

Development and Deployment of Saturated-Core Fault Current Limiters in Distribution and Transmission Substations

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Abstract—Zenergy Power has been developing an inductive-type of fault current limiter (FCL) for electric power grid applications. The FCL employs a magnetically saturating reactor concept which acts as a variable inductor in an electric circuit. In March 2009 Zenergy Power, with funding from the California Energy Commission and the U.S. Department of Energy (DOE), installed an FCL in the Avanti distribution circuit of Southern California Edison’s Shandin substation in San Bernardino, CA. Rated at 15 kV and 1,250 amperes steady-state, the “Avanti” device is the first superconductor FCL installed in a US utility. In January 2010, the “Avanti” device successfully limited its first series of real-world faults when the circuit experienced multiple single-phase and three-phase faults. After successfully validating the performance of a new “compact” saturated-core FCL, Zenergy Power received contracts to install a 12 kV, 1,250 amperes compact FCL in the CE Electric UK grid in early 2011 and a 138 kV, 1,300 amperes FCL at the Tidd substation of American Electric Power in late 2011.

Index Terms—fault current limiters, high-temperature superconductors, saturable cores, short circuit currents, superconducting magnets

I. INTRODUCTION

SINCE 2006, Zenergy Power, Inc. (ZEN) has been developing an inductive type of high-temperature superconductor (HTS) fault current limiter (FCL) for electric power grid applications. The HTS FCL employs a magnetically saturating reactor concept which acts as a variable inductor in an electric circuit. The inductance of the HTS FCL changes instantly in real-time in response to the current in the electrical circuit being protected and varies from a low steady-state value of inductance during normal operating conditions to a high value of inductance during a fault condition that is sufficient to limit the fault current to the desired maximum value. HTS fault current limiting concepts have been extensively reported to date [1-5].

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II. BACKGROUND

Unlike resistive and shielded core FCLs that rely on the quenching of superconductors to achieve increased impedance, saturable core FCLs utilize the dynamic behavior in the magnetic properties of iron to change the inductive reactance on the ac line. Referring to Fig. 1, one can see that there are two rectangular iron cores arranged side-by-side. The iron cores are surrounded by a single HTS coil that encircles the adjacent inner limbs of the iron cores in the middle. A small DC power supply energizes the HTS coil with a DC bias current to create a very strong DC magnetic field that magnetically biases and saturates the iron cores. Conventional copper AC coils are wound on the outer limbs of the iron cores. The AC coils are connected in series to the electrical circuit that is to be protected. These AC coils are wound in opposite magnetic “sense,” so that using this arrangement a single-phase device can be made in which each of the rectangular iron cores acts independently during each positive and negative half-cycle of the AC line current.

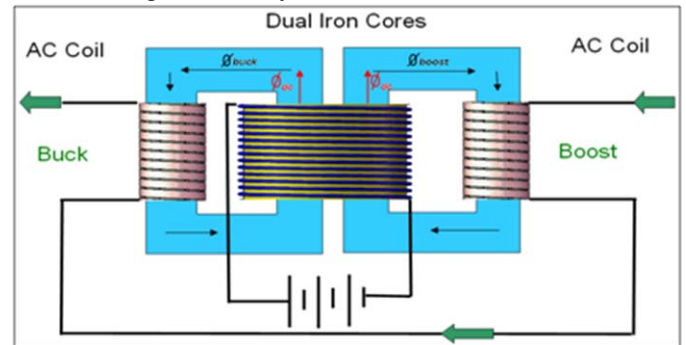


Fig. 1 – The Basic Saturating Reactor FCL Concept Diagram

When the AC circuit is energized and the AC line current is flowing at normal values, the iron is highly saturated and has a low relative permeability. To the ac coils, the iron acts like air, so the ac impedance is small. When an AC fault occurs, the AC amp-turns generated by the AC coils increase linearly with the fault current to force the iron core out of saturation, resulting in increased line impedance during part of each half-cycle. The result is a considerable reduction in peak fault current. Essentially, the saturable core type FCL is a variable-inductance, iron-core reactor [6].

