Saturated Core Fault Current Limiters: successful testing/ service performance

ABSTRACT

Various Fault Current Limiter technologies are under development to tackle increasing fault levels in sub-stations. An FCL clips the fault current to lie within station plant capacity. The paper presents testing/service performance of pre-saturated core FCLs, currently installed in live UK substations. The proven technology uses conventional materials/manufacturing practice used in transformer industry, thereby avoiding the technical risks of High Temperature Superconducting conductor and cryogenics used in competing technologies. Maintenance and reliability levels are comparable to a transformer which is attractive to operating and maintenance staff.

1. INTRODUCTION

Load growth, distributed generation due to renewables and increasing interconnection of networks all lead to higher system fault currents and consequent costly upgrades to sub-station equipment like switchgear, overhead lines, cables and transformers. Fault Current Limiters help limit the prospective fault current to values within plant capacity minimising upgrade costs, besides significantly aiding the integration of renewable generation.

Wilson Transformer Company has partnered with Israeli based GridON Ltd. to design, manufacture and install pre-saturated core FCLs as demonstration/commercial units rated 10 MVA,11 kV (for UK Power Networks) and 30 MVA,11 kV (for Western Power Development, UK) respectively.

2. Road-map of FCL development

CIGRE Technical Brochure 239 [1] consists of four major parts – State of art, Functional specifications, System demands and Testing of FCLs. An extensive reference list of current limiting technologies is also included.

CIGRE Technical Brochure 497 [2] contains an overview of current limiting measures (Fig. 1) and preferred

locations of FCLs, namely in bus-tie coupling, incoming transformer and generator feeders or outgoing feeders (Fig. 2). The brochure describes technical and commercial advantages of each application.

3. Saturated core FCL technology

A. Overview

Proprietary magnetic flux alteration pre-saturated iron core technology described here utilizes standard, proven transformer technology. No exotic materials or superconductors are used.

❞ The proven technology uses conventional materials/manufacturing practice used in transformer industry

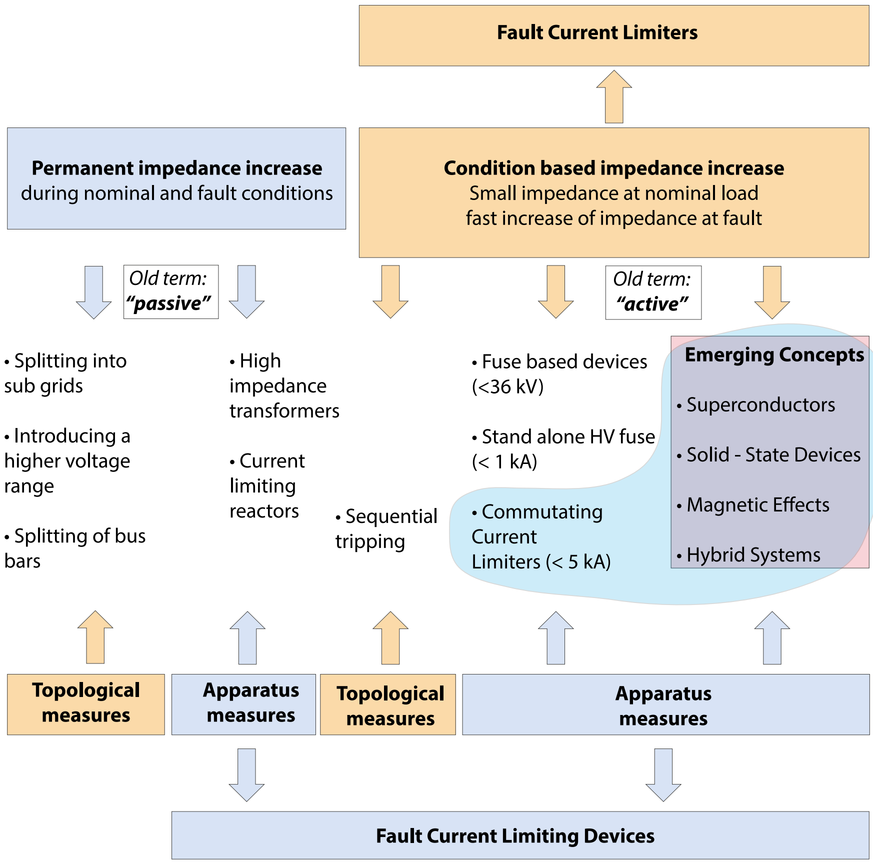

Figure 1. Overview of current limiting measures [2]

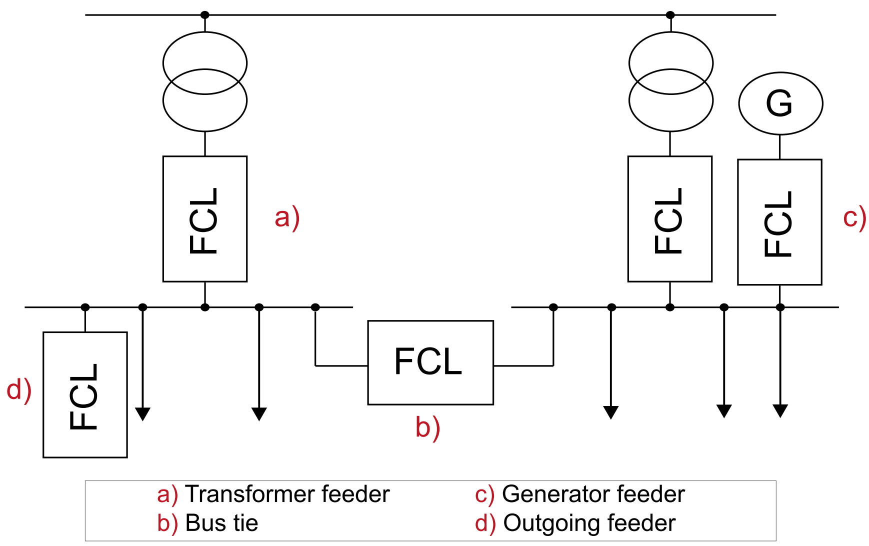

Figure 2. Major FCL locations [2]

