Final Engineering Report

Design, Test and Demonstration of Saturable Reactor High-Temperature Superconductor Fault Current Limiters

Final DOE Technical Report, DE-FC26-07NT43242

By: Frank Darmann, Robert Lombaerde, Franco Moriconi, Albert Nelson

Author: Robert Lombaerde

For: U. S. Department of Energy, National Energy Technology Laboratory

Client: Donald Geiling

March 2012

ZENERGY POWER

1616 Rollins Road, Burlingame, CA 94010 USA

www.zenergypower.com

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Author(s):	Frank Darmann, Robert Lombaerde, Franco Moriconi, Albert Nelson		
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1 Executive Summary

Fault current limiters (FCLs) when utilized in the electric grid will limit the current in the system when a fault, commonly thought of as a short circuit, occurs. (Nominal current in utility electrical lines may easily be as much as 2,000 Amps or more, and during a fault when the lines are shorted together by wind or shorted to ground from a downed utility pole or equipment internal failure, the current can typically be 25,000 Amps, 40,000 Amps, 60,000 Amps or more.) While the usual utility implementation purely for fault limitation is an air-core reactor (utilities often use other means such as splitting electric buses or relocating generator or electrical feeder circuit tie-ins to limit total fault current potential), the air-core reactor will typically have a relatively high nominal insertion impedance and subsequent voltage drop that will increase linearly with current. The Zenergy Power FCL is a saturable reactor high-temperature superconductor fault current limiter design and is rather unique in that it presents low impedance to electrical currents under nominal conditions; however, under fault conditions the impedance is large and will limit the flow of current. A key factor in the Zenergy Power design is that the fault current itself initiates the change to high impedance with no other outside triggering and can, therefore, be considered a "Smart Grid" component. The Zenergy Power FCL reacts quickly, for the impedance change can occur within the first quarter cycle of the 50-Hertz or 60-Hertz current. The Zenergy Power design has no AC load current or voltage through the superconducting components, and once the fault is cleared, the FCL returns instantly to low impedance and is ready for the next fault. The fast reaction time allows the FCL to handle multiple faults in rapid succession. The application of FCLs to an electric grid can provide protection to upstream circuitry already at its maximum rating, lower the maximum fault current in the system, improve the lifetime and reliability of downstream electrical circuits and components, enable the "ride-through" of short duration electrical transients without power interruption, and facilitate interconnection of distributed energy sources (wind, solar, hydro) without increasing the fault current design rating.

Zenergy Power has successfully designed, built, tested, and installed in the U.S. electrical grid a saturable reactor FCL. Beginning in 2007, as SC Power Systems and from 2008 as Zenergy Power, Inc., Zenergy Power employed a DOE matching funding opportunity cost-share grant and American Recovery and Reinvestment Act funding to design, build and test a saturable reactor fault current limiter suitable for commercialization. The demonstration effort began with a very basic FCL design utilizing 1G HTS conductor for a DC bias magnet housed in a LN₂ cryostat. Substantial progress was made in two areas. First, the cryogenics progressed from containers of liquid nitrogen housing the HTS coils to cryostats utilizing dry conduction cooling reaching temperatures down to sub 20 degrees K. Large round cryostats with "warm bore" diameters of 1.7 meters enabled the design of large tanks to hold the AC components. Second, the design of the AC part of the FCL was refined from a six-legged, picture-frame magnetic core "spider" design to a more compact and lighter design with better limiting capability. Refinement of the flux path and core shape led to an efficient saturable reactor design requiring less Ampere-Turns to saturate the core. In conclusion, the refinement of the saturable reactor FCL led to a more efficient design not requiring the HTS wire and associated peripheral equipment for a more economical product in line with the electric utility industry expectations.