Fig. 2 shows the FCL equivalent inductance as a function of the instantaneous line current. Around the bias point (at

commercial 12.47 kV distribution circuit with real residential, commercial and light-industrial customers that has been established by SCE, CEC and DOE to demonstrate innovative technologies of potential value in the modern electric grid.

rating, the FCL can achieve impedance gains of the order of 4 or 5 times that of a current limiting reactor. Similarly, an FCL that has the equivalent limiting capability of a current limiting reactor will have only 20% to 25% of the voltage losses as a current limiting reactor at nominal rating.

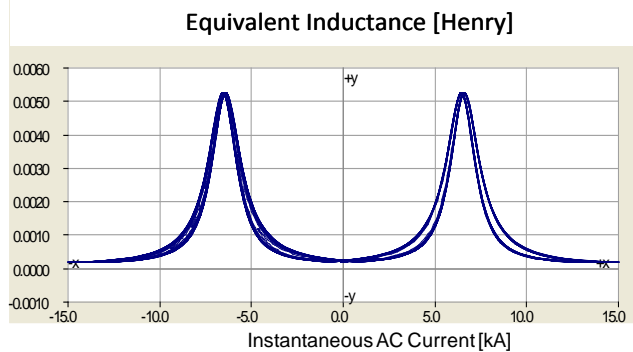


Fig. 2 – The FCL equivalent inductance illustrating low inductance at small currents and non-linear increase of inductance at high currents.

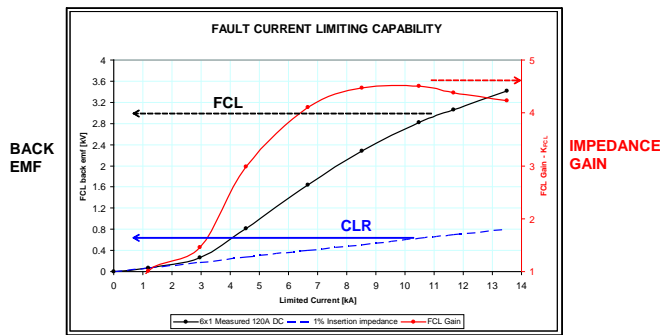


Fig. 3 – Comparison of saturable-core FCL to conventional current limiting reactor (CLR) illustrating impedance gain of 4 to 5 for the FCL.

From the simple schematic in Fig. 1, it is easy to envision a three-phase HTS FCL using a single HTS DC bias coil. Fig. 4 shows an arrangement in which three single-phase devices are arranged radially with their corresponding inner core limbs inside a single cryostat (silver cylinder) containing the HTS DC bias magnet. The copper AC coils (red cylinders) are located on the outer limbs of the iron cores and spaced equidistantly. This arrangement constituted the basic design for the ZEN FCL and was used to construct the FCL device installed at Southern California Edison.

III. THE FCL AT SOUTHERN CALIFORNIA EDISON

With the support of the California Energy Commission (CEC) and the U.S. Department of Energy (DOE), this device, known as the CEC FCL, became the first HTS FCL in commercial service in the United States on March 9, 2009 when it was placed in the Avanti Circuit (otherwise known as the “Circuit of the Future”) in the Southern California Edison (SCE) Company’s Shandin substation in San Bernardino, California. The “Circuit of the Future” is an actual

