WPD INNOVATION

Transforming the electricity network

EDGE-FCLi

Performance Report

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Western Power Distribution 2022

Contents

1. Introduction

The Embedded Distributed Generation Electronic Fault Current Limiting interrupter (EDGE-FCLi) project is funded through Ofgem's Network Innovation Allowance (NIA). EDGE-FCLi was registered in September 2018 and is now in the closedown phase.

The EDGE-FCLi is a prototype solid-state fault current limiter that has been developed to a commercial scale device. The device is manufactured by GridON, Israel and is designed to connect in series with Distributed Generators (DG) on the 11kV network with a maximum 6.2MVA rated output. The device can quickly disconnect the generation from the network upon detection of a fault condition. The EDGE-FCLi is able to limit the fault current contribution from DG and therefore 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 has been delivered collaboratively between Wester 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).

This report summarises the performance of the EDGE-FCLi through the testing and trial phases of the project.

2. Design

2.1. Overview

The EDGE-FCLi installed at the University of Warwick (UoW) primary substation has been designed and manufactured by GridON. The device is a three phase 11kV power electronic fault interrupting device that is designed to operate in series with distributed generators up to 6.2MVA in size. Figure 2-1 shows a simplified diagram of a generic EDGE-FCLi connection to the 11kV distribution network.

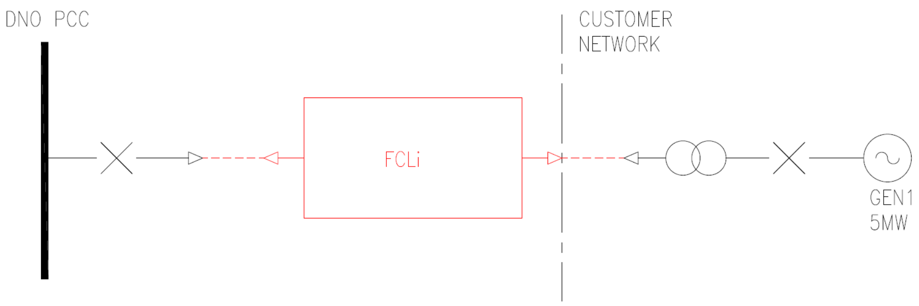


Figure 2-1 Generic EDGE-FCLi connection to the distribution network

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 (approx. 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).

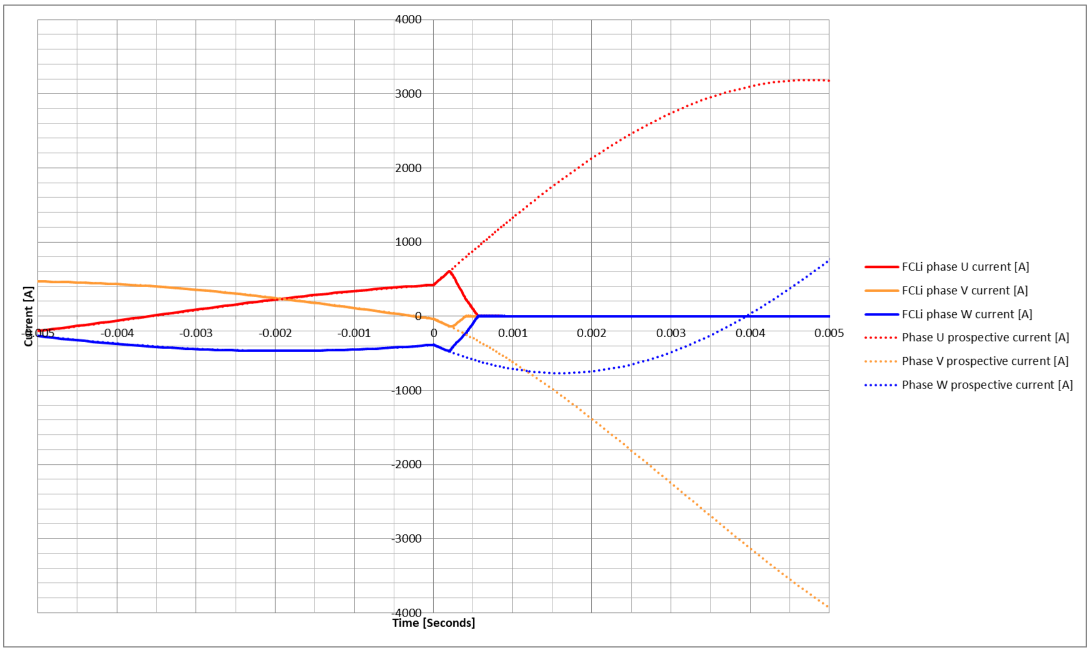


Figure 2-2 Graph of EDGE-FCLi interrupting short circuit current (3-phase fault)

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.

2.3. General Arrangement

The EDGE-FCLi has three separate phase cabinets (one per phase) shown in Figure 2-3. These contain the power electronic modules and all associated busbar interconnections between the power electronic modules and the HV cable bushings.

Figure 2-4 shows the LV cubicle, adjacent to the 11kV termination box, which houses the EDGE-FCLi's main fault detection and control circuitry as well as the AC and DC power distribution equipment to the various subsystems in the device. The cubicle also includes the LVAC auxiliary supply and multicore terminal blocks for the connection to the WPD interface.