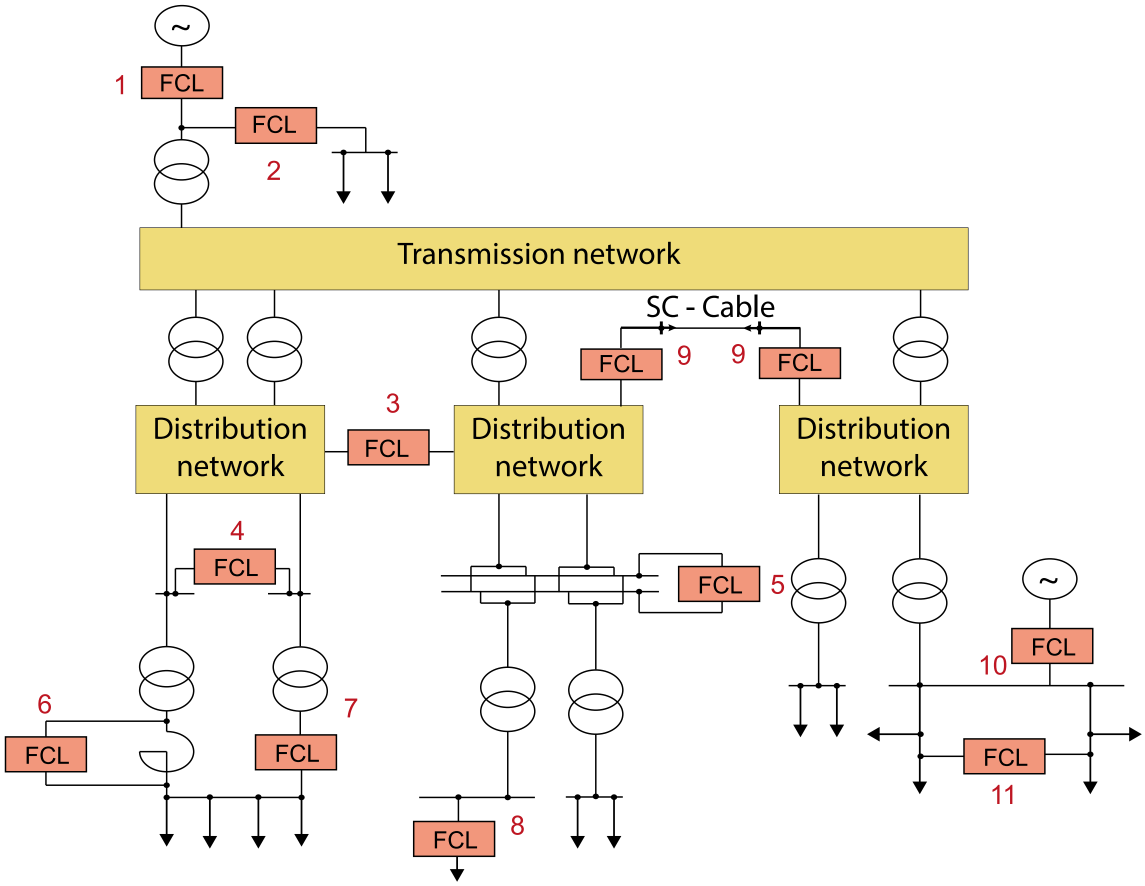

Figure 3. Roadmap for Europe [3]

This enables scale up of products to voltage ratings supported by transformer technology up to transmission levels. These are the first such fully tested, commercially available pre-saturated fault current limiters in service.

The robust failsafe device maintains its fault limiting capability even if auxiliary power and DC bias are lost. Being based on transformer technology, it is reliable and simple to maintain and operate.

A comprehensive monitoring and control system is provided with the FCL to enable seamless integration with existing protection schemes, with minimal changes to protection settings, and to enable real-time and/or event driven view of the FCL operational parameters.

B. Key technology advantages

The technology is backed by several patents and patent pending applications, and offers unique performance advantages over competing technologies:

1. High ratio between limiting-impedance and nominal-impedance – solution allows a broad range of ratios to be designed, up to a ratio of 15.
2. Ability to design for high fault current reduction (up to 90 % if needed) along with very low insertion impedance during normal operation (below 1 %).
3. Standard transformer technology– using no superconductors or exotic materials, using reliable, predictable and well established processes for design, manufacturing, testing, transport, commissioning and operation.
4. Requires similar maintenance as power transformers.
5. Scalability to transmission voltage levels up to 400 kV.
6. Passive, self-triggered device – presents variable impedance controlled solely by the current through it, with no need for an active detection, decision circuit, electronics or algorithm.
7. Immediate recovery from fault and ability to limit multiple consecutive faults – offer the ability to support reclosing schemes with no interruption to normal protection scheme operation.
8. Ease of integration into existing protection schemes, with minimal investment and changes.
9. Fail-safe device – provides fault current limitation even in the event of DC bias loss.
10. PLC-controlled DC biasing to reduce kW losses in FCL.