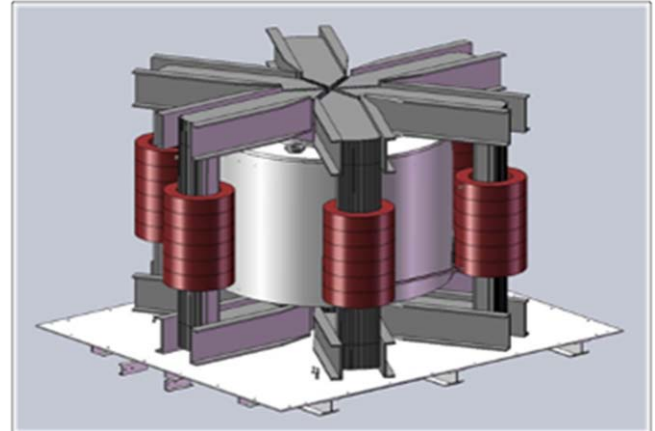


Fig. 4 – A three-phase saturating reactor HTS FCL with a single HTS DC bias coil

The CEC FCL employs cast-epoxy AC coils and a closed-loop cryogenic cooling system that uses sub-cooled liquid nitrogen at approximately 68K to increase the I_c and the working current of the DC HTS bias magnet coil to increase the available DC amp-turns and the range of DC magnetic bias flux. The basic design parameters of the CEC FCL are shown in Table I. Because the Avanti Circuit is a newly constructed distribution circuit with a low duty-cycle and no expected fault issues, the CEC FCL was designed for only modest fault current limiting capabilities and was intended to limit a 23 kA RMS potential steady-state fault current by about 20%. Instead of fault limiting performance, emphasis was placed on accurately modeling and predicting the performance of the FCL and its associated electrical waveforms.

TABLE I CEC FCL DESIGN PARAMETERS

Parameter	Value
Line Voltage	12 kV
Maximum load current	800 A (3 phase, 60 Hz)
Voltage drop at max. load	< 1% (70 V rms)
Prospective fault current	23 kA rms symmetrical
Asymmetry	X/R = 21.6
Fault limiting capability	20%
Fault type	3 phase to ground
Fault duration	30 cycles
Recovery time	instantaneous

The CEC FCL underwent extensive testing at Powertech Laboratories in October 2008. In the absence of an industry standard for HTS FCL testing, a comprehensive test plan that incorporated IEEE standards [7-9] for series reactors and transformers was prepared with input from SCE and the National Electric Energy Testing, Research and Applications Center (NEETRAC), a member-financed, non-profit research laboratory of the Georgia Technical University (Georgia Tech) in Atlanta, Georgia. Special emphasis was placed on comparing the performance of the CEC FCL predicted by

ZEN’s design protocol with the measured performance of the actual device, including AC steady-state current voltage drop (insertion impedance), steady-state AC current temperature rise, AC fault current limiting, and AC coil and DC HTS electromagnetic coupling. The dielectric performance of the CEC FCL was also tested including BIL, DC withstand voltage, lightning impulse and chopped-wave testing as required by the applicable IEEE standards [6-8]. Dielectric testing was performed before fault testing, and then repeated upon the conclusion of fault testing by SCE at their Westminster, California test facility before installation in the Avanti Circuit.

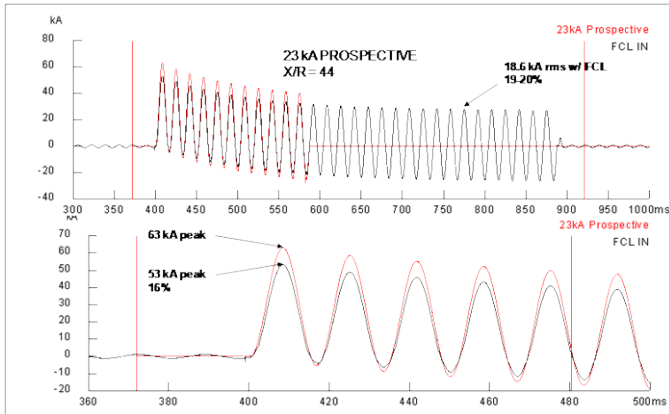


Fig. 5 – Design performance verification test for the CEC FCL showing 20% fault current reduction at 23 kA prospective fault current.