The cable (termination) box houses the 11kV cable terminations as well as the Rogowski coils and measurement CTs that are used as transducer inputs for the in-built EDGE-FCLi fault detection and control circuitry.

Cooling system exhaust ducts are located at the top of the device. These take the hot air from the power electronic modules and direct it to the outside environment. The exhaust ducts also allow venting of high-pressure gases in the highly unlikely event of a catastrophic failure of the EDGE-FCLi.

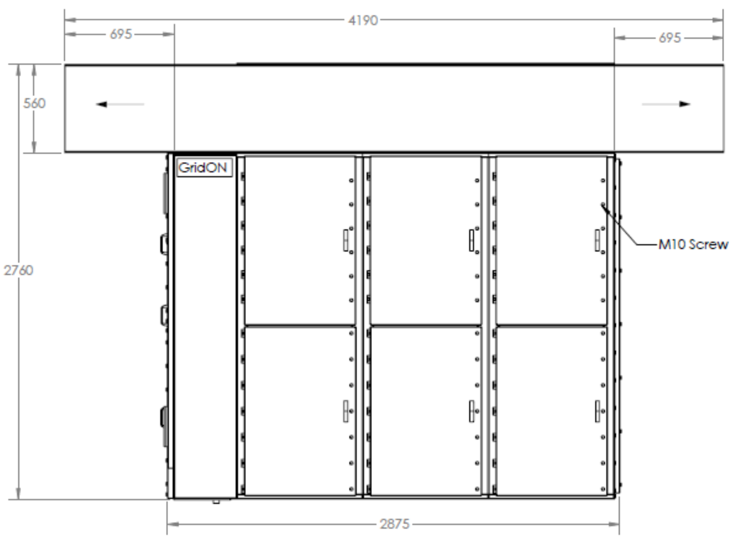


Figure 2-3 General arrangement of EDGE-FCLi (front view)

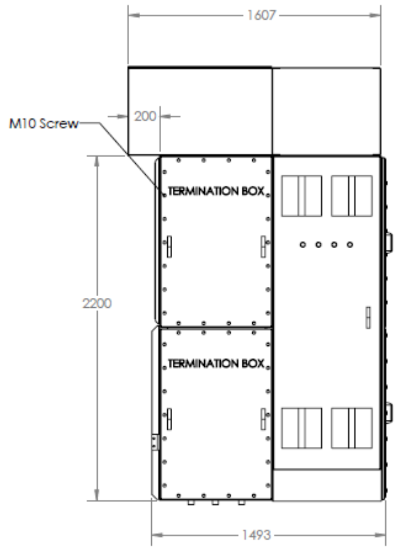


Figure 2-4 General arrangement of EDGE-FCLi (left hand side view)

The EDGE-FCLi is designed to be located indoors or within a GRP housing to protect it from the external environment. Figure 2-5 shows the GRP housing used for the EDGE-FCLi at the University of Warwick 33/11kV substation. For an indoor installation, the device would need to be installed in a purpose-built outhouse or room within the primary substation that can be locked off to avoid unauthorised personnel access.

Figure 2-5 EDGE-FCLi GRP housing at UoW 33/11kV substation

2.4. Network Connection

The trial site for the installation of the EDGE-FCLi was the 33/11kV University of Warwick (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 has been installed to provide control, protection and by-passing of the EDGE-FCLi. Figure 2-6 below shows the single line diagram of the connection with the new equipment shown in red.