> **The FCL is based on a pre-saturated iron core principle. Variable impedance is obtained through utilizing magnetic-flux alterations, enabling increase of its normal impedance as high as 15 fold in the presence of fault currents**

State-of-the-art design simulation tools are used including ANSYS Maxwell Electromagnetic software besides in-house developed design optimization tools. Excellent correlation has been achieved between FEM simulations and test results of commercial product, prototypes and

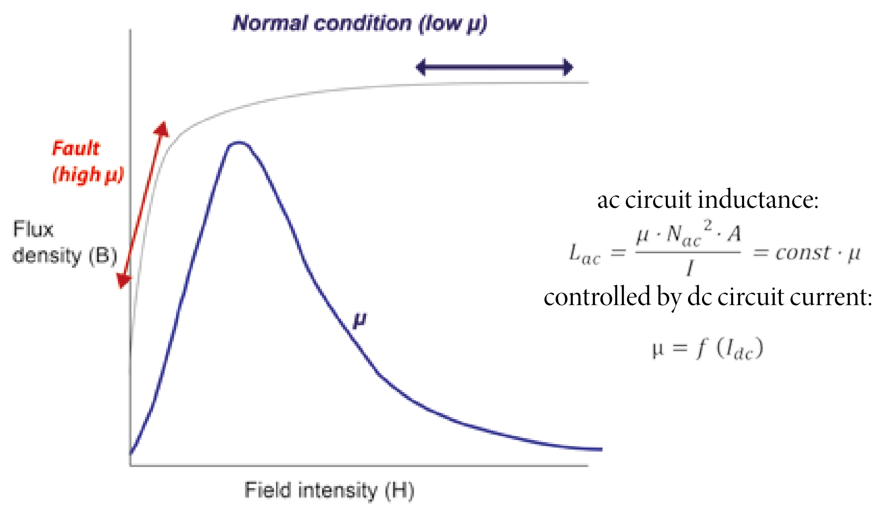

Figure 4. Non-linear magnetic characteristics of a ferromagnetic core

bench models. This further strengthens the predictability of designs.

FCLs are designed, manufactured and tested in the Wilson power transformer factory in Glen Waverly, Victoria, Australia. Short circuit tests are performed externally in an independently certified high power laboratory, under the supervision of GridON and Wilson Engineers, a practice that has been successfully demonstrated repeatedly, with a record of 100 % pass rate.

C. Principle of operation

The FCL is based on a pre-saturated iron core principle. Variable impedance is obtained through utilizing magnetic-flux alterations, enabling increase of its normal impedance as high as 15 fold in the presence of fault currents. The concept utilized the non-linear magnetic characteristics of a ferromagnetic core (Fig. 4):

D. Normal operating condition

An iron core is magnetized by direct current bias from a set of two redundant DC power supplies, flowing through coils around the core (Fig. 5). This bias creates a magnetizing field strong enough to put at least a portion of the iron core into saturation. AC coils which are series connected between a source and a load are wound around that saturated area, carrying the AC current for which the FCL needs to provide current reduction during fault events.

When normal AC current flows through the AC coils, the AC flux generated is not strong enough to get the core out of saturation. The saturated portion of the core behaves similarly to an air core, and both series-connected AC coils present impedance similar to an air-core coil, which is very low.

The voltage drop on the AC coil is proportional to the variation in flux density, and due to the small slope of the magnetization curve in this regime – this voltage drop is very low, typically 1-3 % of the source voltage. Fig. 5 illustrates the operating principle in the saturation regime (the actual physical core geometry may be different from that shown).

A benefit of operating in this saturation state is that because the flux changes are low – the iron core losses are also very low, and losses are mainly determined by the copper losses, which can be controlled by the choice of appropriate wire cross section. Typically, the combined AC and DC losses are in the order of 0.1 % of the power rating of the system.

Fig. 6 highlights the current through the FCL during normal operation, where the FCL is virtually transparent to the system.

E. Fault condition

When a fault occurs, the AC current through the AC coils starts rising rapidly, and a large magnetizing field is created by these coils.

