Programme Area: Energy Storage and Distribution

Project: Pre-Saturated Core Fault Current Limiter

Title: Final project report

Abstract:

Summary report, providing an overview of the project.

Context:

This project's aims were to develop and demonstrate a pre-saturated core fault current limiter device (PCFCL), to reduce the impact of faults on electricity distribution networks. The PCFCL was developed by GridON, based in Tel Aviv, Israel, and was demonstrated in service at a UK Power Networks substation in Newhaven, East Sussex.

Pre-saturated Core Fault Current Limiter Development and Demonstration Project

Project Final Report

Deliverable ST06.D03

Contents

Revision	Rev. Date	Updated by	Comments
1.0	27 Oct 2016	Uri Garbi	First version
2.0	4 Jan 2017	Uri Garbi	Second version
3.0	19 Jan 2017	Uri Garbi	Third version
4.0	24 Jan 2017	Uri Garbi	Fourth version
5.0	19 April 2017	Uri Garbi	Fifth version
6.0	15 June 2017	Uri Garbi	Sixth version
7.0	16 June 2017	Uri Garbi	Final edition

1 Executive Summary

This report summarises the Pre-saturated Core Fault Current Limiter (PCFCL) project, commissioned and funded by the Energy Technologies Institute. The main objective of this project was to define, develop and demonstrate a Fault Current Limiter based on passive saturated core technology. The system was demonstrated for over 3 years in a live network, and provided extensive experience for all the project stakeholders with this technology. GridON has developed its concept into a commercially available product, and gained extensive experience and know-how. UK Power Networks and E.ON Technology gained experience with the installed product, as well as how FCLs should be specified and integrated into the network operationally.

Over the course of the project, the ETI and all consortium members have gained detailed knowledge about the benefits and applicability of the PCFCL for distribution networks in the UK and elsewhere. As a result of the PCFCL project, GridON has a much clearer understanding of the requirements of each market segment, and the most appropriate FCL specification for the different markets (distribution, distributed generation, transmission, and industrial).

Following two years of product specification, development and test, the 11kV, 10MVA PCFCL was then operated at UK Power Networks' substation for over three years, between May 2013 and Sept 2016. The stakeholders agreed to extend the demonstration period beyond the original plan of two years, providing extensive experience in live operation. During its operational period it has not suffered unplanned downtime, or any failure to its components.

The device has seen at least 16 recorded network fault events during its operational period. Data from these events were analysed and performance was found to be in good correlation to the device performance measured under controlled laboratory test conditions, as well as to network simulation modelling. The operator's network protection system operated consistently as expected with the FCL in circuit.

The device behaved as expected during normal operating conditions. The actual loading conditions on site allowed for the FCL to be operated with reduced DC bias (DC bias is a current which is applied from DC power supplies to saturate the PCFCL iron core) and reduced losses. The FCL behaved as expected under these conditions as well. It was consequently demonstrated that future systems may include dynamic bias to minimize operating losses.

The FCL condition was monitored throughout the operational period via online dissolved gas analysis and temperature logging, as well as site inspections and laboratory oil condition tests. The thermal performance of the FCL was as expected from the design and testing.

Test results following its removal from the network confirmed that the condition of the FCL after testing and 3 years' operation remained as designed (with no material degradation or loss of performance), thus confirming its durability for its full design life which is comparable to power transformers' design life.

The project successfully demonstrated the specifications, design, manufacturing, testing, delivery, installation, commissioning and field operation of the PCFCL technology, reinforcing confidence in the product and its readiness for widespread adoption in distribution, transmission and industrial grids.

The experience gained in this project has been put to use in a subsequent project with Western Power Distribution (WPD) with an 11kV, 30MVA PCFCL installed in Birmingham, as well as through further development as part of GridON's European Commission project. The European Commission through its Horizon 2020 initiative funded a project that focuses on improving the PCFCL size, cost and performance envelope.

The project consortium worked effectively and in close cooperation throughout the project. This helped keeping execution well within the authorised schedule and budget.

2 Project overview

The project's objective was to design, develop and demonstrate the operation of a novel passive saturated core fault current limiter in a live 11kV network over a significant trial period.

The chosen location for this demonstration was UK Power Networks' primary substation in Newhaven, East Sussex. This substation (Figure 1) has three 10MVA transformers, two operating in parallel, and one is on standby. The installation of the FCL enables running all three transformers in parallel. Without the FCL this arrangement would result in fault level that exceeds the site equipment ratings.

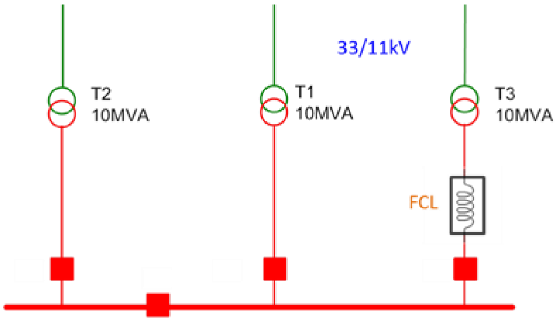


Figure 1 – Single line diagram of the substation

At the beginning of the project, GridON's technology was new, and required a proof of concept. A decision was made to design, build and fully test a 1MVA prototype, with the same current ratings as the eventual 10MVA unit, but at 1/10th of the voltage level. It was also decided that although the 1MVA unit would be designed for 1.1kV – it would still be designed to fully withstand all insulation levels as an 11kV unit.

The 1MVA unit design started in the Q4 2011. It was manufactured during Q1 2012 and underwent full factory and short circuit testing in March 2012.

The test results showed good correlation to simulations, and the unit passed all the voltage withstand tests successfully. Thermal behaviour was also demonstrated. Following the successful testing – it was decided to proceed with the design of the 10MVA unit.