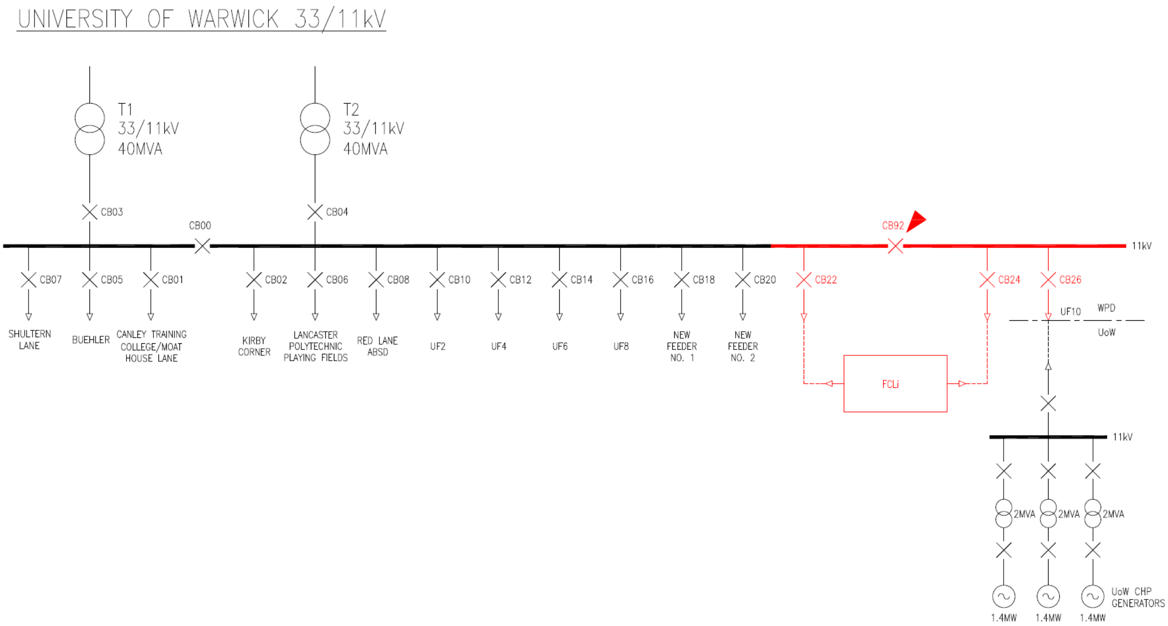


Figure 2-6 Final single line diagram of 33/11kV UoW substation

The bus section circuit breaker CB92 was included in the design to allow the EDGE-FCLi to be bypassed and keep the customer 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 is prudent for the innovation trial. However, at locations where the fault level is a concern, the use of a bypass circuit breaker should be reviewed.

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.

3. Testing

3.1. Overview

The EDGE-FCLi was rigorously tested to ensure that it was safe to connect to the 11kV network. The device underwent factory testing at GridON's facilities in Israel, followed by short circuit testing at the KEMA third party laboratories in Prague, Czech Republic. Finally, a long duration performance test, or 'soak test' was performed with the device installed at its final location at the trial site. The following sections describe each testing stage in further detail.

3.2. Factory Acceptance Testing

The FCLi underwent FAT between 26 May 2020 and 1 June 2020 at GridON's testing facilities in Israel. The FCLi successfully passed the FAT according to the approved test specification. Figure 3-1 shows the FCLi device during the tests in the factory and Figure 3-2 shows the device being packed for onward shipment to the KEMA laboratory in Prague, Czech Republic for the Short Circuit Testing.

Figure 3-1 FCLi during FAT test in Israel

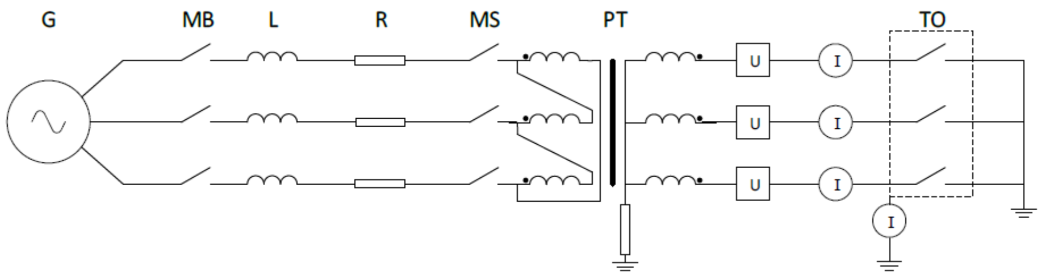
Figure 3-2 FCLi being packed after successful FAT

The FAT was witnessed remotely over video conference due to the COVID-19 pandemic. This proved to be an effective way of progressing the project programme under the severe restrictions on international travel.

The FCLi performed well during the FAT. Most notably, the device passed the 95kV Lightning Impulse (LI) tests as well as the temperature rise test. It was observed that the forced air-cooling system was able to keep the Insulated-gate Bipolar Transistor (IGBT) heat sink temperatures well below the maximum levels at the rated load current (328A).

3.3. Short Circuit Testing

The FCLi was tested at KEMA's third party laboratory in Prague, Czech Republic. To perform the testing, the device was placed in series with one of their generator sets as shown in Figure 3-3. The prospective (or calibration current) is set by manually adjusting the inductance and resistance in the circuit with the FCLi disconnected from the circuit. After the prospective current is set correctly, the FCLi is switched into the circuit and the test is performed.



G	= Generator	TO	= Test Object	U	= Voltage Measurement to earth
MB	= Master Breaker	L	= Reactor	I	= Current Measurement
MS	= Make Switch	R	= Resistor		
PT	= Power Transformer	C	= Capacitor		

Figure 3-3 Test circuit in place during short circuit testing at KEMA

The testing applied several different short circuit prospective/calibration currents to the device to simulate specific network fault conditions that would be expected at the trial site. These were documented in the testing specification and are briefly summarised in Table 3-1.

Table 3-1 Summary of short circuit prospective/calibration currents applied to the EDGE-FCLi

Test ID	Fault Type	Prospective Current (RMS kA)	X/R Ratio for Prospective Current	Notes
1	3-phase	0.46	14	Full asymmetry in one of the phases to be greater than 1.1kA peak. Simulates a remote fault on the network i.e., at the end of an adjacent 11kV feeder that yield low fault current infeed from the generator
2	3-phase	0.33	14	Full asymmetry in one of the phases to produce 840A peak. Simulates the worst-case transient event i.e., a prospective current just below the fault detection setting of the FCLi (the FCLi should not interrupt)
3	3-phase	2.10	14	Full asymmetry in each of the phases in turn to be greater than 5.3kA peak. Simulates a medium sized three phase fault i.e., located midway down an adjacent 11kV feeder
4	3-phase	25.0	14	Full asymmetry in one of the phases to be greater than 62.5kA peak. Simulates the maximum expected fault current i.e., a fault at the generator terminals
5	Phase-to-phase	21.7	14	Full asymmetry in one of the phases to be greater than 55.1kA peak
6	Single phase-to-ground	1.00	14	Maximum asymmetry in the tested phase greater than 2.54kA peak

The FCLi is configured with fault current detection settings that have been specifically chosen for the UoW site during the design phase of the project. These fault detection criteria are programmed into the FCLi by default.

