

SATURATED-CORE FAULT CURRENT LIMITER FIELD EXPERIENCE AT A DISTRIBUTION SUBSTATION

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ABSTRACT

Zenergy Power has been developing an inductive-type of fault current limiter (FCL) for electric power grid applications. In March 2009 Zenergy Power installed a FCL in the Avanti distribution circuit of Southern California Edison's Shandin substation in San Bernardino, CA, rated at 15 kV and 1,200 amperes steady-state. In January 2010, this device successfully limited its first series of real-world faults when the circuit experienced multiple single-phase and three-phase faults. Zenergy Power also received contracts to deliver an 11 kV, 1,250 amperes FCL for the CE Electric UK grid and a 138 kV, 1,300 amperes FCL for the Tidd substation of American Electric Power.

INTRODUCTION

Since 2005, Zenergy Power (ZEN) has been developing proprietary high-temperature superconductor (HTS) fault current limiter (FCL) technology. The ZEN FCL is an inductive type of FCL that uses a magnetically saturating reactor concept to act as a variable inductor in an electric circuit. Unlike resistive and shielded core FCLs that rely on the quenching of the superconducting material (a sudden transition from the superconductive state to a normal resistive conductor state when a critical current level is reached) to achieve increased impedance, saturating-core FCLs use the dynamic behaviour in the magnetic properties of a magnetic core (nominally grain-oriented silicon steel, but other materials are possible and offer unique performance characteristics) to change the inductive reactance on the AC circuit being protected.

OPERATING PRINCIPLE

The basic operating principles of the ZEN FCL are easily explained with a simple diagram. Referring to Figure 1, 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 centre of the device. A low voltage DC power supply energizes the HTS coil with a high DC bias current to create a very strong DC magnetic field that magnetically saturates the iron cores. The outer limbs of the iron cores are wound

with conventional copper coils that are connected in series with the AC circuit that is to be protected. The DC bias magnetic flux is unidirectional as determined by the direction of DC bias current flow and the HTS coil winding orientation. The AC flux generated by the line current in the series-connected AC coils alternates direction in synchrony with the periodic inverting of the AC line current sine wave. Consequently, the AC magnetic flux alternately “boosts” and “bucks” the DC bias magnetic flux in the portions of the iron cores under the AC coils.

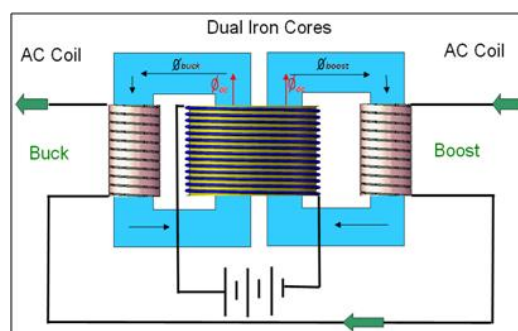


Figure 1. Basic saturating reactor FCL concept.

If the magnitude of the AC magnetic flux is small in comparison to the DC bias magnetic flux, the iron cores remain magnetically saturated, and the AC circuit impedance is low. When the magnitude of the AC flux generated by the AC line current is sufficient to overcome the DC bias magnetic flux and to start to drive the iron cores out of magnet saturation, the impedance increases suddenly, acting to limit the AC line current flow. The response time is sufficient to effectively limit the first ¼-cycle peak of the AC line fault current. When the fault clears, the constant DC bias magnetic flux restores the magnetic saturation of the iron cores, reducing the AC impedance to the low steady-state value.

CALIFORNIA GRID OPERATION

Background

ZEN has built and tested dozens of prototype FCLs, including two full-scale distribution-voltage devices, based on the architecture shown in Figure 1. After major

refurbishment and modification following extensive testing, the second of these full-scale FCLs was installed in a field demonstration in the Avanti circuit of the Southern California Edison (SCE) Shandin Substation located in San Bernardino, CA, as shown in Figure 2.



Figure 2. The CEC FCL installed at the SCE Shandin Substation in San Bernardino, California, USA.

This comprehensive field demonstration, which ran from March 2009 until October 2010, was partially sponsored by both the California Energy Commission (CEC) and the U.S. Department of Energy (DOE), with significant in-kind support by SCE, and was the first instance of a HTS FCL being used in commercial service in the U.S. electric grid. The Avanti circuit, also known as the “Circuit of the Future,” is a specially configured and instrumented distribution circuit serving residential and commercial customers that is used by SCE, DOE and CEC to test and evaluate promising “smart grid” and grid modernization technologies. The focus of the demonstration project was two-fold. The first objective was to establish that ZEN could design and qualify a FCL to a precise operational performance specification defined by SCE. The second objective was to thoroughly evaluate the operations and maintenance considerations associated with the use of a HTS FCL in commercial service and to define the requirements and protocols for widespread adoption of HTS FCLs by electric utilities. The demonstration program was a complete success on both counts.