Figure 2 - PCFCL installed at Newhaven substation

Significant effort was put into writing specification documents which would result in a unit that satisfies all site conditions and requirements. This work involved load flow analysis and short circuit analysis in several running arrangements. UK Power Networks also developed engineering standards for GridON FCLs for future use.

The 10MVA unit was designed and manufactured during Q2 and Q3 of 2012, and underwent full factory testing and short circuit testing at an independent third-party high power test facility during Q4 2012. All tests passed successfully and the unit was approved to be shipped to site.

The 10MVA FCL arrived in the Newhaven Town substation in March 2013, and was then commissioned and put into service in May 2013 (Figure 2, Figure 3 and Figure 4).

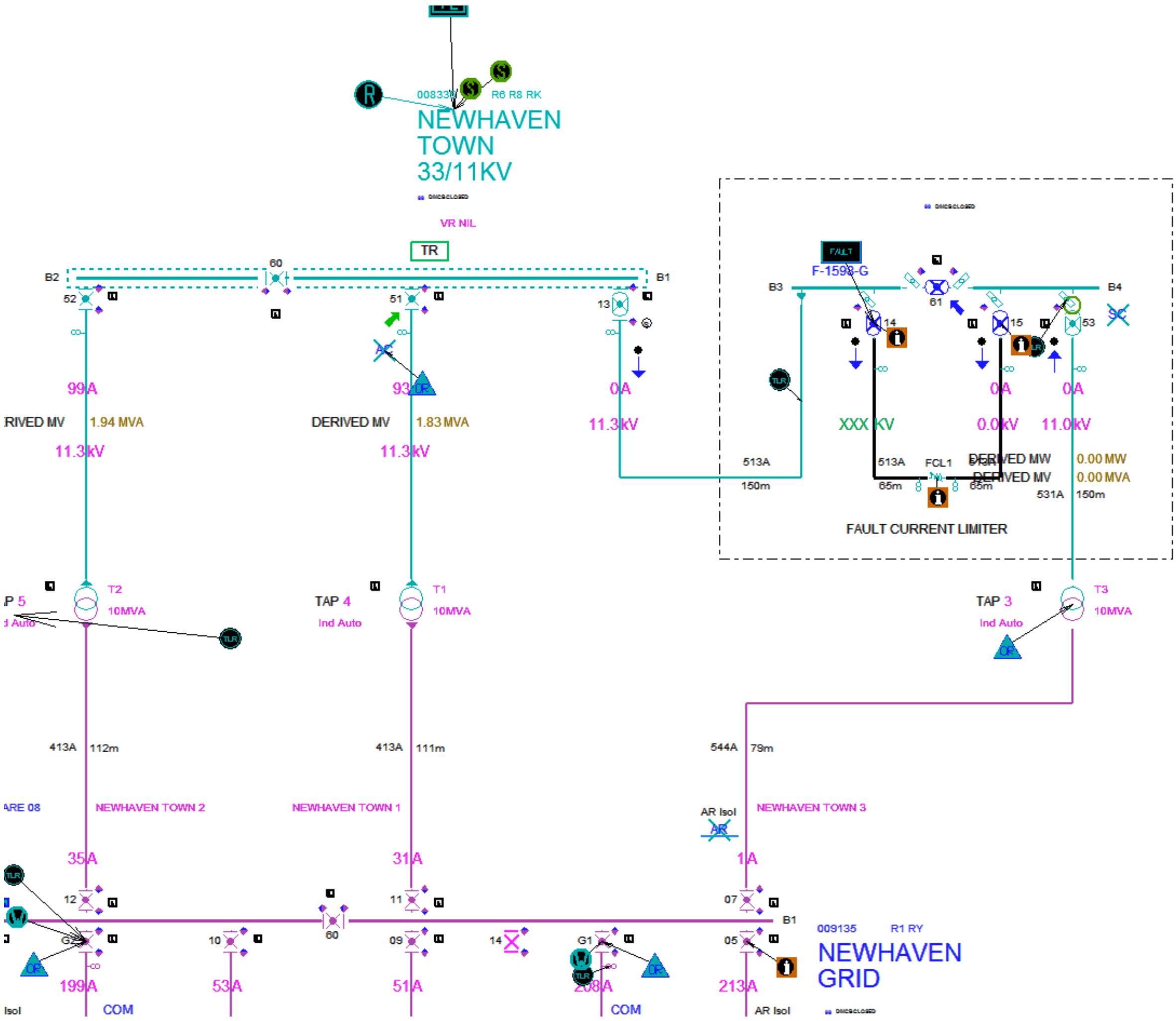


Figure 3 - Screenshot of PowerOn system with the FCL connected

The unit was in operational service in the network until Sept 2016 (40 months) until it was decommissioned, as originally planned, for post-demonstration testing. During its operational period significant amounts of normal state data were gathered, as well as data from 16 network faults, during which the FCL operated as expected.

The FCL operated reliably during the operational period, and has enabled running the substation with 3 transformers in parallel, increasing the security of supply to customers.

At the end of the operational period, the FCL was subjected to additional electrical testing and condition assessment and was found to be in excellent condition, indicating the high quality and robustness of its design and build.

As a result of the successful demonstration period, the consortium decided that finding a new home for the FCL is more desirable than scrapping it. UK Power Networks have agreed to moth-ball the unit and keep it on site until new use would be identified for it.

Figure 4 - PCFCL installed in the Newhaven Town substation

3 Principle of operation

Saturated core FCLs utilize a ferromagnetic core which is put into deep magnetic saturation. Figure 5 illustrates the constant magnetic flux used to saturate the core. DC power supplies are used to generate DC bias current which is introduced into the DC coils shown at the top and bottom of Figure 5.