As part of the test specification, WPD requested that GridON change to a different set of fault detection criteria for some of the prospective current tests to validate that the device could be reprogrammed and correctly interrupt fault current at the new setting.

Figure 3-4 shows the FCLi interrupting the 460A RMS prospective current. The current interruption can be seen in the green line. Figure 3-5 shows the FCLi interrupting the 460A RMS prospective current with the non-default setting. The current interruption can also be seen in the green line. Throughout the testing the FCLi correctly interrupted the short circuit current at both fault detection settings.

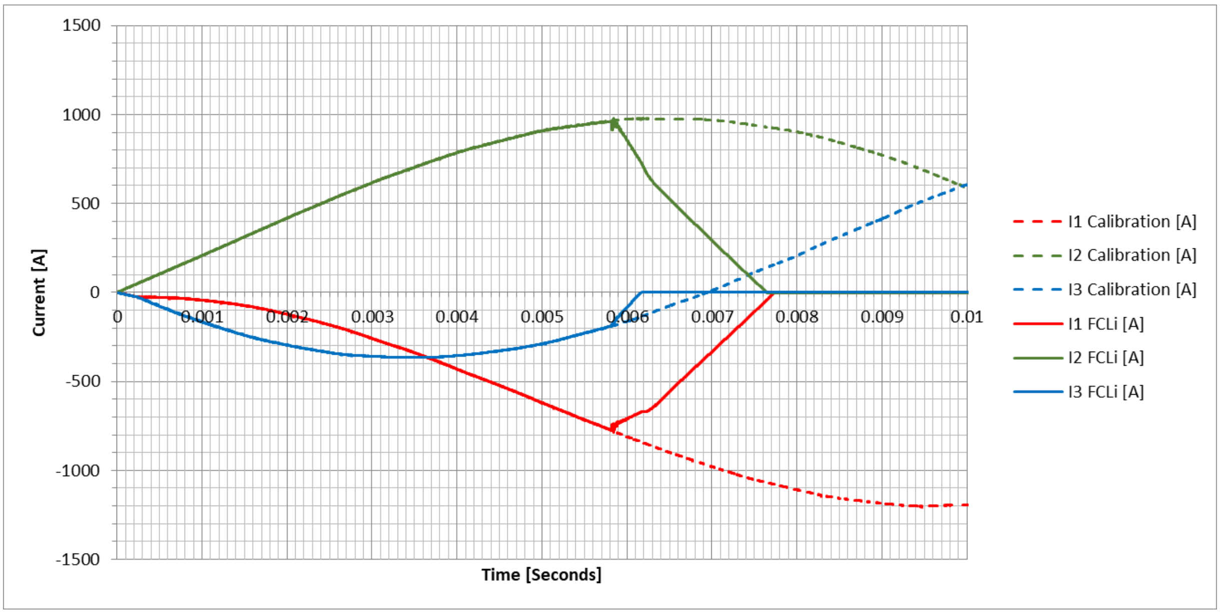


Figure 3-4 3ph 460A RMS prospective current – detection thresholds setting 1

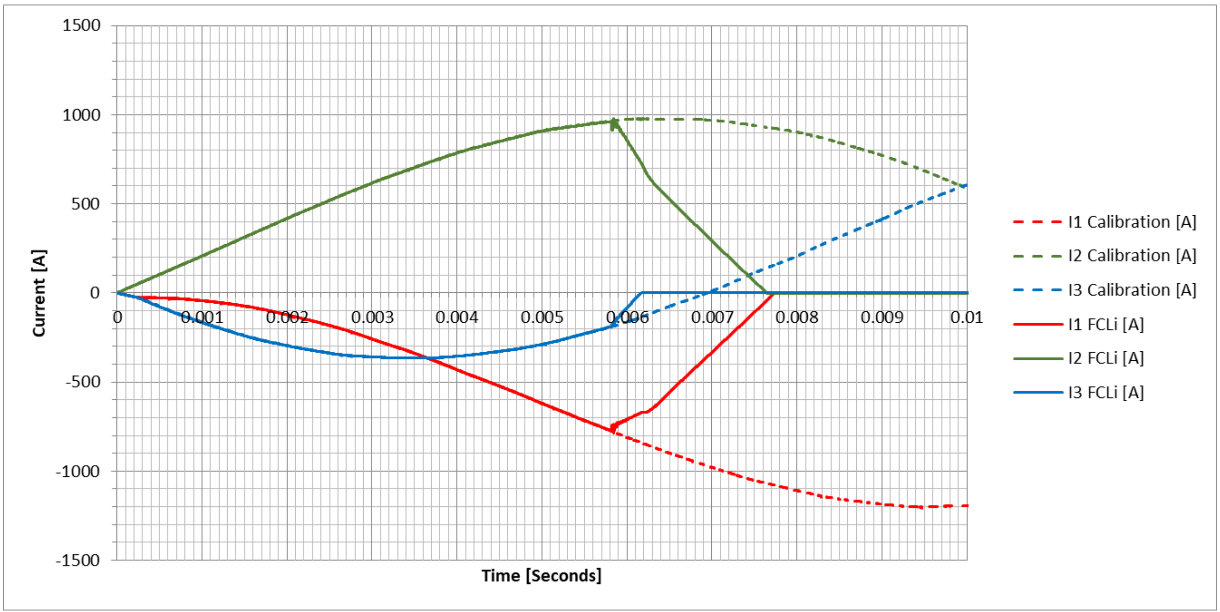


Figure 3-5 3ph 460A RMS prospective current – detection thresholds setting 2

The FCLi operates very rapidly under very close-in faults i.e., a fault at the generator terminals. Figure 3-6 shows the device undergoing a 25kA RMS prospective current test. The device operated in less than 200µs from the initiation of the short circuit current.