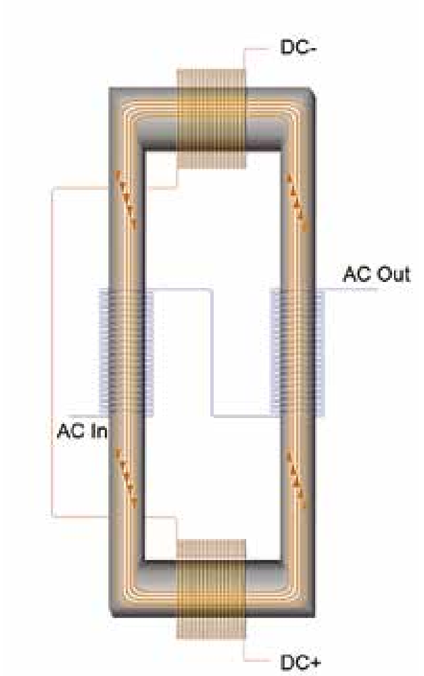

Figure 5. Normal operating condition

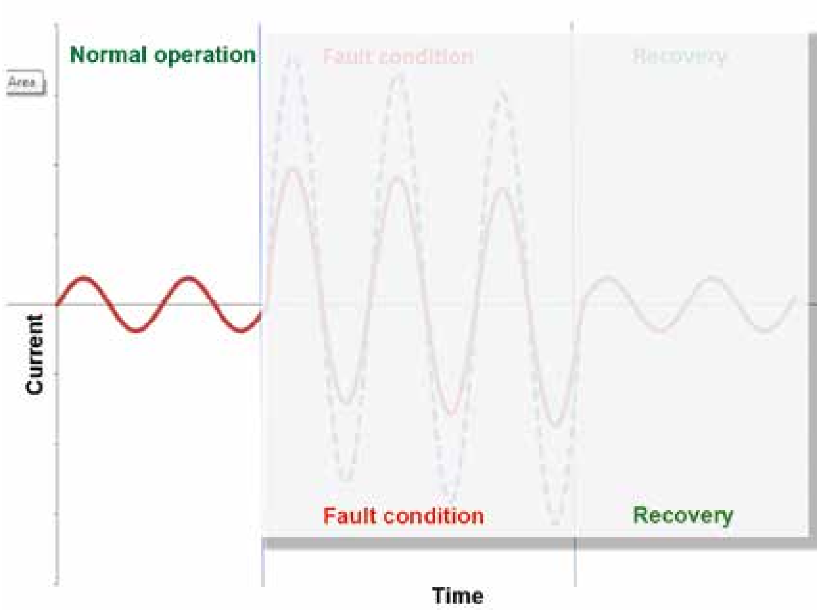

Figure 6. Current through the FCL during normal operation

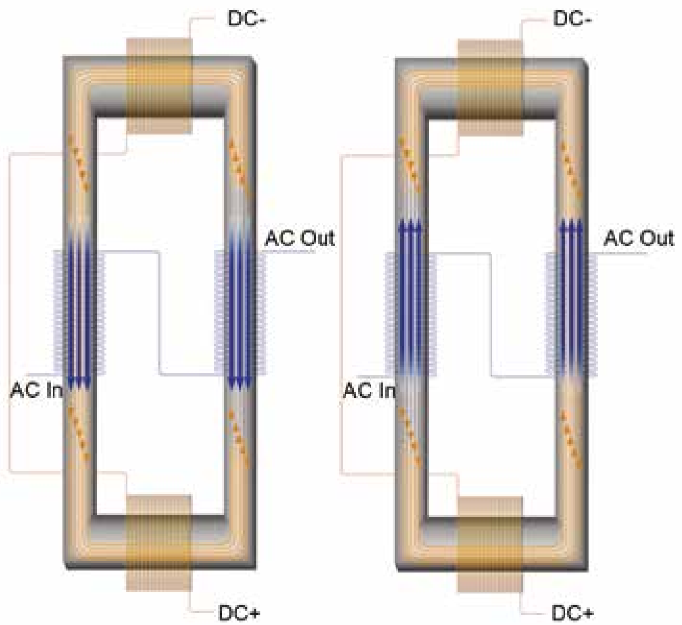

Figure 7. Fault condition

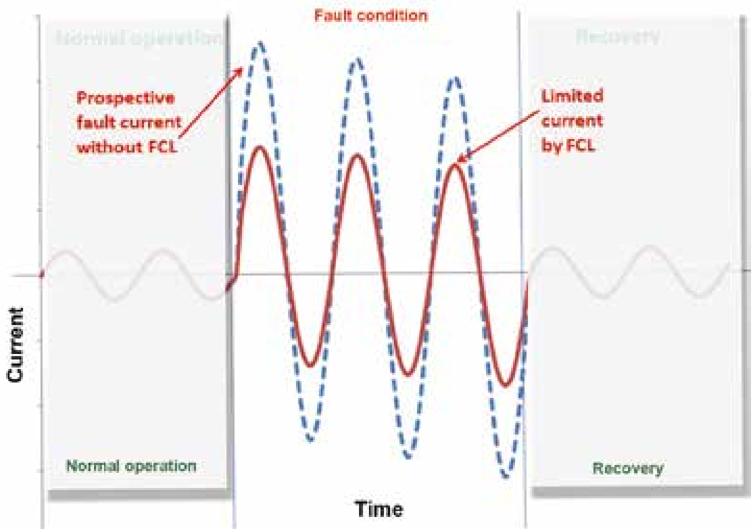

Figure 8. Prospective fault current (without FCL in the circuit) and limited current by FCL

Figure 9. 10 MVA, 11 kV FCL in service in UK Power Networks

As illustrated in Fig. 7, in each AC half cycle one side of the core gets de-saturated by the counter-flux from the AC coil, which causes that coil's impedance to increase instantly and significantly. Similarly, the other side of the core gets de-saturated in the second AC half cycle, and so on. This increase in the FCL impedance acts to choke the fault current and reduce it to a level acceptable to the system in which it is installed.

Fig. 8 illustrates the prospective fault current (without the FCL in the circuit) which would flow through the faulted point, and the current limited by the FCL.

F. Recovery

When the fault is cleared from the system, the counter flux created by the AC coils is reduced instantly, and the FCL instantly recovers to its saturated state, presenting very low impedance between the source and load.

4. 10 MVA, 11 kV FCL in service in UK Power Networks

A 10 MVA, 11 kV FCL (Fig. 9) was commissioned into service at the UK Power Networks primary substation in Newhaven, East Sussex in May 2013. This demonstration FCL was funded and procured by the Energy Technologies Institute (ETI). The FCL has completed two years of reliable operation with no down time and effective performance in limiting the fault current during multiple network fault events, including multi-consecutive faults.

A prototype 1 MVA FCL was built prior in order to establish the accuracy of simulation and modeling methodologies, and to prove the performance envelope of the device and its auxiliaries. The prototype was designed and tested to withstand full impulse voltages, and 10 MVA current rating.

The 10 MVA design incorporated all lessons learned from the prototype and was

> **The field results, test results and network simulation results all showed good correlation among them, and demonstrated the FCL operating as designed and tested**

> **The FCL recovers back to normal impedance and normal load current immediately (within 1 msec) after the fault is cleared, and therefore never interrupts the load current**

fully tested to applicable transformer/ reactor standards, in the factory and a certified short circuit test laboratory. The test results, including over 50 stringent fault tests, fully aligned with product specification and design.

Prior to the FCL installation, the network was fully modeled in power systems analysis software by E.ON Technologies, consultants to this project. Load flow and fault scenarios in any location in the network could be simulated. The software introduced a simple model of the FCL to assess impact on the system with the FCL present.

Online monitoring equipment on the FCL enabled analysis of its behaviour in both normal and fault regimes. Normal behaviour has been analysed continuously, while fault events triggered precision transient waveform capture. These waveforms were then analysed offline to determine the electrical performance of the FCL as well as fault level reduction in the network due to the FCL presence.