The work funded by this project assisted Zenergy Power's efforts to design, build and prove the commercial potential of the saturable core FCL concept and to demonstrate its fault current limiting potential with full-scale prototypes. Computer models enabled Zenergy Power to first predict the fault current limiting of a design and then to verify the design's performance from actual measurements taken at test laboratories. The original plan was to build three sets of FCLs with voltage classes of 15 kV, 69 kV, and 138 kV over five Budget Periods (BPs), however, positive results of the initial tests on the low-voltage FCLs initiated a revised plan of only two budget periods leading directly to a 138 kV FCL. The key factor in this decision was that the superconductor components and the AC electrostatics were completely separate, and for a HV design the electrostatic considerations within the AC components "tank" alone were the major risk factor for the design to work.

Although the 138 kV paper design had been finished and major components were to be procured under issued purchase orders, the project was terminated due to the realization that with proper flux manipulation and containment, the FCL could be designed with a copper coil replacing the HTS wire and its associated cryostat, cold heads, cryogenic compressors, chillers, HVAC units, auxiliary power supplies and distribution systems, controls and notably, the associated poor reliability and high maintenance requirements of these cryogenic components and auxiliary support systems. The Zenenergy Power management team decided to steer the direction of the company away from HTS wire magnets and focus on copper magnet FCLs to take advantage of their inherent lower cost and higher reliability. Crucial to this decision was the realization that the projections for the increase in performance and cost-down of HTS conductor and cryogenic systems projected over the next 5 years at the start of the project in 2007 had not materialized and were not likely to do so for the foreseeable future.

The original goal for the DOE funding of the Zenenergy Power project "Design, Test and Demonstration of Saturable Reactor High-Temperature Superconductor Fault Current Limiters" was to stimulate the HTS wire industry with first 1G then 2G HTS wire applications. Over the approximately 5 years of Zenenergy Power's use of HTS wire, the cost over time had not dropped nor had the availability increased (today the availability of 2G wire is essentially non-existent outside of specific programs and partnerships of the few performing 2G HTS conductor manufacturers). Zenenergy Power had foreseen a large potential for FCLs at a reduced price from the initial models built with 1G wire. The attraction of 2G wires at greatly reduced prices from 1G made the commercial production of FCLs feasible for the utility industry. However, the price of HTS wire has not dropped as expected, and today one cannot buy quantities of 2G wire and the price is higher than the limited available amounts of 1G wire. With the recent reductions in the DC magnet bias flux required to operate the Zenenergy Power FCL, the commercial pathway for Zenenergy Power to provide a reliable and reasonably priced FCL to the utility industry is to use conventional resistive magnets rather than HTS magnets. Since the premise of the original funding was to stimulate the HTS wire industry and Zenenergy Power has determined methods to use copper based magnets, the DOE and Zenenergy Power decided to mutually terminate the project.

2 Introduction and Background

To promote the HTS wire industry the United States Department of Energy provided matching funds for several HTS projects. In September 2007, SC Power Systems, Inc. was granted DE-FC26-07NT43242 to Design, Test and Demonstrate Saturable Reactor High Temperature Superconductor Fault Current Limiters. The original proposal was split into five budget periods which encompassed design, building and testing of three classes, 15 kV, 69 kV, and 138 kV, FCLs. Subsequent to the award, SC Power Systems joined with Australian Superconductor, and Trithor GmbH to form Zenenergy Power, Plc headquartered in the UK. The merger in 2008 produced a synergistic company of design and modeling in Australia, FCL manufacturing in the US, and a turnkey superconducting magnet source in Germany. The Saturable Reactor HTS FCL, which was first researched in Australia as far back as the late 1990s, was refined and analyzed from models tested under fault conditions. Design equations were verified from the models, and Zenenergy Power produced an FCL for the California Energy Commission in conjunction with Southern California Edison and placed it in the SCE grid in San Bernardino, CA for eighteen months. The saturable reactor FCL design relies very heavily on a large mass of iron which must be saturated with a DC magnetic bias flux. The original presumption was that this DC magnetic flux biasing could be done most efficiently with an HTS magnet. The improvements over time of the Zenenergy Power FCL have centered on the constant reduction of iron mass and size to develop a commercially viable product for the utility industry. The progressive development of the saturated reactor FCL led to the elimination of the HTS wire as more efficient methods of core saturation were developed which could be accomplished without the cryogenics and their associated poor reliability and maintenance requirements. Without the need for HTS wire in the FCL, the original purpose of the matching grant was not met and DOE and Zenenergy Power mutually terminated the FCL project.