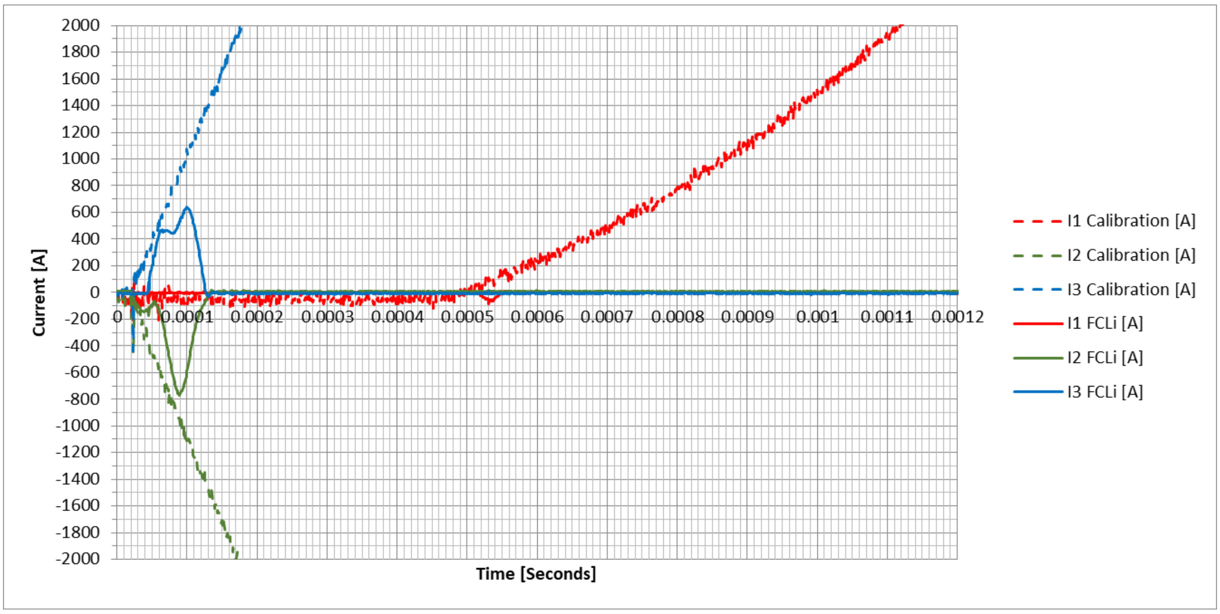


Figure 3-6 3ph 25kA RMS prospective current – detection thresholds setting 1 (zoomed in on x-axis)

The device behaved correctly for all simulated fault conditions, including those that simulate remote faults (i.e., a lower prospective current applied to the device). The device also interrupted the prospective short circuit currents before the first peak of the waveform in all relevant tests.

The device also successfully suppressed the overvoltages induced during the short circuit current interruption. The largest overvoltage was observed during the 460A RMS prospective current test and was limited to approximately 24kV. Figure 3-7 shows the current and voltage waveform recordings for the 460A RMS test. The figure shows the overvoltage reaching its maximum value in phase L2 (U2).

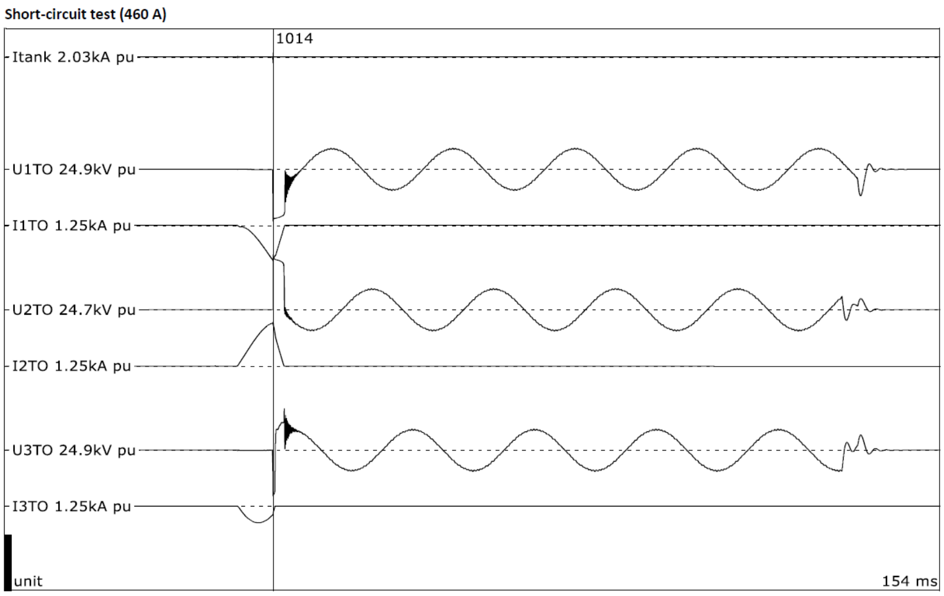


Figure 3-7 3ph 460A RMS prospective current – V, I waveforms – detection thresholds setting 1