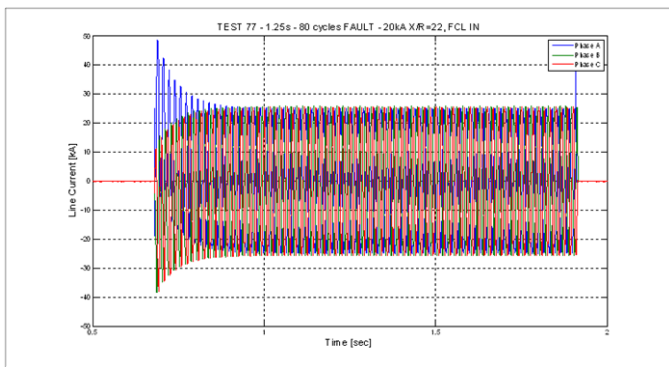


Fig. 6 – 82-cycle endurance fault test of the CEC FCL

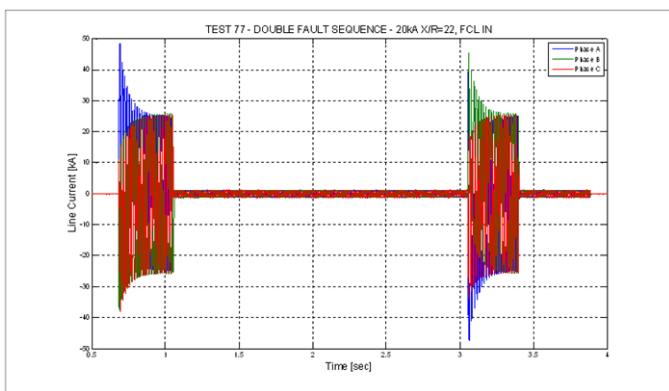


Fig. 7 – A double-fault sequence simulating re-closer operation on the CEC FCL

In all more than 65 separate test events were performed on the CEC FCL, including 32 fault tests. A typical fault test sequence involved the application of full-load steady-state

current and voltage (1,250 amperes RMS at 13.1 kV), the application of 30-cycles or more of fault current up to nearly 60 kA first-peak, and returning to the full-load conditions upon clearance of the fault. The CEC FCL performed extremely well and exceeded expectations by withstanding more than an expected lifetime of actual faults during a week of testing. Fig. 5 shows a typical fault sequence test in which the AC fault current is limited by approximately the targeted 20% reduction level. Fig. 6 is an endurance test of the CEC FCL in which it was subjected to an 82-cycle fault, and Fig. 7 is a double-fault sequence test, which was performed to measure the CEC FCL performance under an automatic re-closer scenario. Fig. 8 shows the CEC FCL in the Avanti Circuit at SCE’s Shandin substation, where it will remain through the end of 2010.



Fig. 8 – The CEC FCL installed at the SCE Shandin Substation in San Bernardino, California.

IV. OPERATIONAL EXPERIENCE AT SCE

The FCL operates in San Bernardino, CA, where the ambient temperature reached 108°F (or 42°C) in July 2009. During the past 18 months, the refrigeration portion of the device operated nearly 24/7. Only once, during a hot summer week, did the device experience venting of the cryogenics fluid and require replenishment of the liquid nitrogen. Once, an unexpected loss of DC magnetic bias occurred, causing the FCL to remain in-line in the unbiased condition for over one hour. The results of this event were published in a recent paper [10]. Following this event, the FCL was integrated with an automatic bypass switch that removes the FCL from the grid in case of a problem.

The FCL experienced three outages of substation power. It was able to ride-through the outages without suffering any downtime. It operated properly and safely by sending the correct alarms and bypass commands to the host utility, Southern California Edison. One of the three substation power outages is illustrated in Fig. 9. This particular event occurred June 27, 2010 at 1:30AM. An unexpected event on the 115kV high-voltage side caused a voltage dip and an outage at the 12kV substation side. The outage lasted more than 2 minutes. The FCL is equipped with a DC UPS and battery. As specified by the host utility, the FCL signaled the condition and immediately issued a bypass command, followed by a DC shut down. Fig. 9 shows how the DC magnet was gracefully shutdown. Upon resuming AC power, the cryogenic compressor was restarted, and cryogenic

conditions returned to normal, as shown in Fig. 10. At this point, the HTS magnet was ready to be energized and the FCL could have been switched in-line again. Note that a full ride-through of the event could have been possible, without bypassing the FCL, if the host utility had desired it.