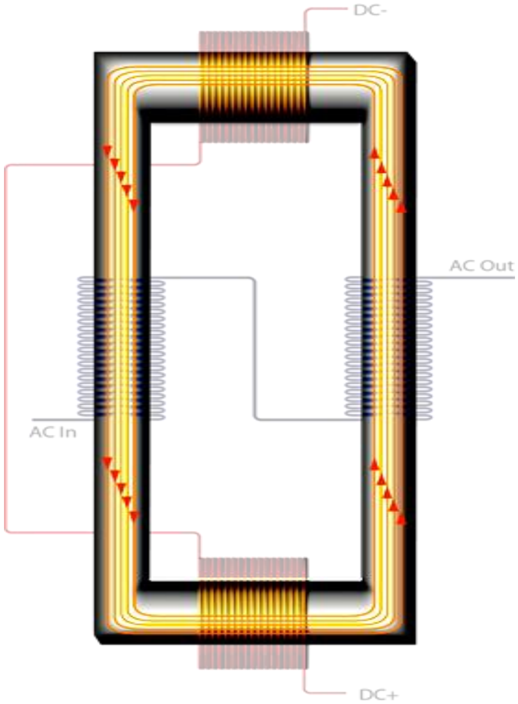


Figure 5 - Operating principle

As long as the current in the AC coils (which are series connected into the network) is within normal ratings, the core remains saturated, and the impedance of the AC coils remains low (a saturated ferromagnetic core behaves similarly to an air core). During a fault event the current in the AC coils rises significantly and generates a flux that counters the constant biasing flux. In each half cycle one leg de-saturates, and the impedance of the AC coil around that leg increases significantly and provides fault current limiting. Upon fault clearing, the AC flux reduces back to low levels, the core regains saturation, and the impedance of the FCL immediately decreases, enabling instantaneous resumption of normal load current.

4 Device characteristics

4.1 Equipment ratings and performance

Ratings for the specific FCL device for the project are shown in Table 1 below[1].

Table 1 - Equipment ratings and performance

Description	Specification
Device type	Self-triggered, failsafe, pre-saturated core fault current limiter
Fault limiting response time	1 msec
Recovery time from fault	1 msec
Service conditions	Outdoor
Standard specification	IEC 60076
Rating	10MVA
Nominal system voltage	11 kV
Highest voltage for equipment	12 kV
Rated lightning impulse withstand voltage	75 kV
Rated short duration AC withstand voltage	28 kV
Rated frequency	50 Hz
Rated continuous current	525 A
Rated overload current (3 hours)	800 A
Maximum hot spot temperature at rated continuous current at ambient temperature 40 °C	125 °C
Maximum hot spot temperature at rated overload current at ambient temperature 40 °C	140 °C
Maximum duration of short-circuit current	3 s
Maximum withstand short circuit current in absence of fault current limiter (prospective current) Maximum withstand peak short circuit current in absence of fault current limiter (prospective current)	9.3 kA rms 23.65 kA peak
Rated continuous impedance (at rated continuous current)	0.257 Ω, 2.1% at full rated current, 1.05% at half rated current

[1] GridON can manufacture FCLs to a wide range of specifications to suit specific application requirements.

Description	Specification
Overall losses at full rated load[2] Overall losses at half rated load (with optional DC-bias control)	22 kW +/-10% 6 kW +/-10%
AC auxiliary supply requirements (to feed DC power supply units for bias current)	400 VAC, 60 A, 3-phase
Auxiliary supply for FCL control cubicles	230 VAC, 16A, 1-phase
Cooling	ONAN

[2] Due to actual load conditions on site, it became possible to significantly reduce DC bias losses during the operational period by applying reduced DC bias current

4.2 Short circuit limitation performance

Table 2 below shows the FCL's current limitation performance test results from the testing carried out at an independent short-circuit test facility.

Table 2 - Short circuit current limiting performance

Short circuit type	Prospective current [A rms]	Limited current [A rms]	Fault current reduction [%]
Phase-to-earth fault	1170	953	18.6
	1530	1110	27.5
	1940	1240	36.1
	2540	1394	45.1
	2925	1476	49.5
	3785	1724	54.5
	4390	1970	55.1
	4720	2100	55.5
	5320	2180	59.0
3-phase fault	1170	959	18.0
	1500	1160	22.7
	1982	1289	35.0
	2530	1510	40.3
	2985	1582	47.0
	3790	1900	49.9
	4220	2020	52.1
	4760	2250	52.7

Current levels are AC RMS, 200msec after fault inception. These are results from tests at an independent high-power short circuit test laboratory.

Note: the FCL is designed to withstand prospective fault currents up to 9.3kA rms, 23.65kA peak, which is the upstream fault level on site.

4.3 General arrangement

Figure 6 shows the 10MVA FCL General Arrangement.