The “Avanti” FCL was nominally a 15 kV class (110 kV BIL), 1200 amperes rms, 60-Hz device that was designed to limit a 23 kA rms symmetric prospective fault by at least 20% while producing no more than 70 V back-emf at rated steady-state current). The FCL was subjected to extensive full-power (rated voltage and current) testing, fault testing, and standards testing at Powertech Laboratories, Surrey, B.C., Canada in October 2008, and a second set of high-voltage electrostatics acceptance testing (lighting impulse, chopped-wave, voltage withstand, and partial discharge) was performed at SCE’s laboratories in Westminster, California in December 2008. In the absence of accepted industry standards for FCLs, a comprehensive test plan based on IEEE standards for transformers and series reactors [1-3] was developed in collaboration with SCE and

NEETRAC¹. In all, 65 separate tests events were performed, including 32 full-power fault tests with first peak fault current levels up to 59 kA.

Fault tests included individual fault events of 20-30 cycles duration, as well as multiple fault events in rapid sequence (to simulate automatic re-closer operation) and extended fault events of up to 82 cycles duration (to simulate primary protection failure scenarios). The design, development and testing of the FCL has been extensively documented in several papers [4-5].

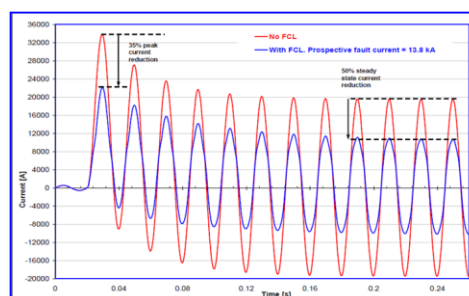


Figure 3. Current limiting behavior of the ZEN FCL.

Operating Experience

The operations and maintenance experience gained and the resulting protocols for the design, installation, control, monitoring, and employment of FCLs in the electric grid were the most important results of the “Avanti” FCL demonstration. The operating environment at the Shandin substation was a severe, U.S. southwest desert environment with hot (daytime temperatures well in excess of 40 °C), dry, dusty, high-wind conditions. Additionally, a residential neighbourhood located nearby imposed severe ambient noise requirements. The FCL performed well throughout the demonstration, but several significant modifications were made in collaboration with SCE. Significant observations from the demonstration project include:

- The enclosure environmental conditions must be maintained within a narrow band for the reliability of the control, instrumentation, cryogenic refrigeration and DC power supply equipment – additional air conditioning was installed in the FCL enclosure to satisfy hot-day cooling requirements.
- Air-cooled cryogenic refrigerators were satisfactorily employed (with sufficient enclosure air conditioning), but water-cooled cryogenic refrigerators may be more robust in the field.
- A sub-cooled liquid nitrogen re-condensing cryogenic system was successfully employed. Current FCLs will use a “dry-type” conduction-cooling cryogenic system free of liquid cryogens.
- The FCL control system is able to shut itself down in

¹ National Electric Energy Testing Research Applications Center, The Georgia Technical University, Atlanta, Georgia, USA.

the event of loss of station power – several substation blackouts were experienced – and to automatically restart when station power is restored, including the restoration and stabilization of cryogenic refrigeration.

- A UPS was installed to provide control, instrumentation and DC bias current for up to two hours during station outages.
- While multiple channels of FCL system “health” data were provided, SCE desired a “watch-dog” monitoring system that provided a “Go” (all systems normal) or a “No-Go” (some system off-specification) with an automatic bypass switch to remove the FCL from service in the event of a “No-Go” condition.
- The FCL control system was successfully integrated through a secure Ethernet connection into the SCE SCADA system; a MODBUS control scheme enabled secure, real-time monitoring and operation from the SCE Control Room.
- If the FCL is being relied upon for system protection, the system must be configurable (through temporary buss-splitting, for example) to control fault duty levels in the event the FCL must be removed for maintenance or repair.
- Saturated-core FCLs as small inductors during steady-state conditions and large inductors during fault conditions must be evaluated for compatibility with existing circuit resistance and capacitance values to ensure voltage stability on the protected circuit – a separate paper discusses this requirement [6].
- The effects of saturated core FCLs on circuit breaker transient recovery voltage must be evaluated to ensure adequate rating of circuit breakers and determination of maximum allowable interrupt currents – a separate paper discusses this requirement [7].

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 Figure 4, 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.