3.4. Long duration performance test

The LDPT was the last stage of testing prior to connection of the FCLi in series with the 11kV generator at UoW. The design of the LDPT involved connecting the FCLi to the UoW substation local LVAC supply and driving a current (approx. 35A) through the device using a programmable three phase load bank for a duration of four calendar weeks. A simplified schematic diagram of the LDPT test circuit is shown in Figure 3-8. The aim of the test was to complement the testing carried out during the FAT and to ensure that the device can carry load current for extended periods of time without failure or nuisance tripping.

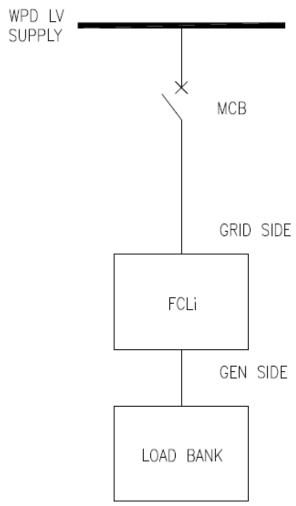


Figure 3-8 Simplified schematic of LDPT test circuit

The LDPT was initiated on the 15 February 2021 and ran for four calendar weeks, concluding on the 15 March 2021. The FCLi successfully passed the test, operating as expected for the duration of the test with no causes for concern. A thorough examination of the device and the associated GRP enclosure was carried out immediately after disconnection from the LVAC supply. No observations were raised as part of this inspection, which meant that preparations could immediately begin for the final connection to the 11kV network.

4. Field Trial

4.1. Overview

The EDGE-FCLi was successfully energised on the 11kV network at the UoW 33/11kV primary substation on 13 May 2021. We were able to energise the EDGE-FCLi without an outage on the UoW CHP generator by utilising the bypass circuit breaker (CB92) across the device. Although this option was available, we liaised closely with the UoW energy centre to communicate the energisation schedule to ensure that there was minimum disruption to their activities.

Unfortunately, the EDGE-FCLi experienced several unplanned outages during the field trial. The following sections describe the main issues and learning points that were recorded from the trial at UoW.

4.2. Built In Test

The Built in Test (BIT) mechanism is a protective feature of the EDGE-FCLi that momentarily interrupts the phase currents in a regular cycle to test that the power electronics modules are still functioning correctly. The BIT is performed automatically during normal operation of the device and is designed to trip the device only when it has detected a faulty power electronic module. However, during the trial the BIT function caused two spurious trip events, and these are described in the following sections.

4.2.1. Built in Test Trip 1

The EDGE-FCLi disconnected itself from the network on 19 May 2021, approximately six days after the initial energisation. After the initial investigation on the cause of the trip event, it was found the device tripped due to the BIT functionality incorrectly interpreting that there had been a power electronics failure within phase 3 of the unit. The reason for the BIT failure and trip was that the BIT protection function was triggered incorrectly when there was insufficient phase current magnitude to the specified requirement. The current was in the range of 25A when it is required to be in the range of 40A as per the design. This failure was attributed to noise in the transducer measurement system under field trial conditions. This also explains why this condition was not observed in the factory testing prior to the installation at the UoW site.

To resolve this issue the software was modified to raise the phase current threshold at which the BIT function is triggered to above 40A to avoid the impact of noise on the triggering logic. After a period of software implementation and verification by the manufacturer, the software was successfully uploaded to the device and the EDGE-FCLi was reconnected to the grid on 19 July 2021.

4.2.2. Built In Test Trip 2

The EDGE-FCLi was successfully reconnected following the software modification described in Section 4.2. However, the device only continued to operate for nine days until a further trip event occurred on 28 July 2021. After an initial investigation it was again observed that the device tripped due to a failure of the BIT protection function. The EDGE-FCLi control system logs various parameters in its internal memory and these log files were issued to the manufacturer to undergo a more detailed investigation into the cause of the error. While this investigation was ongoing the EDGE-FCLi was left disconnected from the 11kV network, and the site was restored to its normal configuration.

The manufacturer carried out an analysis of the detailed log files and reported that, in the lead up to the error, the EDGE-FCLi successfully passed several BIT initiations; however, the timing duration of a BIT triggered on phase 2 of the device was much smaller than the nominal duration programmed into the software. This then caused the second trip as described above. Subsequently, the manufacturer has carried out extensive testing and simulations in their laboratory to try and replicate the fault. However, none of the investigations yielded any root cause.

The last step was to send the EDGE-FCLi Micro Controller Unit (MCU) printed circuit board back to the GridON factory for detailed inspection. Following receipt of the unit in Israel, GridON carried out an extensive inspection of the printed circuit board and found two metal filings lodged on the MCU electronics were the source of the BIT fault. These are shown in Figure 4-1 and Figure 4-2 respectively. The first filing was found to have no impact on the control system operation. However, the second filing (shown in Figure 4-2) broached two signal pins on the printed circuit board and analysis showed that this caused a resistive coupling between the two pins, spuriously triggering the BIT function and causing the issue at the site. It is important to note that the issues experienced in the live trial were isolated to the BIT function only, and there were no indications that the fault current limiting capability of the device was affected.