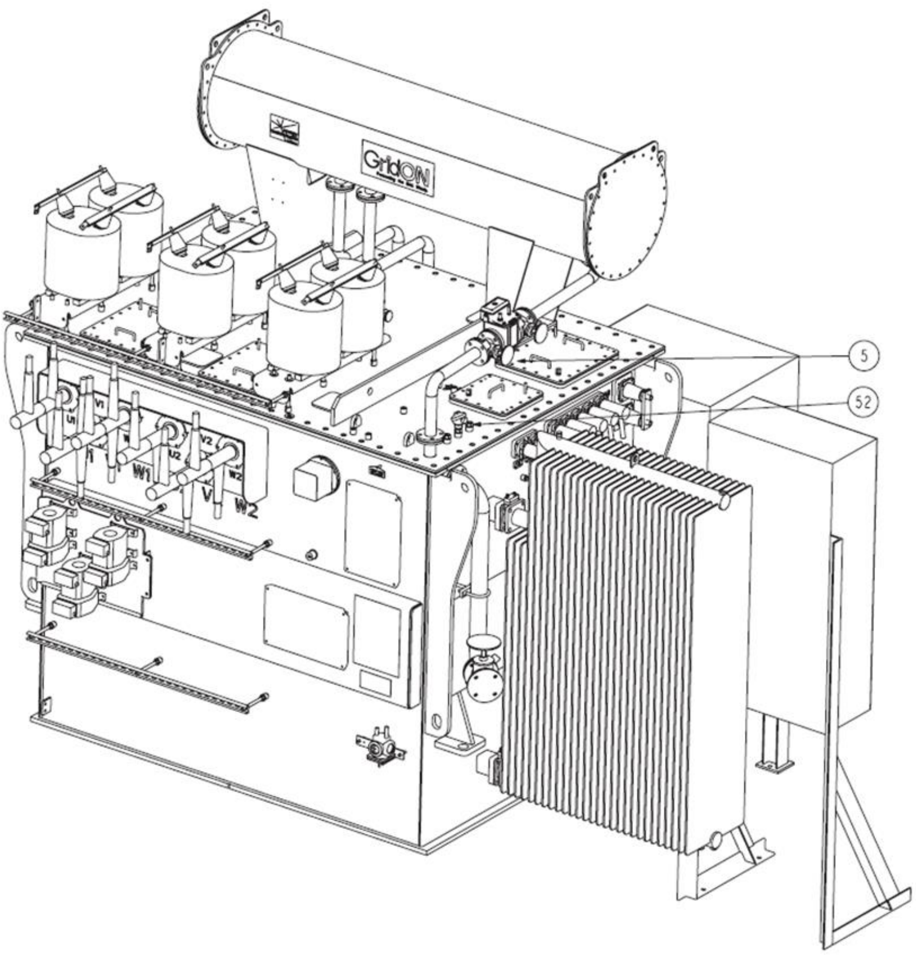


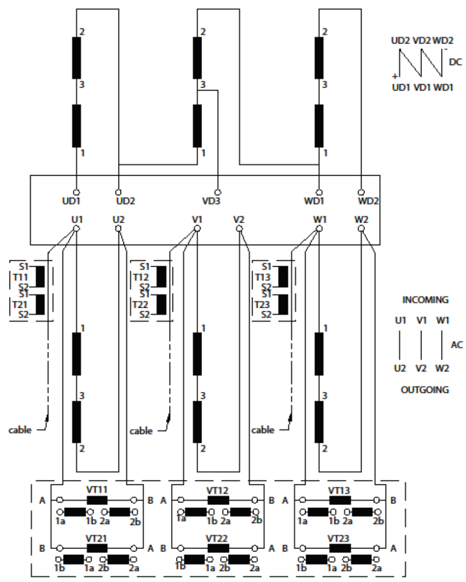
Figure 6 - General arrangement

4.4 Rating and diagram plate

Figure 7 shows the PCFCL's rating and diagram plate

GridON
Protecting the Grid Wisely

PRE-SATURATED CORE
FAULT CURRENT LIMITER
MADE IN AUSTRALIA
TO IEC 60076



COOLING TYPE		ONAN
RATED POWER MVA		10.0
RATED VOLTAGE kV	AC	11.0
	DC	-
RATED CURRENT Amp	AC	525
	DC	221
MAX TEMP RISE °C	TOP OIL	60
	AVG WDG	65
INSULATION LEVEL kV	AC	LI 75 AC 28
	DC	LI 0 AC 2
AVERAGE IMPEDANCE OHMS @ RATED CURRENT		0.257
MIN. IMPEDANCE OHMS @ RATED SHORT CIRCUIT CURRENT		1.70

FREQUENCY	Hz	50
NO OF PHASES		3
VECTOR SYMBOL		OPEN STAR
MASS UNTANKING	kg	26250
MASS EACH COOLER (excluding oil)	kg	510
MASS TOTAL (including oil)	kg	40000
MASS TRANSPORT (excluding oil)	kg	31300
MASS TRANSPORT (including oil)	kg	36200
INSULATING OIL MAIN UNIT	litre	6750
INSULATING OIL EACH COOLER	litre	151
INSULATING OIL TOTAL	litre	7100
PERMISSIBLE PRESSURE MIN/MAX	kPa	0/180
WTC SERIAL NO		P1027A
YEAR OF MANUFACTURE		2012

CURRENT TRANSFORMERS TO IEC 60044-1

CT NO1	FUNCTION	AMPS RATIO	ACCURACY CLASS	BURDEN (VA)	Fs	EXT %	I thn/ I dyn (kA)
T11 T12 T13	METERING & WTI	500/5	0.2	50	10	120	30 (1 sec)/75
T21 T22 T23	METERING	3000/5	0.2	100	5	120	16 (1 sec)/40

VOLTAGE TRANSFORMERS TO IEC 60044-2

	VOLTS	ACROSS	VOLTS	ACROSS	PHASES	ACCURACY CLASS	INSUL LEVEL	BURDEN	Hz	VOLTAGE FACTOR
VT 11, VT12, VT13	6600	A - B	110/110	1a-1b/2a-2b	1	0.2	LI75 AC28	20/20	50	1.2 CONTINUOUS
VT 21, VT22, VT23	3700	A - B	110/110	1a-1b/2a-2b	1	0.2	LI75 AC28	20/20	50	1.2 CONTINUOUS

NOTES :
FCL IS PROVIDED WITH THE FOLLOWING SPECIAL FITTINGS
(REFER INSTRUCTIONAL MANUALS):

EXTERNAL COMPONENTS

DR-FCL, DR-C50 AND ESUB.NET MONITORING SYSTEMS
CALISTO2 DGA AND MOISTURE MONITOR
LUXTRON FIBRE-OPTIC PROBES
MAGNA POWER DC POWER SUPPLY (2 Nos.)

energy technologies institute

WILSON TRANSFORMER

UK Power Networks

720-1027C-1
720-1027X-1_UnitA RevO

Figure 7 - Rating and diagram plate

5 Performance summary

5.1 Normal operation regime

The FCL is designed to have negligible effect on the network when the network is in a normal (un-faulted) state, and throughout the operational period it was demonstrated that the FCL indeed had no material effect on the network's normal state performance.