The field results, test results and network simulation results all showed good correlation among them, and demonstrated the FCL operating as designed and tested.

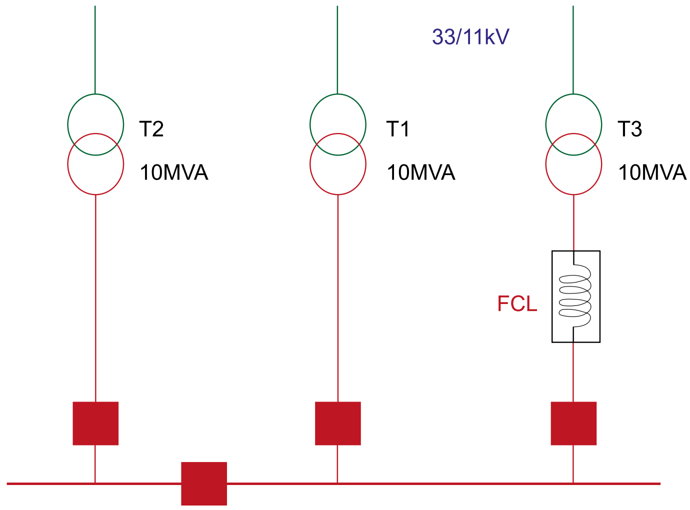

Figure 10. FCL installation on the tail of T3 - a 10 MVA, 33/11 kV transformer

Table 1. Key parameters

Parameter	Value
Line voltage	11 kV, 50 Hz, 3-ph
Nominal load current (power through)	525 Arms (10 MVA)
Prospective fault current	5.34 kArms, 13.6 kA peak
Limited fault current	2.22 kArms, 9.13 kA peak
Fault current reduction (clipping)	58% of steady state rms (33 % of first peak)
Tested fault withstand duration	3 seconds
Recovery from fault to normal load	Instantaneous (less than 1 msec)
CB reclosing	Fully tested with 500msec dead zone between faults
Voltage drop duration normal operation	0.8-2 %
Power frequency voltage withstand	28 kV
Lightning impulse withstand	75 kV

5. Performance of the 10 MVA FCL

The FCL has been installed on the tail of a 33/11 kV 10 MVA transformer (Fig. 10). This substation has 3 transformers, and before the FCL was installed, only 2 transformers could operate in parallel, with the 3rd in standby, since fault levels would have exceeded the switchgear ratings. The FCL installation enables the parallel connection of all 3 transformers. The transformer feeder location was chosen for the FCL installation as it was the most convenient location in this substation, minimizing installation costs and outages.

A. Short-circuit tests:

The FCL was tested under multiple fault conditions and fault levels.

Fig. 11 shows a phase-phase-ground fault, with prospective current (in fine line) of 4.36 kA with maximum asymmetry. The limited currents are shown in solid lines.

Fig. 12 shows test results of instantaneous recovery from a fault with maximum asymmetry back to normal load.

Fig. 13 shows test results of consecutive fault limiting. The FCL is limiting current on a faulted line, the circuit breaker clears the fault and the FCL recovers immediatelyto normal state,then after a 500msec dead time the CB recloses back to the faulted line.

B. Short-circuit performance at site:

First fault event

Figures 14-15 show the first fault event as measured by the online monitoring system of the transformer without the FCL (T2).

The fault event starts as a phase to phase to earth fault. Phases B and C are faulted while