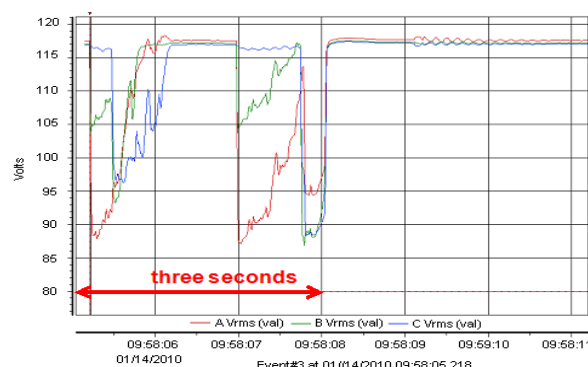


Figure 4. Multiphase sequence of fault events lasting over a three second period.

DEVELOPMENT OF COMPACT FCL

Despite the unqualified success of the “Avanti” FCL demonstration project, the large size and weight of the air-dielectric, closed-core FCL architecture relative to its electrical power rating challenged the economic value proposition at distribution voltages. At the same time, the air-dielectric design complicated scaling-up the device to higher voltages. In light of these observations, ZEN conceived of an open-core FCL design that used an oil dielectric and conventional transformer design and manufacturing techniques to create a much smaller FCL with greater fault limiting performance and much higher voltage and power ratings. This new design was designated the “Compact FCL.”

ZEN, with financial support from DOE and the Consolidated Edison Company of New York (ConEdison), built and tested four full-scale distribution-voltage Compact FCL prototypes using different internal designs. A unique feature of the Compact FCL is that there is no physical interface between the “AC side” of the device (the line current and voltage in the circuit being protected) and the “DC side” of the device (the HTS DC bias coil and its associated power supply). The AC coils and bus-work are located inside a dielectric tank, and the HTS DC bias magnets are placed in cryostats that surround the tank.

Another important design innovation is the use of “dry-type” cryogenics to conductively cool the HTS coil without the use of liquid nitrogen. Conduction cooling allows the HTS coil to be cooled below the nitrogen freezing point, thereby improving the performance of the HTS wire and reducing the amount used in the magnets. “Dry-type” conduction cooling also avoids concerns about large volumes of liquid cryogenics in confined spaces and potential pressure vessel and stored energy. Figure 5 shows a recently completed 15kV class FCL with two “dry-type” conduction cooled coils surrounding an oil-filled dielectric tank with the AC coils. This device is 75% smaller and

lighter than the equivalent device shown in Figure 2.



Figure 5. Compact FCL with “dry-cooled” HTS magnets surrounding an oil-filled dielectric tank with AC coils.

AMERICAN ELECTRIC POWER PROJECT

ZEN has entered into an agreement with American Electric Power (AEP), Columbus, Ohio, to partner for the demonstration of a 138 kV three-phase FCL as a part of ZEN’s ongoing DOE-sponsored FCL development program. A single-phase 138 kV FCL prototype will be built and tested in the first half of 2011, and a three-phase FCL demonstration unit will be built, tested and installed in AEP’s Tidd substation located near Steubenville, Ohio in early 2012. 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.

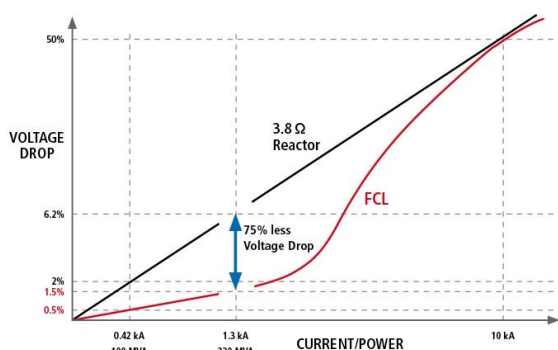


Figure 6. Comparison of voltage drop between a current limiting reactor and the ZEN FCL.

AEP presently uses a conventional 3.8 Ω current limiting reactor to protect the circuit from excess fault currents. This reactor causes a 6% voltage drop on a base load of

320 MVA. When the ZEN FCL is installed the circuit will have the same amount of fault current protection; however the steady-state voltage drop will be 75% less – only 1.5% on a base load of 320 MVA. Please see Figure 6.

Acknowledgments

The FCL at SCE’s Shandin substation was partially sponsored by both the California Energy Commission (CEC) and the U.S. Department of Energy (DOE), with significant in-kind support by SCE.

The compact FCL designs were developed and tested with financial support from DOE and the Consolidated Edison Company of New York (ConEdison),

The 138kV three-phase FCL is part of ZEN’s ongoing DOE-sponsored FCL development program and partnered by American Electric Power (AEP), Columbus, Ohio.

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