The voltage drop across the FCL was in the range of 0.6% to 0.8% of the system phase voltage, which is the expected value under the load currents on site. The voltage profile of the network was not impacted by the FCL. There was no notable phase imbalance, and there was no detectable change in the harmonic profile of the network's voltages with the FCL in operation.

Figure 8 shows a weekly profile of the current through the PCFCL from midnight on Monday through midnight the following Monday. The figure shows minimum, maximum and average values of the 3 phase currents over 10 minutes sampling periods. As can be seen – the load current rises at the beginning of the work week, subsides in the afternoons and during night-time, and remains lower through the weekend.

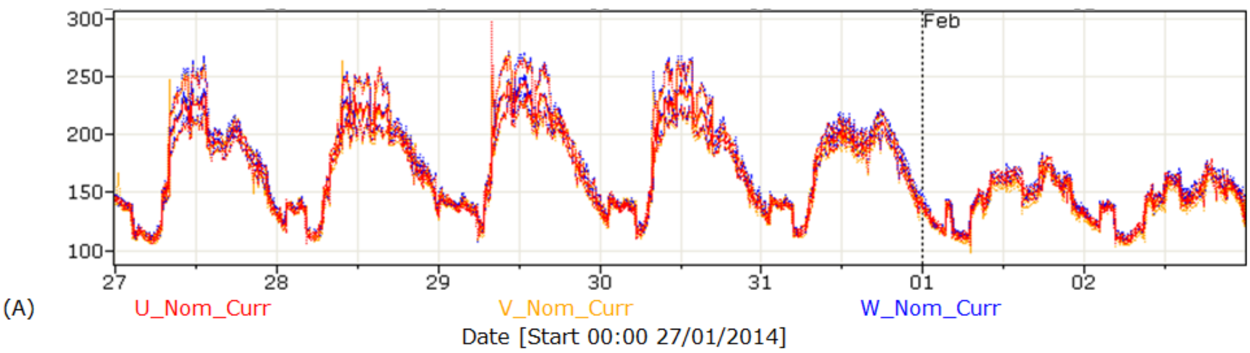


Figure 8 - Weekly load current through the PCFCL

Losses in the FCL were as expected. The overall factory tested losses at full rated current were 21.3kW which amount to 0.21% of the 10MVA power through the device. However, due to the relatively low actual loading conditions on site, it became apparent that the DC bias could be reduced. Consequently, DC losses were reduced by 38%.

GridON has subsequently installed another FCL in one of Western Power Distribution's primary substations in Birmingham. In this FCL (30MVA continuous, 38MVA overload for 8 hours), GridON has implemented dynamic DC bias control which follows the actual AC load current on site, thus optimizing the biasing power consumption in real time. It has been shown that such a mechanism could be implemented in the Newhaven Town FCL – which would have resulted in 75% reduction in losses. This would have brought overall AC and DC losses of this FCL to about 5kW, which represents 0.05% of the rated 10MVA power through the device. This dynamic DC bias control is now available as an option in GridON's offering and is beneficial in installations where the average load current is significantly lower than the full rated load current.

Physical parameters of the FCL were monitored continuously throughout the operational period. These include oil and winding temperatures, dissolved gasses in oil and moisture. All of these parameters were well within the norms.

Throughout the operational period, the FCL underwent multiple inspections and condition assessments, similar in scope to what is practiced for power transformers, but more frequently for learning purposes. All of these assessments indicated that the device remained in good condition, suitable for continued normal operation, with no trends indicating any concerns to its well-being.

Further testing and condition assessment after completion of the operational demonstration period further confirmed that the condition of the device and its continuing performance both remained according to specification, and that the device was indeed suitable for operation throughout its entire design life.

The PCFCL has not suffered any malfunction[3] during its 40 months of operation, and therefore did not require remedial actions. It can therefore be considered as fully reliable during the demonstration period.

[3] The power analysis logging devices (off the shelf equipment which was installed as a learning tool for this project) that are used to log normal and fault operational data had occasional issues with their FLASH memory disk, but this has not impacted the PCFCL operation.

5.2 Network-fault events

Table 3 (below) and Table 4 (on page 18) present the observed network faults for which the monitoring systems recorded data. There was good correlation between designed, tested, network simulation models and the measured values in field operation. This confirmed that the real-world, in-field performance matched that measured during more than 50 fault tests in the independent short-circuit testing under controlled conditions before installation.