3 Technical Approach and Results

3.1 How the Saturable Reactor HTS Fault Current Limiter Works

The saturable reactor fault current limiter works on the principle that an AC coil with an air core will have relatively low impedance, but if a (magnetically unsaturated) iron core is placed in the air core of the AC coil, the coil will have much higher impedance. If the iron core in the AC coil is magnetically saturated, then the impedance will again be low and will approach that of an air core coil.

- AC coil with air core – low impedance
- AC coil with iron core (magnetically unsaturated iron) - high impedance
- AC coil with iron core (magnetically saturated iron) – low impedance (close to air core value)

Figure 1: AC Coils with Iron Cores Saturated by DC-Powered HTS Coil

Figure 1 depicts two AC coils with iron cores and an HTS magnet powered by a DC power supply able to saturate both cores with magnetic flux. Note: the AC current into the coil on the left side will generate a magnetic flux that boosts the flux generated by the DC magnet in the associated iron core. The same AC current passing through the coil on the right side bucks the flux generated by the DC magnet in the right-hand core. If this were a saturated reactor fault current limiter, the nominal AC load current (which typically needs to be significantly less than the limited value of any fault current) would flow through the AC coils with little impedance due to the saturated iron cores. (The magnetic field generated by the HTS magnet is much greater than the magnetic field generated by the AC current in the AC coil.) When a fault occurs, the fault current is sufficiently large that the flux generated in one iron core from the fault current through the AC coil during one-half cycle will be enough to desaturate the iron – resulting in the AC coil having much greater impedance and limiting the fault current. Upon reversal of the AC cycle, the other iron core will desaturate during the second half-cycle and again limit the AC current flow as the first iron core resaturates. The key to the operation of the saturated reactor FCL is sizing the iron core and the DC magnetic flux bias magnet to have low impedance under normal operating conditions when the iron cores are magnetically saturated by the DC magnet, but designing the AC coils to generate enough magnetic flux to desaturate the iron cores based on the predicted amount of prospective fault current and the acceptable value of limited fault current.

3.2 Budget Period 1

Zenergy Power's first FCL was built to prove the saturable reactor concept. It was built with narrow picture frame style cores and used a nitrogen filled cryostat to cool the HTS 1G wire. Figure 2 is the FCL before it was enclosed.

Figure 2: First FCL Produced by Zenergy Power

3.2.1 Testing First Prototype at PG&E San Ramon, CA

In general, the first prototype HTS FCL device succeeded in accomplishing about 90% of the overall objectives during the first phase of testing at PG&E San Ramon, California. Specifically, Zenergy Power personnel were able to:

- Configure the test yard equipment to provide the desired levels of voltage and current,
- Reliably and accurately measure the steady-state and transient voltages and currents,
- Repeatedly measure the test yard voltages and currents with a high degree of repeatability,
- Repeatedly and reliably trigger a bolted three-phase fault at a zero-crossing voltage of one phase of the circuit,
- Measure the steady-state impedance of the HTS FCL,
- Measure the steady-state voltage drop of the HTS FCL,
- Record the steady-state voltage and current waveforms (both AC and DC) of the HTS FCL,

- Measure the steady-state and transient heat-loads and cooling requirements of the HTS FCL,
- Measure the fault transient response (both AC and DC) of the HTS FCL, and
- Obtain measurements of several other parameters (such as temperature, mechanical loads and flux levels) for the HTS FCL.

