative. This monitoring period will allow additional data to be gathered on the reliability and availability of the unit in the field, and the validity of inspection and maintenance intervals. Furthermore, it will give suitable additional time to witness the device operating for a real-world network fault. A further appraisal of the EDGE-FCLi can then be made after the monitoring period has concluded.

14. Contact

Further details on this project can be made available from the following points of contact:

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Glossary

Acronym	Definition
AC	Alternating Current
BaU	Business as Usual
BIT	Built In Test
CHP	Combined Heat and Power
COVID	Coronavirus disease 2019
DC	Direct Current
DG	Distributed Generation
EDGE	Embedded Distributed Generation Electronic Fault Current Limiting interrupter
FAT	Factory Acceptance Testing
GB	Great Britain
GRP	Glass Reinforced Plastic
HV	High Voltage
IGBT	Insulated Gate Bipolar Transistor
KEMA	Keuring van Elektrotechnische Materialen te Arnhem
LDPT	Long Duration Performance Test
LI	Lightning Impulse
LVAC	Low Voltage Alternating Current
MCU	Micro Controller Unit
NIA	Network Innovation Allowance
PEA	Project Eligibility Assessment
RMS	Root Mean Square
UKPN	UK Power Networks
WPD	Western Power Distribution

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