Table 3 - Selected fault events - described in detail

	Event Date	Fault description	Fault Level (Unlimited branch/Limited branch)	Fault reduction by the FCL	Fault duration
1	FEB 23, 2014	Phase to earth fault evolving to phase-to-phase to earth fault	3100A / 1470A rms	44%	750 msec
2	MAR 26, 2014	Phase-to-phase to earth fault evolving to a 3-phase fault	3300A / 1300A rms	35%	750 msec
3	MAR 26, 2014	3-Phase fault – shortly after the previous fault (CB closed back to the faulted line)	3300A / 1200A rms	35%	750 msec
4	JUL 23, 2014	Phase-to-phase fault evolving to a 3-phase fault	3450A / 1450A rms	49%	220 msec
5	JUL 23, 2014	3-Phase fault – shortly after the previous fault (CB closed back to the faulted line)	3450A / 1450A rms	49%	220 msec
6	NOV 16, 2014	3-phase fault	3200A / 1100A rms	45%	650 msec

Notes:

1. The fault reduction by the FCL is calculated as reduction of fault current from the available (prospective) fault current through the FCL branch (which is not the same as the actual fault level in the unlimited branch).
2. Following fault clearance the FCL recovers immediately.
3. Faults 1-5 are with 2 transformers in service. Faults 6-16 (see Tables 3 and 4) are with 3 transformers in service.
4. It is worth mentioning the fact that most faults in this location lasted around 650-750 msec, requiring the FCL to carry the limited current during this period. The FCL operated smoothly during all these faults requiring no user intervention.

Figure 9 and Figure 10 show waveforms of limited fault current through the FCL during two consecutive fault events (March 26th, 2014):