Testing was less than 100% successful, because of two observed issues with the HTS FCL device. The first issue, a known leak in the cryostat vacuum space, resulted in much higher liquid nitrogen consumption than expected. The second issue, a higher than desired steady-state insertion impedance, appeared to result from lower than expected magnetic flux saturation levels in the outer limbs of the HTS FCL iron cores. This was ultimately attributed to measured lower than target value flux levels in the iron cores, which were determined to result from the existence of parallel reluctance paths or other flux "short circuits" stemming from certain mechanical construction characteristics of the HTS FCL.

3.2.2 Testing First Prototype at Powertech, Surry, British Columbia, Canada

High-power testing performed at Powertech Labs followed a test plan summarized in SCP test report SCPS-TR 07_03-03. High voltage fault current tests were conducted at 2.5, 5, 10 and 12.5 kA, under a variety of reactive and resistive source impedances. X/R ratios were in the range of 10-11. Fault current reduction levels achieved were 14%, 14%, 20% and 22% respectively for tests conducted at 2.5, 5, 10 and 12.5 kA RMS. Peak measured fault current for the test conducted at 12.5 kA was measured at 16.5 kA. As expected, at full-rated power conditions (12.47 kV and 10,000 amps RMS) at Powertech, fault current reduction levels achieved were much lower than the low voltage testing performed at PG&E.

Summarizing other test results includes:

- Maximum Symmetrical Current: 12.5 kA RMS
- Maximum Asymmetrical Current: 39 kA
- No appreciable variations or excursions in cryostat temperature
- No significant AC coil to DC coil coupling was observed.
- Up to the lab's thermal limits, the HTS FCL was subjected to the labs full-power, steady-state voltage and current, faulted and returned to nominal steady-state operations within 30 cycles.
- Insertion impedance was reduced or improved by more than 50% as compared to the earlier testing performed at PG&E. Additional modeling and analysis, performed to determine how to lower the insertion impedance to meet SCP standards, revealed the need to improve the low-reluctance flux return path.

With the exception of insertion impedance, finite element analysis (FEA) modeling results concurred with the test results. The higher measured insertion impedance was attributed to insufficient iron core saturation in the vicinity of the AC coils. Thermal and electrical FCL stressing proved the basic design was sufficiently robust for electrical distribution system service.

The HTS FCL results exceeded and accomplished 100% of the overall objectives during this second phase of testing. Specifically, SCP personnel were able to:

- Configure the test yard equipment to provide the desired levels of voltage and current,
- Reliably and accurately measure the steady-state and transient voltages and currents,
- Repeatedly measure the test yard voltages and currents with a high degree of repeatability,
- Repeatedly and reliably trigger a bolted three-phase fault at a zero-crossing voltage of one phase of the circuit,

- Measure the steady-state impedance of the HTS FCL,
- Measure the steady-state voltage drop of the HTS FCL,
- Record the steady-state voltage and current waveforms (both AC and DC) of the HTS FCL,
- Measure the apparent steady-state and transient heat-loads and cooling requirements of the HTS FCL,
- Measure the fault transient response (both AC and DC) of the HTS FCL, and
- Obtain measurements of several other parameters (such as temperature, mechanical loads and flux levels) for the HTS FCL.

The performance of the HTS DC bias coil was measured several times using several methods throughout the testing program, and its performance was nominal at all times with no variation or deterioration detected.

The results of the first and second phase testing programs were used to modify Zenergy's modeling and simulation algorithms, engineering and design techniques, and baseline FCL manufacturing processes for the DOE three-phase, 15 kV-class, 2G+1G HTS FCL, which was designed, built and tested in fiscal year 2008.