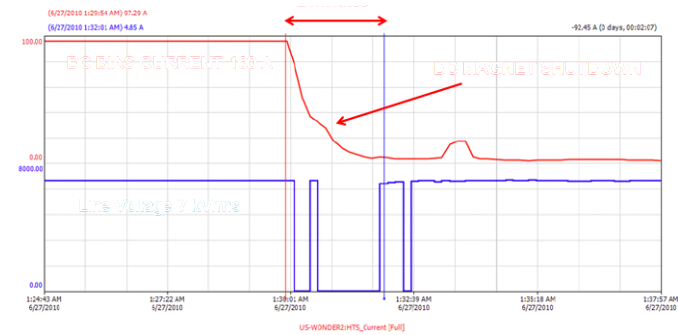


Fig. 9 – Loss of substation power and subsequent command to perform a controlled shut down of the DC magnet.

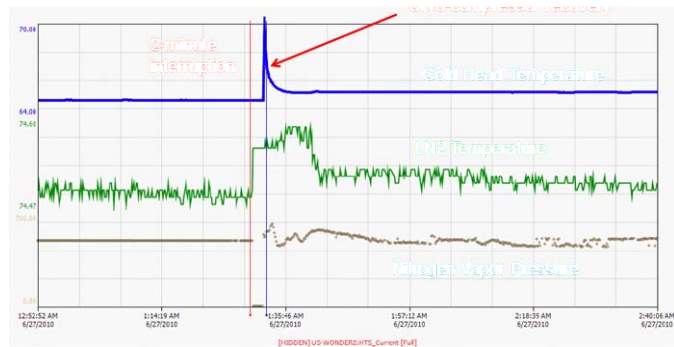


Fig. 10 – Cryogenics system returns to normal once substation power is restored.

The FCL is installed with an industrial programmable logic controller (PLC). The PLC allows Zenergy Power to fully monitor the device and fully communicate with the protection and control systems. The controller provides alarms, bypass commands, and shutdown signals to the utility control room via MODBUS communication. The controller also shares data with the utility SCADA system for monitoring purposes.

Cyber security was essential for Southern California Edison. To fulfill this requirement, Zenergy Power provided a dual-Ethernet port connection with secure data transfer and communication capabilities with two physically separate channels for independent SCE and Zenergy Power communications.

On January 14, 2010 the FCL experienced its first-ever in-grid fault. Based on the voltage data located at the load side of the FCL, as shown in Fig. 11, the event evolved from a phase-to-phase fault, to a three-phase fault, to a temporary recovery, to a phase-to-phase fault, to another three-phase fault, ending with an open line and clearing. This very unusual, mostly symmetrical, multi-fault event occurred over a three-second period. Physically the event was initiated by the overhead conductors of A and B phases slapping together during high wind conditions near the end of the Avanti Circuit. This phase-to-phase fault lasted about 250 milliseconds, when Phase C also faulted, thus evolving into a three-phase fault, lasting about half a second. The air

insulation recovered its full strength for about one second, but then the conductors of phases A and B again arced to each other for about three quarters of a second. The arc was about to be extinguished at this time; however, Phase C also arced, becoming another three-phase fault. The event ended about a quarter of a second later when Phase B conductor opened, dropped to the ground, and the circuit was eventually cleared. During this sequence of events the FCL operated as designed and limited the fault current.

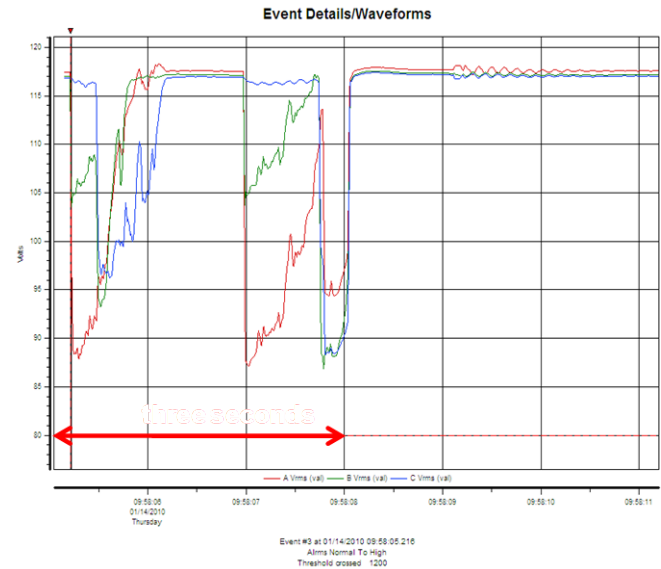


Fig. 11 – Multiphase sequence of fault events lasting over a three second period. This was the first in-grid fault experienced by the CEC FCL. It performed as designed and limited the fault current.