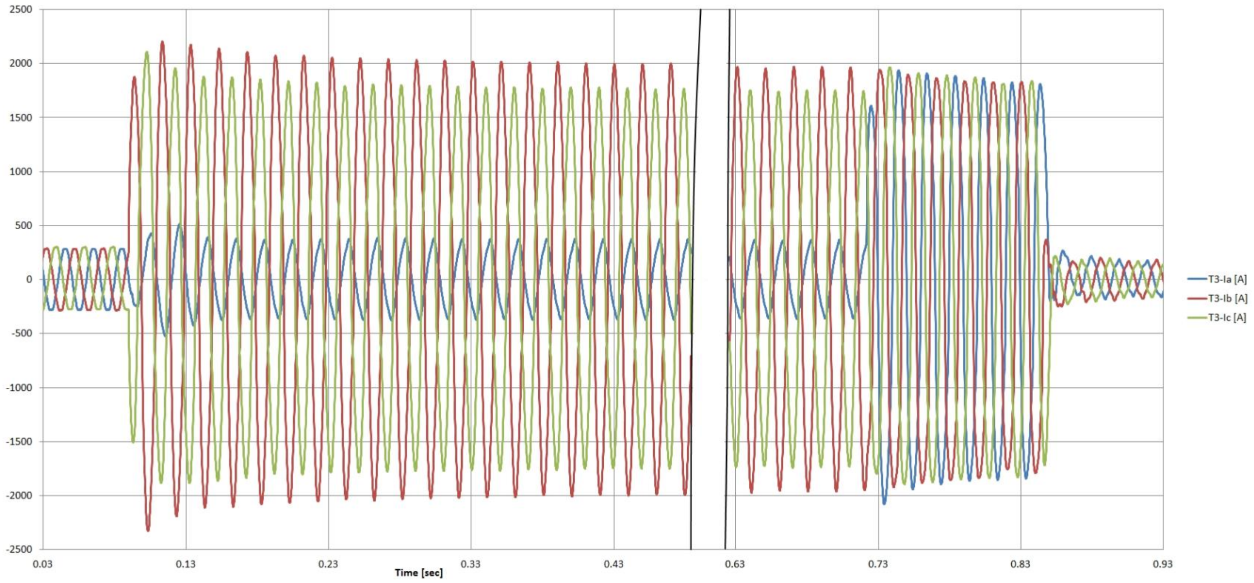


Figure 9 - Current through PCFCL during first of two consecutive fault events

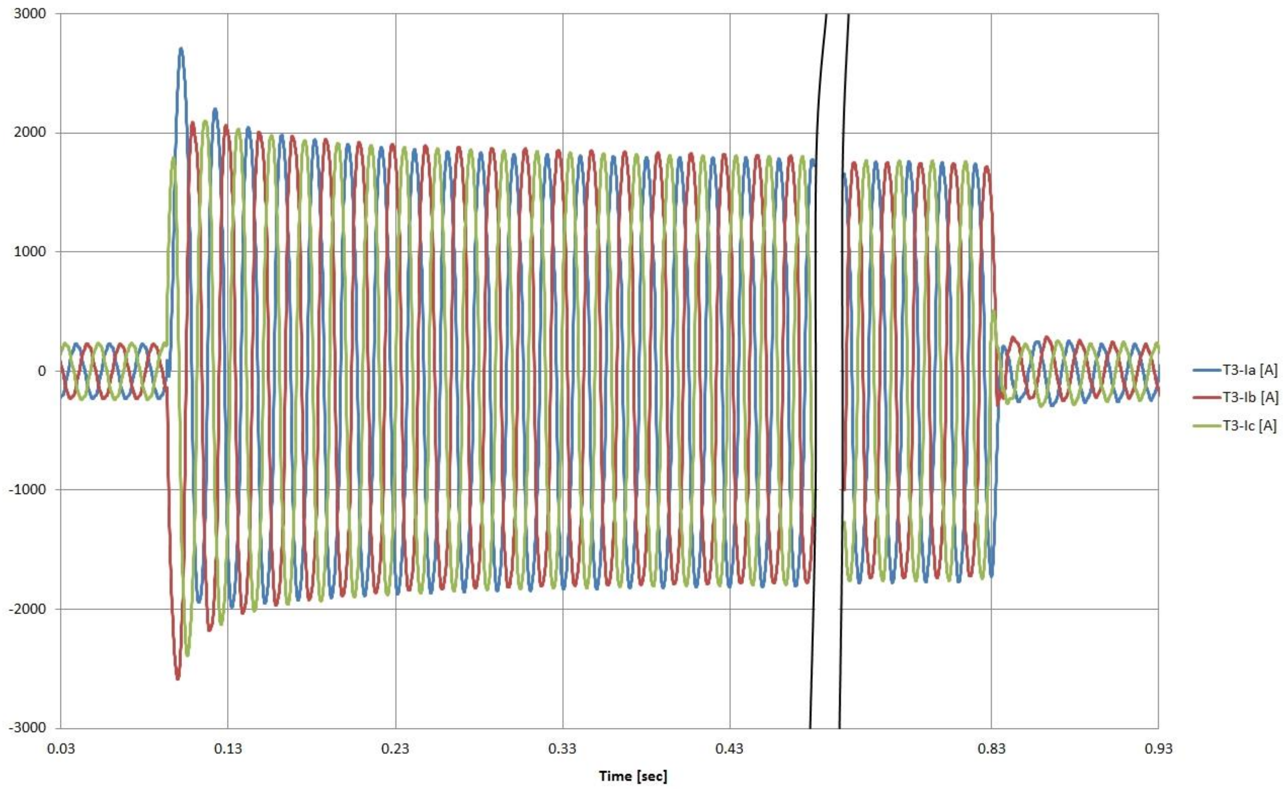


Figure 10 - Current through PCFCL during second of two consecutive fault events

Notes:

1. Figure 9 shows the 3 phase current waveforms through the FCL. Initially, several cycles of normal load current are shown. Then a fault event starts around t=100msec resulting in sharp increase in current. The current shown in the figure is reduced by 35% compared to the prospective fault current without the FCL present. Initially two phases are faulted (phases B and C) and towards the end of the fault – all three phases are faulted. Once the fault is cleared, around t=850msec, the FCL instantaneously recovers to normal load current.
2. The second fault event depicted in Figure 10, which closely followed the first one after some switching operations were attempted to locate the fault in the network, starts as a 3 phase fault from its beginning, since the relevant breaker simply connected to the same faulted network section.
3. The gap in the graphs is due to the recording device configuration which is set to record the waveforms at the beginning and the end of long-duration fault events.
4. It can be seen that the PCFCL recovers instantaneously to normal load upon clearance of the fault.

Table 4 - Additional fault events - described in high level

	Event Date	Fault description
7	JUN 23, 2015	Started as single phase to earth fault, transitioned into phase to phase fault and ended as 3 phase fault. Duration 270msec. Unlimited fault level – 3600Arms.
8	JUL 01, 2015	Started as phase to phase fault and transitioned into 3 phase fault. Duration 674msec. Unlimited fault level – 3700Arms.
9	AUG 09, 2015	Started as phase to phase fault and transitioned into 3 phase fault. Duration 450msec. Unlimited fault level – 4000Arms.
10	SEP 17, 2015	Brief Transient phase to phase fault. About 600A rms limited current. 900A rms unlimited current.
11	SEP 17, 2015	Brief Transient phase to phase fault. About 700A rms limited current. 1000A rms unlimited current.
12	SEP 28, 2015	Brief Transient phase to earth fault. About 500A rms limited current. 545A rms unlimited current.
13	SEP 28, 2015	Brief Transient phase to earth fault. About 520A rms limited current. 630A rms unlimited current.
14	JAN 22, 2016	Phase to phase fault. Duration 170msec. Unlimited fault level – 1630Arms. Limited fault current – 950Arms.
15	JAN 23, 2016	Phase to phase fault. Duration 140msec. Unlimited fault level – 1530Arms. Limited fault current – 940Arms.
16	JUN 21, 2016	Phase to earth fault. Duration 830msec. Unlimited fault level – 1370Arms. Limited fault current – 870Arms.

Note:

1. The fault events shown in Table 4 are described only in high level, due to availability of only partial data that was gathered by the monitoring systems installed on site

6 Objectives and outcomes

6.1 Objectives

This project was conceived with the purpose of converting an academic concept into a commercial product, in order to provide network operators with a useful tool to control increasing fault current levels. As such, it was imperative to include a DNO as a key participant in the project, along with the device developer, to ensure that the real network challenges were identified and matched with an appropriate solution.

The ETI decided to sponsor this development including a substantial field trial duration, in order to assess not only the performance of the system, but also its long term reliability and ease of operation. The vision was that such a demonstrator would serve as a reference to the industry, and accelerate FCL deployment, particularly in the UK distribution network.

Furthermore, it was envisaged that this project would serve as proof of manufacturing capability of such devices, their testing procedures and installation and maintenance practices.

6.2 Outcomes

The project fully achieved its objectives. It successfully demonstrated a 10MVA FCL in live operation for 40 months, and effectively limited 16 faults. The FCL proved to be robust, reliable and required minimal maintenance.

The project has firmed-up capabilities and methodologies for designing and building passive saturated-core FCLs for any configuration. Significant experience has been gained in manufacturing limitations, specification process, test methodologies, shipping and installation constraints etc.

The project directly assisted GridON in winning a second contract (which ended with successful deployment of a 30MVA FCL), and provided further useful demonstration and learning for the consortium members, and for all UK DNOs and other customers.

In summary, the design, test and field operation of the FCL have resulted in an extensive knowledge base and learning in a variety of areas, from specifications of different fault current limiters for different market segments and applications, up to field reliability, maintenance and operational experience in different network running arrangements.

This learning has initiated several development directions for GridON, described herein, some already deployed in an additional field installation.