The investigation highlighted that the BIT protection system had been configured to be over-sensitive to possible internal power electronic faults. This was the result of a conservative approach taken during the design phase due to the innovative nature of the unit.

There is important learning generated from these series of events. In particular, the BIT protection functionality design should be reviewed in detail prior to the decision to move ahead with the BaU adoption of the EDGE-FCLi. An initial suggestion on any updated design would be that if there is a failure of a BIT test, subsequent tests are carried out to confirm that the failure is indeed a problem with the power electronics and not a spurious timing or measurement transducer anomaly. This would likely greatly reduce the likelihood of the EDGE-FCLi, and the associated generating customer being disconnected from the network unnecessarily.

Figure 4-1 Image showing metal filing no. 1

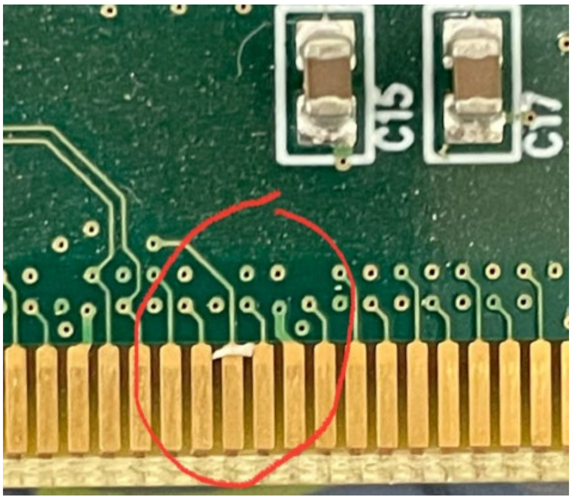


Figure 4-2 Image showing metal filing no. 2

After the investigation was concluded, GridON proposed two additional minor updates to the control system software to improve the operation and diagnostic capabilities of the device. The first software change relaxed some of the pre-qualification timing settings for certain trip conditions. This had the effect of making the device slightly less sensitive to reduce the future likelihood of spurious trip events. Secondly, GridON made some modifications into the way the device logged its internal diagnostic information. The project team confirmed that all changes were suitably tested in GridON's factory prior to the updates being made at the trial site.

The investigatory works and the updates to the software, including the adequate testing and validation took a significant amount of time after the second BIT trip. GridON attended a site visit at UoW on 22 November 2021 to install and configure the remedial works to allow the device to be reconnected. In addition to the updates described above, GridON performed routine maintenance on the device as per their operation and maintenance manual. This included a full visual inspection of the internal phase compartments, low voltage cubicle and HV cable termination cubicle. The filters locating in the air intake ducts on the external GRP housing were also replaced by the GridON team.

The device, however, was not reconnected during this time due to a telecontrol system review that was taking place in parallel. This is discussed in detail in Section 4.5 below.

4.3. Generator circuit breaker tripping

If the EDGE-FCLi detects a network fault, experiences a device malfunction, or loses its auxiliary LV supply, the unit disconnects itself from the network by tripping its feeding circuit breakers (CB22, CB24) and CB26 that supplies the CHP generators at UoW. Figure 2-6 shows the final single line diagram of the UoW site and indicates in red the new 11kV circuit breakers added to the existing switchboard to integrate the EDGE-FCLi.

When the project team was carrying out the remedial works discussed in Section 4.3, it was observed that the automatic tripping of CB26 was an unnecessary action, especially when cycling the LV auxiliary supply to the EDGE-FCLi during testing and commissioning activities. There is a risk that the CHP generators can be accidentally disconnected unnecessarily leading to a customer outage. After a review of the protection scheme, the tripping of CB26 did not serve any identifiable technical purpose and therefore the decision was made to remove the associated trip links from the circuit breaker trip circuit.

4.4. Telecontrol

An important aspect of the learning from the trial is related to the telecontrol configuration used on the EDGE-FCLi. The control engineers responsible for operating the device remotely communicated feedback to the project team on improvements that could be made to this interface.

The control engineers' main concern was that the "IDLE" and "RECOVERY" mode labelling on the control screens was significantly different to traditional network equipment, which could cause some misunderstanding when trying to operate the device remotely. To improve the telecontrol functionality, a set of simplified operational flow charts were produced based on the existing EDGE-FCLi's operational modes. These flow charts were then shared and refined based on the feedback received from control. The EDGE-FCLi has two main operational modes that can be executed from the control centre. The first is "RECOVERY" mode, which closes the IGBT switches in the device, making it ready to be energised at 11kV. The second original telecontrol was the "IDLE" mode, which opens the IGBT switches in the device and puts the device into a 'sleep' state. We have now redefined these modes as "ON" and "OFF" respectively, to make it clearer and simpler for the control engineers to interpret the function of the modes.

Figure 4-3 and Figure 4-4 below show examples of the simplified control flowcharts that were used to guide the redefinition of the operational modes.