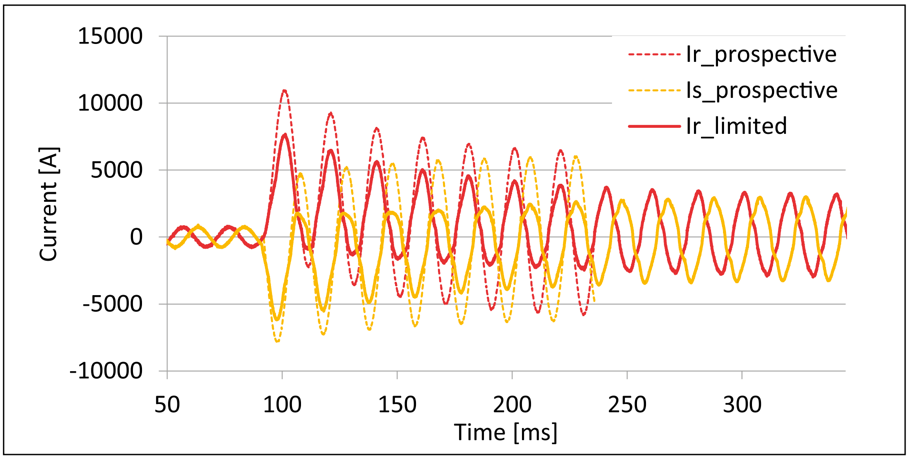

Figure 11. Test results of a phase-phase-ground fault

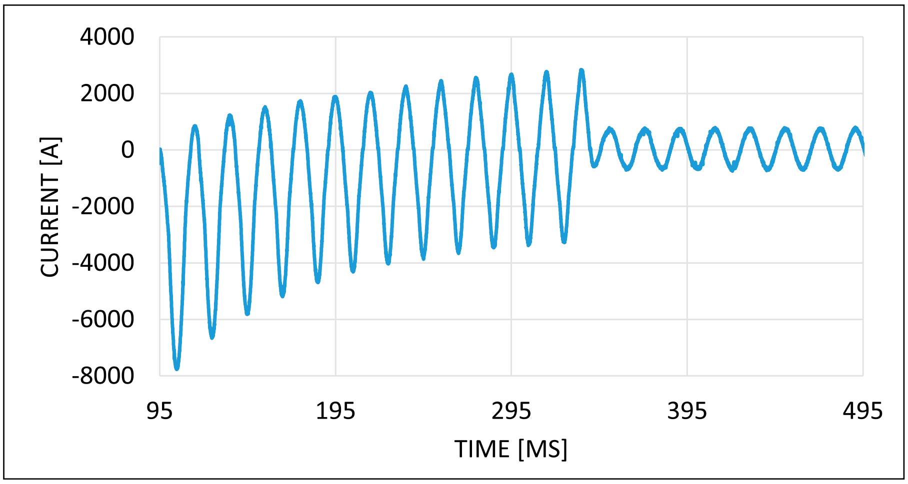

Figure 12. Test results of instantaneous recovery from a fault

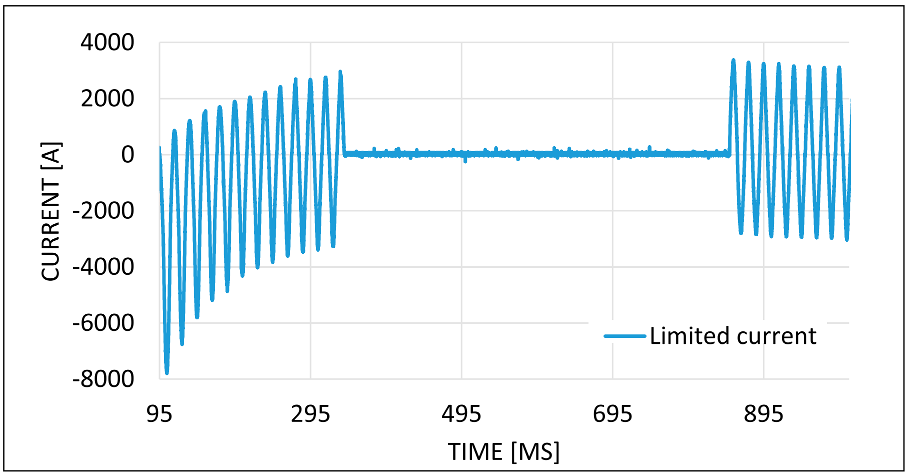

Figure 13. Test results of consecutive fault limiting

phase A remains un-faulted. The fault evolves into a 3 phase fault after 630msec. These two figures are indicative of the prospective fault level, i.e. the fault current without an FCL in circuit. The overall duration of the fault event from its inception until its clearing was 760msec. The fault current level from this transformer is 3.3 kA RMS.

At the same time, T3, with FCL connected on its tail, has recorded data as shown in Figs. 16-17. The currents through this branch are significantly reduced by the FCL, to a level of 1.3 kA RMS. The FCL limits both the phase to phase and the 3 phase fault currents.

Once the fault is cleared, the current through T3/ FCL goes back to its normal level instantly, allowing the continued and uninterrupted power flow from this branch. This is done completely passively and the FCL is immediately ready for subsequent fault operation.

Second fault event

Shortly after the clearing of the first fault, a second fault occurred on the same location in the network. Since the FCL has recovered instantly from the previous fault, it safely limited the second fault current (Figs. 18-20)

6. 30 MVA, 11 kV FCL in service in WPD Distribution Networks, UK

A 30 MVA, 11 kV FCL (Fig. 21) was commissioned into service at the Western Power Distribution Castle Bromwich sub-station, UK in April 2015. Its specifications are far more demanding than the 10 MVA unit. The FCL has been installed on one of the dual LVs of a 132/11-11 kV, 60 MVA transformer.

The 30 MVA design incorporated all lessons learned from the prototype/demonstrator units and was fully tested to applicable transformer and reactor standards, in the factory and a certified short circuit test laboratory.

7. Performance of the 30 MVA FCL

This FCL has been tested for 1575 A continuous operation, and 2000 A overload current for 8 hours and over 50 % first peak fault current reduction.

This unit has been short circuit tested to withstand multiple fault events, up to 13.1 kA RMS and 33.4 kA peak prospective current, and for fault duration of 3 seconds.

The FCL recovers back to normal impedance and normal load current immediately (within 1 msec) after the fault is cleared, and therefore never interrupts the load current, enabling the operator to maintain normal operating and protection procedures.

The device has been fully tested to transformer and reactor standards, and is rated for 95 kV peak lightning impulse withstand.

99 Extensive experience has been gained in design, manufacture and testing of saturated core FCLs at the Wilson Transformer manufacturing facility in Melbourne, Australia

8. Testing of FCLs

IEEE Draft Guide for FCL Testing [4] recommends a full suite of Routine and Type Tests.

9. Challenges

Technical challenges to be overcome on the saturated core FCLs are: electromagnetic compatibility, control of high magnetic fields, short circuit performance, dynamic forces, core saturation, temperature rise, reliable DC bias current supply and control, system studies to predict impact of FCL on the system, and solving large multi-physics simulations on high-performance computers.

10. Conclusions

Extensive experience has been gained in design, manufacture and testing of saturated core FCLs, in a range of current/load conditions, at the Wilson Transformer manufacturing facility in Melbourne, Australia. The units operating in the UK sites have seen trouble-free service both during normal load and during fault events. Fully tested, HTS-free FCLs are commercially available for both Distribution and Transmission networks.

References

[1] CIGRE Technical Brochure 239 (2003), Fault Current Limiters in Electrical Medium and High Voltage Systems.
[2] CIGRE Technical Brochure 497, Application and feasibility of Fault Current Limiters in Power Systems, WG A3.23, June 2012.
[3] SFCL - Roadmap for Europe, SCENET, 2001.
[4] Draft Guide for Fault Current Limiter (FCL) Testing PC37.302/D2, December 2013.