3.2.3 Southern California Edison FCL, installed in Avanti Grid, San Bernardino, CA

This distribution class (15 kV) saturated reactor FCL was the first Saturated Reactor FCL installed in the United States electrical grid. The demonstration lasted for eighteen months and proved to be a learning experience for all parties. The unit was the object of several tours – specifically CIGRE, and DOE and the source of several papers on FCLs. The FCL also experienced a real fault in the Avanti grid. Figure 3 shows the 15 kV FCL with several panels removed during the HV testing at Powertech in Surry, British Columbia, CN.

Figure 3: Zenergy Power's 15 kV FCL at HV Test

Figure 4 shows the Zenergy Power 15 kV FCL installed at the Avanti Substation of Southern California Edison. The FCL was installed on the low-voltage side of a 115 kV to 12 kV transformer in line with a feeder circuit. This particular feeder circuit was a live, commercial circuit with residential, commercial and light industrial customers designated the "Circuit of the Future," which had been specifically configured to demonstrate new technologies for the electric grid. The bypass switch was installed to facilitate isolation of the FCL for maintenance and repair and for quick, remote removal from the circuit in the event of any problems. The FCL installation was metered for voltage and current on both sides of the FCL, and the station was equipped with digital fault recorders in order to collect data on events at the substation and the performance of the FCL under normal and transient conditions.

Figure 4: Zenergy Power's 15 kV FCL Installed at SCE Avanti Substation with Bypass Switch

The goals of the SCE demonstration program, which was also supported by the California Energy Commission (CEC), were to demonstrate that ZP could design a FCL to a specific set of performance requirements, build the device, test it to verify that it met the specified requirements, and qualify it for installation in the SCE grid. A key aspect was to improve the models used in the software design programs that could accurately predict performance. Through several refinements ZP has implemented a PSCAD model of the FCL and has been able to predict the performance of the device. Figures 5 and 6 show the comparison of the predicted fault limitation and the actual measured fault limiting.

Figure 5: Calculated FCL Limiting of 17% of 21 kA Fault

Figure 6: Powertech Result Showing 19% Fault Reduction of 23 kA Fault

The design of the Avanti FCL followed the ZP original picture frame model with twelve limbs (four limbs per phase, each joined top and bottom with yokes to make six rectangular closed cores for a total of 24 laminated magnetic steel structures per FCL) and a cryostat in the middle. The cryostat used super-cooled liquid Nitrogen created by two cold heads in the cryostat which employed a drip condensation method for super-cooling. The two air-cooled cryogenic compressors provided redundancy (only one was needed to maintain normal operations), and the FCL was monitored by a microcontroller with remote monitoring capability. Two major problems were encountered and corrected during the course of the demonstration program. First, the microcontroller had a memory leak and memory overflow causing the unit to shutdown. This was resolved by implementing an industry standard Siemens PLC for the microcontroller and SCE installing an automated bypass switch (the bypass switch was not related specifically to the memory overflow problem, but the overflow problem underscored the need for SCE to be able to remotely connect and disconnect the FCL). Second, the installation was in the Southern California desert area with very hot temperatures in the summer. When the outside temperature reached over 108 degrees F the HVAC system could no longer cool the cryogenic compressors and the system shut down. The solution was to install a larger capacity HVAC system and a sunshade over the cryogenic and instrumentation area.

Summary of the operational experience at the Avanti Substation includes:

- 18 months of operation
- Operated in a harsh, hot, dry, dusty environment
- Maximum ambient temperature reached was 108°F in Summer '09
- Heavy winds and considerable wind-borne dust and debris
- Experienced one loss of DC with consequent "resonance" condition (IEEE paper)
- Successful integration with automatic bypass switch
- Experienced one fault event with multiple faults in quick succession (14 January '10)
- Experienced three "auxiliary power failures"
- Effective bypass of FCL and shut-down of the HTS coil (as expected)
- "Auxiliary power failures" caused by grid disturbances
- Instantaneous bypassing achieved by SCE (2 out of three)
- Successful recovery after 2-minute black out of auxiliary power
- Performed routine maintenance on cryogenics compressors
- Replaced cryogenic compressor after 8000 hours
- Replenished LN2 after HVAC loss (hot Summer 2009)

The fault event was recorded by SCE instrumentation on 14 January 2010 and is presented here to show the capability of the FCL.