V. THE COMPACT FCL

In the course of building and testing the CEC FCL, ZEN conceived a new concept for saturating reactor FLC design that had the potential to considerably reduce the size and weight of the device, while allowing the dielectric rating of the FCL to be increased to transmission voltages of 100 kV and higher. This concept became known as the “Compact FCL,” and in order to test the concept and evaluate alternative methods for implementing it, ZEN, with financial support from the U.S. Department of Energy and the Consolidated Edison Company of New York, built and tested four full-scale prototypes using different internal designs.

All of the Compact FCL prototypes were built using standard “oil-filled” liquid dielectric transformer construction techniques. This allowed the required dielectric offset distances within the FCL to be minimized, greatly reducing the FCL prototypes’ size and weight for equivalent performance. Another important design innovation was the use of “dry-type” cryogenics to conductively cool the HTS coil without the use of liquid cryogenics. This allowed the operating temperature of the HTS coils to be reduced below the freezing temperature of liquid nitrogen, enabling further increases in the I_c and working current of the 1G HTS wire used in the DC bias magnet system and correspondingly higher DC amp-turns to magnetically saturate the iron cores. The use of conduction cooling also removes potential utility concerns about having large volumes of liquid cryogenics in confined spaces and potential pressure vessel over-

pressurization, rupture and venting concerns.

Table II shows all four of the Compact HTS FCL prototypes that were built and tested. These prototypes had the same nominal 15 kV design voltage and 110 BIL rating, but differed in their steady-state AC current ratings and targeted AC steady-state current insertion impedance and AC fault current limiting performance. The designed AC steady-state current levels ranged from 1,250 amperes RMS to 2,500 amperes RMS, and the targeted AC fault current reduction levels ranged from about 30% up to more than 50% of a 25 kA RMS potential steady-state fault current with an asymmetry factor yielding a first-peak fault current approaching 50 kA.

TABLE II COMPACT FCL DEVICES TESTED AT POWERTECH LABS IN JULY 2009

Parameter	Units	FCL # 1	FCL # 2	FCL # 3	FCL # 4
Line-to-Line Voltage	kV	12.47	12.47	12.47	13.8
Number of Phases	#	3	3	1	1
Line Frequency	Hz	60	60	60	60
Prospective Fault Current	kA	35	46	80	25
Limited Peak Fault	kA	27	30	40	18
Prospective Fault Current RMS Symmetrical	kA	20	20	40	11
Limited Symmetric Fault Current	kA	15	11.5	18	6.5
Load Current Steady-State RMS	kA	1.25	1.25	1.25	2.5 – 4.0
Voltage Drop Steady-State Maximum	%	1	1	1	2
Line-to-Ground Voltage	kV	6.9	6.9	6.9	8.0
Asymmetry Factor	#	1.2	1.6	1.4	1.6
Source Fault Impedance	Ohms	0.346	0.346	0.173	0.724
Fault Reduction	%	25	43	55	41

The Compact FCL prototypes underwent full-power load and fault testing at Powertech Laboratories in July 2009 using essentially the same comprehensive test plan that was employed for the CEC FCL. In all 118 separate tests were performed on the four Compact FCL prototypes, including 55 calibration tests, 12 load current only tests, and 51 fault tests. In many cases, the measured performance exceeded expectations, and the test program completely validated both the performance potential of the Compact FCL design and the efficacy of ZEN’s design protocol.

Fig. 12 shows the results of a typical AC load current voltage drop or insertion impedance test which displays good agreement between the predicted and the measured performance. Fig. 13 shows a fault current test in which the Compact FCL prototype reduced a prospective 25 kA RMS fault current by about 46%.