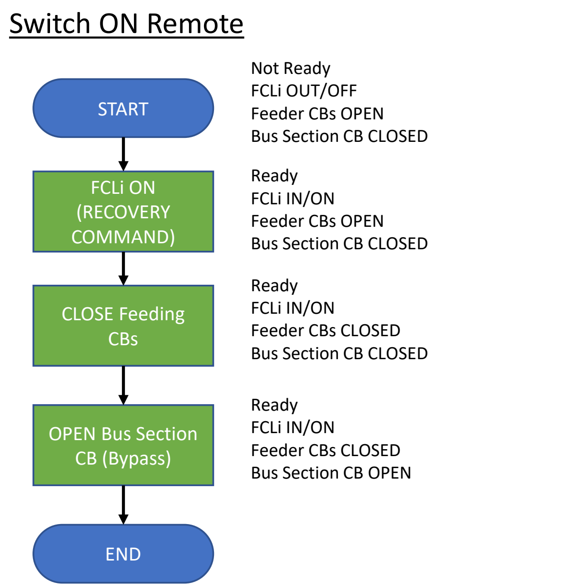


Figure 4-3 EDGE-FCLi remote switch on flowchart

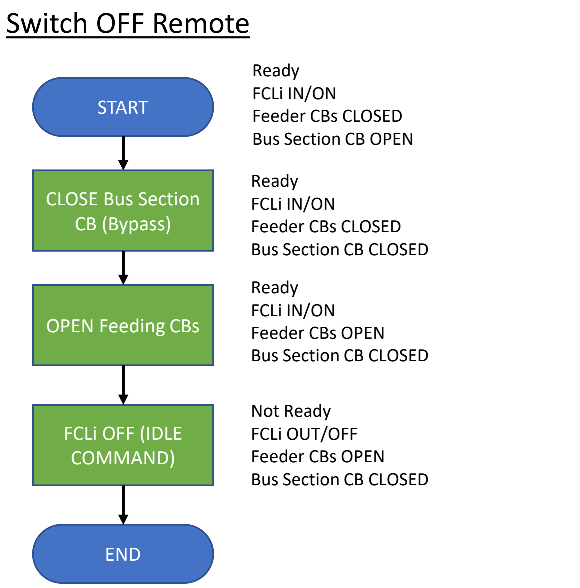


Figure 4-4 EDGE-FCLi remote switch off flowchart

4.5. Energisation and reconnection

The project team tested the telecontrol modifications and successfully reconnected the device to the 11kV network on 17 March 2022. The device has been in continuous operation for just under a month and the software modifications have been working correctly, carrying out successful BIT operations since the reconnection. In the time the device has been connected there have been no network faults that have caused the EDGE-FCLi to operate. It is proposed to keep the device energised after the project closedown, so that the EDGE-FCLi can operate for any network faults that occur in the future. The response and behaviour of the EDGE-FCLi to a real-world network fault will be captured, analysed and reported on accordingly.

5. Conclusions

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 live network at the UoW and therefore the fault detection and limiting performance of the device in the field is yet to be proven.

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 the LDPT or 'soak test' prior to energisation at 11kV and also in the temperature rise test. However, the device has only been connected in series with the generators at UoW for a short duration over the field trial. The forced air-cooling system that uses a bank of fans to push air through the IGBT heatsinks and exhaust the hot air out of the GRP enclosure performed as per the GridON design document and had a suitable safety margin to avoid the IGBT temperatures from exceeding their thermal limitation. It was observed that the air intake filters on the EDGE-FCLi were heavily polluted with dust and debris during a planned maintenance activity carried out by GridON as part of the work to resolve the BIT failures. It is recommended that the filters are regularly cleaned/replaced as per the installation and maintenance policy document to avoid cooling system derating for prolonged periods of operation.

There were some concerns during the design phase that the lack of environmental management (i.e., air conditioning) inside the GRP housing would lead to unsuitably humid conditions for the internal electronics enclosed in the EDGE-FCLi LV cabinet, especially in the winter months. Furthermore, the EDGE-FCLi was left unenergised for long periods of time during the trial and there were also additional concerns that a lack of air flow through the device coupled with the rudimentary space heaters in the GRP would exacerbate this issue. However, the project team have not observed any problems derived from the ambient conditions in the GRP housing over the duration of the trial period. It is advisable, however, to closely monitor the EDGE-FCLi for spurious alarms during the colder winter months and schedule regular visual inspections as per the installation and maintenance policy document.

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. Therefore, the performance analysis in this document needs to be taken in this context. The BIT mechanism was tested in the factory acceptance tests carried out in GridON's facilities. However, these tests were unable to identify the initial BIT issue (Section 4.2.1) because the factory tests were carried out in a controlled environment with very low noise on the supply circuits. The subsequent investigation into the BIT mechanism found that GridON were triggering the BIT function when a single load current measurement when above a pre-defined threshold, which is highly susceptible to signal noise interference. A more suitable solution would be to take multiple readings of the load current and average them to reduce the impact of noise. This, however, could not be achieved without significant modifications to the control hardware and software, so a simple workaround of raising the load current trigger threshold was implemented. Whilst this workaround was successfully implemented and tested in the field, it is recommended that the BIT mechanism is fundamentally redesigned for any future devices that are procured.

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 aim will be to analyse the performance of the EDGE-FCLi over a longer duration with the goal of seeing the device respond to actual fault events on the 11kV network.

Glossary

Acronym	Definition
AC	Alternating Current
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
RMS	Root Mean Square
UKPN	UK Power Networks
WPD	Western Power Distribution

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