6.3 Specification development

Significant work went into the specification process of the FCL. While natural tendency is to specify the device aggressively, it was found that a cost effective device is a result of understanding design trade-offs and adjustment of the specifications to factor in these trade-offs. For saturated core FCLs the key parameters are normal state impedance, fault state impedance, and the difference between limited fault current and maximal normal current. Power loss is also a factor that influences the cost. During the demonstration period it was realized that, due to the fact that actual site load current is usually lower than the specified rated load, it is possible to reduce the biasing losses significantly compared to the original specifications. It was later realized that this is expected in many networks and, as a result, in a subsequent project with another customer (WPD), GridON implemented a dynamic DC bias mechanism that follows the actual load conditions on site. This method enables losses to be reduced to a small fraction of the worst case losses, and offers excellent operating cost advantages. This method is now field proven and ready for further commercial use.

6.4 Technology development

One of the key risks at the beginning of the project was predictability of the PCFCL performance parameters when scaling up beyond a lab bench prototype. The non-linear nature of the saturated core design required a methodology to be developed that would verify the performance of a given design with good expected correlation to a real life model. Therefore, the design process of the FCL has been strongly focused on achieving close correlation between simulations and test results. This process was very important for reaching a reliable modelling and design platform for GridON's future products. A 3D electromagnetic finite element modelling simulation methodology was chosen. As a risk mitigation measure, it was decided to first build a prototype rated for $1/10^{th}$ of the actual device's power ratings. It was designed, manufactured and fully tested under normal, short circuit and high voltage conditions. The test results were fed back into the design and simulation process, and models were adjusted in order to ensure that the design and verification methodology were robust. Following satisfactory results, the 10MVA device was built and tested, and was found to correlate well to its simulation models.

6.5 Build and Manufacturing

The FCL was designed and manufactured using readily available materials, techniques and components, and excludes any exotic materials. The main FCL parts which consist of copper coils and electrical steel core were manufactured by Wilson Transformer Company, with the same materials used in commercial power transformers and in a regular power transformer factory, with no changes to the production line. Auxiliary systems also consist of components which are standard and available off-the-shelf. This has been a critical aspect in the design, in order to assure that the device can be serviced easily throughout its long lifetime. Another benefit of this approach is the ability to provide these FCLs to customers in short lead times.

This approach created several challenges, mainly in the need to iterate through the design several times, due to constraints posed by the standard materials, manufacturing techniques and off-the-shelf component limitations. However, these were quite worthwhile given the advantages mentioned above.

6.6 Operational period

During its operational period, the FCL functioned through multiple network fault events, and under different operating conditions on site. The FCL was found to be robust and, most importantly, failsafe – i.e. no matter the network fault types or the condition of the FCL's auxiliary supply or any other factor, it ALWAYS provides at least the guaranteed fault current reduction. This enabled the network operator to keep running the FCL continuously throughout the 40 months of operation.

Throughout the operational period, the operator's protection system has worked as expected both in normal operation and during network fault events, with the FCL limiting the fault current. The protection relays have continued to function normally, and faulted locations in the network have been isolated as expected by respective circuit breakers. Only minor changes to relay settings were required to take into account the fault current reduction with the FCL in circuit. The ability to continue using the existing protection scheme has been demonstrated and offers ease of integration of the FCL into the network.

Comprehensive testing of the device's condition following 40 months of field operation showed no abnormal degradation of the device. In fact its condition is similar to what is expected of power transformers, which is a good indication of its anticipated long lifetime.

6.7 Conclusions and future directions

GridON is in a position to offer saturated core FCLs to multiple customers in a broad range of voltage and power ratings, with high confidence of successful up-scaled designs. GridON foresees high potential for its saturated core FCLs specifically in the mid-high voltage networks. This very robust technology can scale to transmission ratings, where alternative technologies are challenged.

Following interaction with multiple potential customers, with numerous operational scenarios reviewed, it became apparent that some applications may benefit from a size-reduced device and in some cases a broader performance envelope, particularly to allow compact designs that allow normal current and fault current to be closer in value.

While the PCFCL provides a cost-effective solution for high voltage networks, GridON has therefore invested in further development of a second product family which was designed specifically for low-mid voltage applications. Connecting distributed generation sources introduces extra fault currents. Network operators will not authorize connection of gas generation, biogas cogeneration and other renewable resources, without proven means for protecting the distribution network from excessive fault currents. Such requirements often result in significant postponement of the connection and loss of potential revenues. In some cases, where the distribution network is already over-subscribed for new connections, it may not be possible for a new plant to connect at all.

With growing business and production growth, many industries require increased supply of energy, and increasingly using electricity to offset former fuel-based energy. Oil & Gas rigs consume very high amounts of energy and rely on uninterrupted operation. With the fast growth of internet and cloud services, large numbers of data centres are being built and their energy consumption is growing rapidly. Many industries - such as semiconductor, chemical processes, steel and cement - are extremely sensitive to electricity disruptions which often lead to severe business impact and financial losses.

GridON has therefore developed an add-on system that manipulates the DC biasing circuit during fault events (as part of the European Commission Horizon 2020 project). With this improvement the FCL may be designed with 50-75% reduction in mass compared to the baseline technology. It also allows a significantly larger fault-to-normal impedance ratio, and the ability to limit the fault current to levels close to nominal current or even below it. The smaller volume and footprint also enable price reduction of such systems. This technology has been fully tested and proven at this stage, and is now ready for commercialization. GridON is targeting this cost-effective product family specifically for decentralized and renewable power producers, distribution network operators, and industrial customers.

7 Concluding comments

The saturated core fault current limiter technology offers a field-proven genuine path for multiple network voltages and power ratings, all the way up to transmission levels.

This project has been executed by the consortium according to approved budget, and with an extended demonstration period agreed.

All parties involved in the project have worked in unison and in a constructive manner to achieve the project's goals.

For further information please refer to:

Energy Technologies Institute: www.eti.co.uk

GridON LTD.: www.gridon.com

8 References

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