A particularly important result from the Compact FCL testing program was the fact that the AC coils and the DC HTS Coil exhibited very little electromagnetic coupling. Fig. 14 shows that the DC current in the HTS bias coil varied only by 5% as the Compact FCL was subjected to up to a 30 kA peak fault current. These results were very typical for all of the Compact FCL devices during fault current testing. The

steady-state voltage drop of the Compact FCL typically remained low with increasing AC currents and also exhibited very “clean” AC power characteristics with Total Harmonic Distortion levels well within the requirements of IEEE 519-1992 [9].

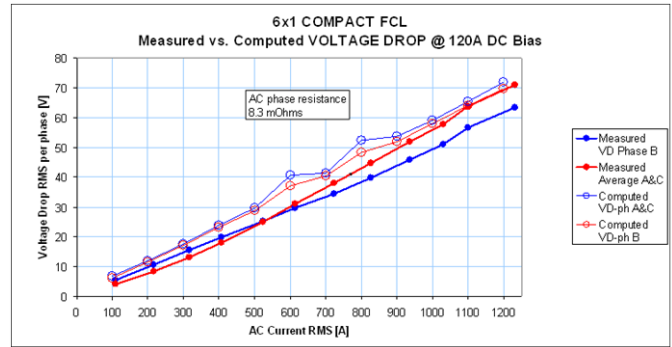


Fig. 12 – Typical AC steady-state load current voltage drop measurements illustrating good agreement between predicted and actual performance.

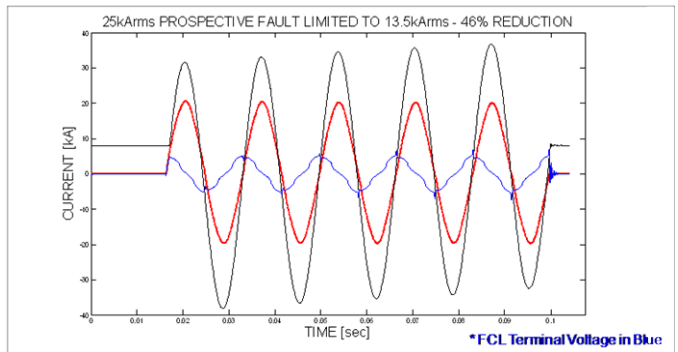


Fig. 13 – Compact FCL fault test showing a prospective 25 kA fault current limited by 46%. The black curve is the prospective fault current, the red curve is the limited fault current, and the blue curve is the voltage measured at the FCL terminals

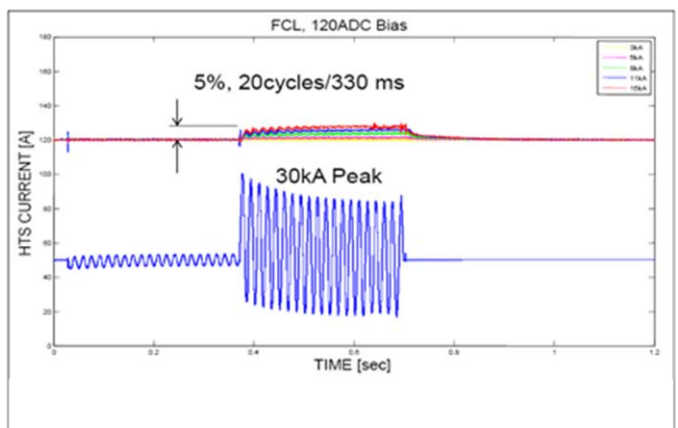


Fig. 14 – AC coil and DC HTS coil electromagnetic coupling during AC fault current testing illustrating the minimal coupling between the two coils.

VI. ADDITIONAL FCL PROJECTS IN PROGRESS

As a result of the successful testing of the Compact FCL prototype, ZEN has initiated the commercial sale of the Compact FCL for medium-voltage applications. Through the experiences of the CEC and DOE projects, ZEN has advanced the product development as illustrated in Fig. 15.

In January 2010 ZEN received a contract for a 15 kV-class Compact FCL, 1.25 kA nominal operating current, 50 Hz,

capable of limiting a 3-second fault and reducing it by at least 30%. It will be tested at KEMA USA late 2010 or early 2011 and delivered to the system integrator, Applied Superconductor Ltd, in early 2011 for installation in a CE Electric substation in the UK. A drawing illustrating its rough design and layout is shown in Fig. 16.