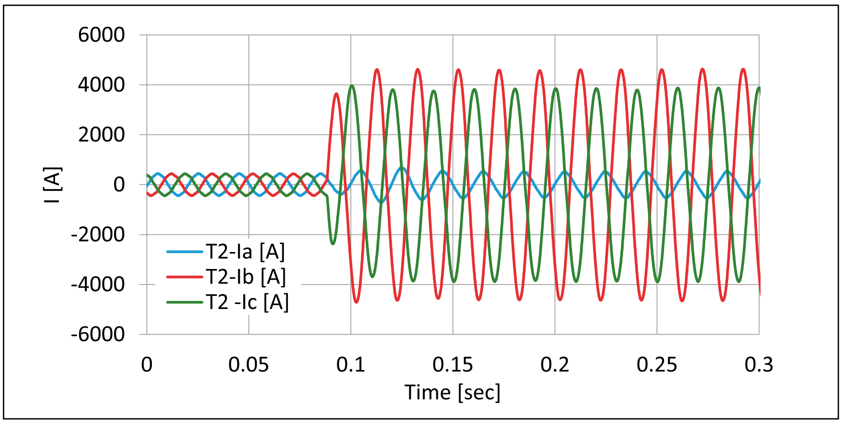

Figure 14. T2 Currents – Fault 1 start

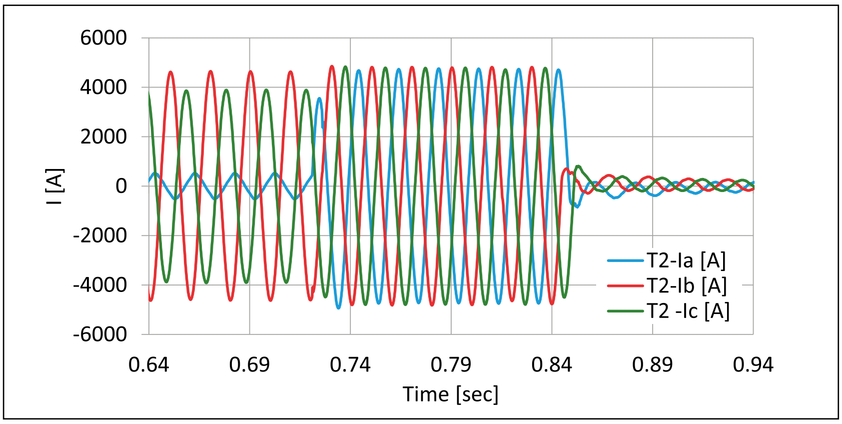

Figure 15. T2 Currents – Fault 1 end

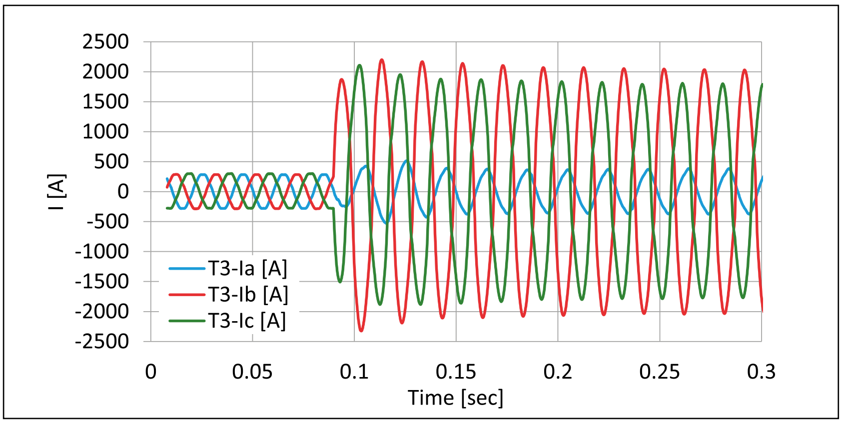

Figure 16. T3 & FCL Currents – Fault 1 start

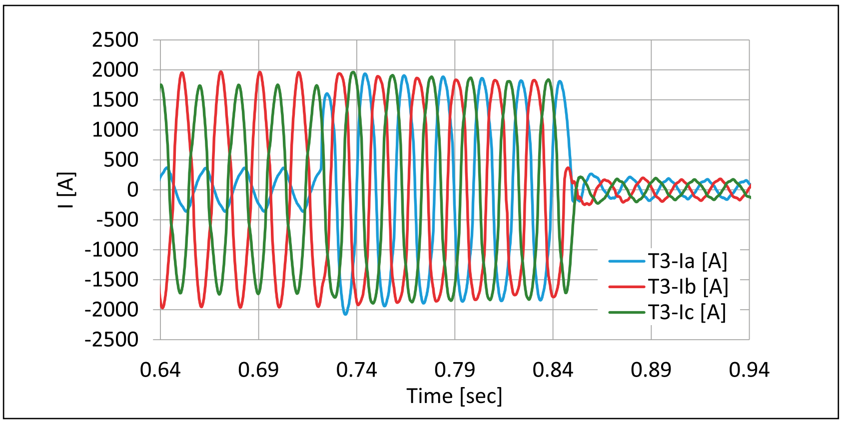

Figure 17. T3 & FCL Currents – Fault 1 end

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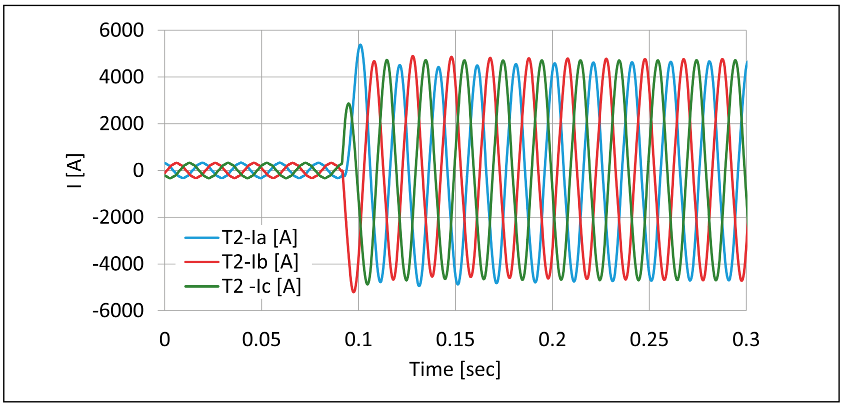