In the UK, the distribution network operators such as CE Electric, Energy North West, Scottish Power, E-On Central Networks, and EDF Energy Networks have become intensely interested in fault current limiters. All five of the above DNOs have commitments to host a 15 kV-class FCL sometime in the next 2-3 years. The reason for this enthusiasm is that with some 15% of England's distribution network already at 85% of its fault level design capability, there will be limited head room to allow for the connection of renewable (and more specifically) distributed generation which is required to support the UK Government's Low Carbon reduction targets. One of the solutions to freeing up network capacity to allow the connection of this generation will be the utilization of Fault Current Limiters.

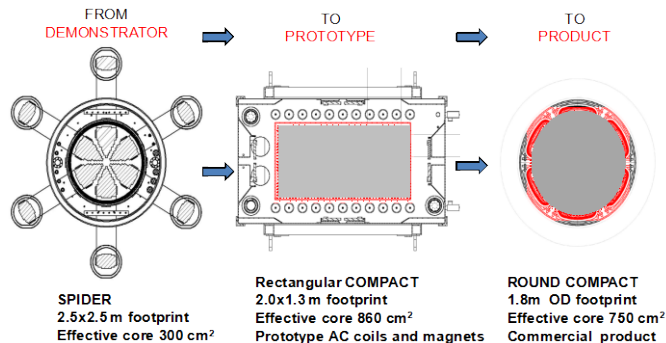


Fig. 15 – The path to commercial product. On the left is the first generation FCL that was tested, installed and operated in the grid to show performance and reliability. In the middle is the rectangular prototype Compact, which was built and tested to validate a smaller and more efficient FCL. And on the right is our now-standard round Compact FCL for distribution-class applications that takes advantage of all lessons learned throughout the process

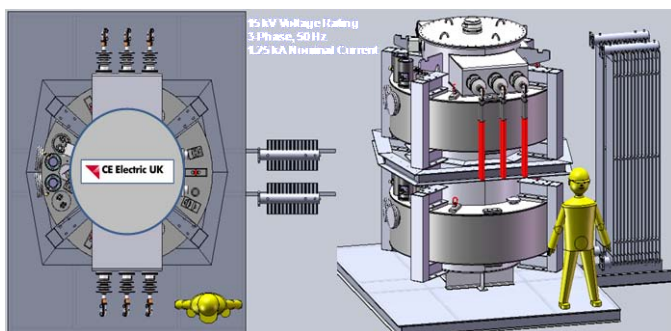


Fig. 16 – Design and layout of commercial 15 kV-class FCL for installation in a CE Electric substation in early 2011.

Also, ZEN has entered into an agreement with American Electric Power (AEP), Columbus, Ohio, to partner for the demonstration of a 138 kV three-phase Compact FCL as a part of ZEN's ongoing DOE-sponsored FCL development program. A single-phase 138 kV Compact FCL prototype will be built and tested in early 2011, and a three-phase Compact FCL demonstration unit will be built, tested and installed in

AEP's Tidd substation located near Steubenville, Ohio at the end of 2011. This device will be designed to operate at 1.3 kA steady state and reduce an approximate 20 kA prospective fault by 43% and instantaneously recover under load. The device will be installed on the low side of the 345 kV to 138 kV transformer and will protect the 138 kV feeder.

VII. SUMMARY

Zenergy Power has now had the experience of installing and operating a fault current limiter in the Southern California Edison electricity grid. As a result we can say that:

1. We successfully integrated a superconducting FCL in the grid,
2. The operational experience has been a big success for both ZEN and Southern California Edison,
3. Both parties gained invaluable experience by operating through all four seasons,
4. Zenergy Power learned to address unplanned events such as loss of station power, and
5. The host utility learned about preventive maintenance and how the device responded to real fault events.

As a result of this experience, Zenergy Power has received contracts for the installation of a 15 kV-class device in the UK and a 138 kV-class device in the US.

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