Figure 18. T2 Currents – Fault 2 start

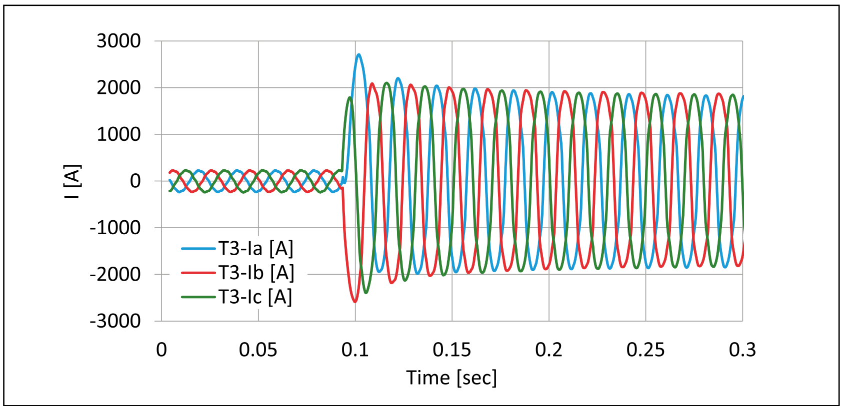

Figure 19. T3 & FCL Currents – Fault 2 start

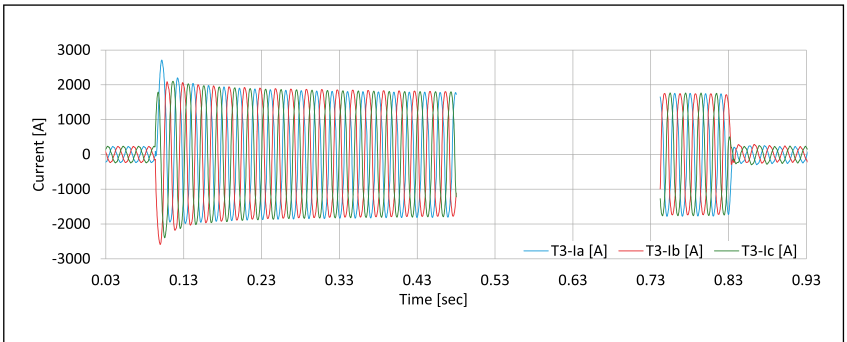

Figure 20. T3 & FCL Currents – Fault 2 full duration and recovery

Acknowledgements

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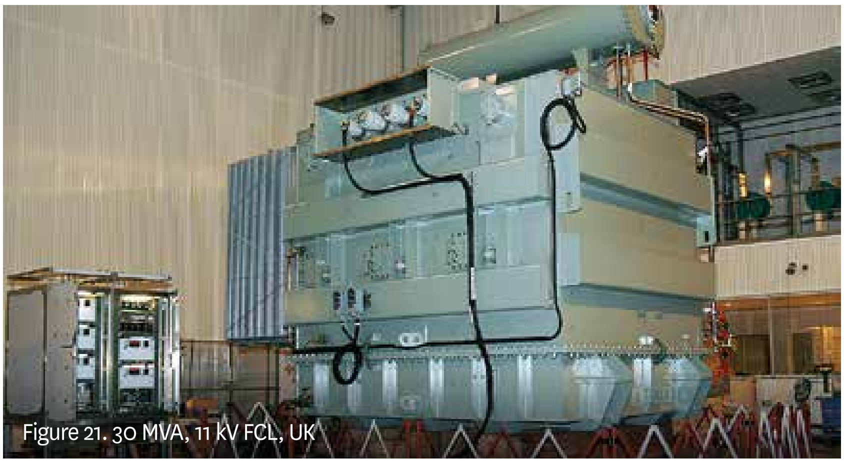

Figure 21. 30 MVA, 11 kV FCL, UK

Authors

Mohinder Pannu is Strategic Engineering & Projects Manager at Wilson Transformer Co Pty Ltd, developing new product applications for the Power industry. He holds a B.Tech (Hons) in Electrical Engineering from The Indian Institute of Technology and an MBA from Monash Mt Eliza Business School. He has background experience in Power Transformer Design, Quality and Test. He is a member of Cigre Australian Panels A2 and D1.

Yoram Valent, GridON's CEO and Co-Founder, has spent the past 25 years in senior positions in technology companies, from start-ups, through to multi-billion dollar, publicly traded corporations. As president of a networking solution provider, Radlan Inc., Yoram led to its successful acquisition by Marvell Technology Group ("MRVL"). He later served as vice president at Marvell; overseeing a matrix organization across the US, Israel and Asia. Prior, Yoram was the president of California-based NetReality Inc. Yoram holds a B.Sc. in Industrial Engineering and Management and M.Sc. in Computer Automation and Robotics.

Uri Garbi is Vice President, Research & Development, at GridON. Uri has spent the past 20 years in senior R&D positions in the high-tech industry, mostly in the electronics and semiconductor space. He has managed large engineering teams in Texas Instruments and Zoran Corporation, leading multi-site, multi-national research and development projects. Uri was a member of the Israeli management team in both companies. Previously, Uri completed 6 years of military service performing various R&D roles in an elite technological unit of the Israeli Defense Force. Uri holds a B.Sc. (cum laude) in Electrical Engineering from the Technion – Israel Institute of Technology, and a M.Sc. in Electrical Engineering from Tel-Aviv University.