A summary of the experience of ZP FCL for SCE includes:

- First successful integration superconducting FCL in US grid
- Operational experience at SCE has been a big success for both ZP and SCE
- Resonance study revealed minimal effects and defined protocol for FCL grid application analysis
- Both parties gained invaluable experience by operating through all four seasons
- ZP learned to address unplanned events such as loss of station power
- The host utility learned about preventive maintenance and how the device responded to real fault event

3.2.4 Utility Partner Implementation

Upon the success of the SCE FCL, ZP implemented a utility partner investigation. Zenergy Power and Seattle City Light agreed to pursue an FCL for their grid. The design parameters were:

- Line Voltage 26 K Volts
- Steady State Current 1200 Amps
- Prospective Fault Current 30 K Amps
- Fault Current Clipping (Desired) 40 – 50 %
- Allowable Voltage Drop 1 %

These parameters led to a very large and expensive FCL in the picture frame or spider type design. Zenergy Australia determined that a more compact design would be feasible and suggested a new implementation. Table 1 lists the comparison of the two designs, and Figure 8 contrasts models of the two concepts.

Parameter	Spider	Compact
Iron Core Weight (lbs)	252K	67K
Cost of Iron @ \$3.00/lb	\$ 756K	\$ 201K
FCL Size (core iron + AC coils)	19' x 19'	10' x 7'

Table 1: Comparison of Spider versus Compact Design

Figure 8: Spider and Compact FCL Design Examples

While the Seattle City Light partnership did not come to fruition due to budget constraints and loss of personnel in Seattle, ZP was able to determine realistic utility wants and needs. The spider (picture frame) design was deemed not feasible for production due to the excessive size, weight, and cost.

3.2.5 The Compact Design

The premise of a compact FCL design to reduce the size and weight led ZP to investigate several configurations. The compact design still works on the same saturated reactor principle as the spider except instead of an interior core saturated by the HTS magnet and the AC coils over the outside limbs of the picture frame cores, the iron core with AC coils are all encased by the HTS magnet. The size of the core/AC coils is now limited by the interior bore of the HTS magnet.

Before committing to spend the monies to manufacture full-scale prototypes, ZP through its Australian sister company built several small feasibility models to verify the design. While the mini prototypes would receive scaled-down stresses, they would nonetheless prove the design feasible. Figure 9 shows a typical compact mini prototype.

Figure 9: Mini 6x1 Feasibility Prototype

With the agreement of the DOE and the RRT, ZP proceeded to design and build three prototype compact FCLs to test for their fault current limiting capability. The prototype compact FCLs are commonly referred to by their numeric code, “Y x Z” where Y is the number of cores per layer and Z is the number of layers. The 6x1 is composed of 6 cores arranged in one layer and is a three-phase device. The 3x2 has three cores in each of two layers and is also a three-phase device; the 2x1 is composed of two cores arranged in one layer and is a single-phase device.

The HTS magnets were of a rectangular or “race-track” design and produced by ZP’s sister company in Germany. The design was similar to the magnets employed in a HTS billet heater product for the metals extrusion industry. The magnets were able to be fabricated from existing designs saving design time and allowing the project to be fast-tracked. T&R Electric in Colman, South Dakota was the manufacturing partner for the compact FCL build. Figure 10 provides a comparison of the different models built for the compact design and shows the interior construction. Figures 11-13 are of the actual full size FCLs. The FCL designs were built taking advantage of the ZP design

concept of the AC and HTS portions being completely separate. The design consisted of a stack of two HTS magnets. The three different FCLs (the AC portion of the FCL) in their stainless steel tanks were lowered into the magnet stack for testing. The ZP trailer was setup with the DC power supplies, cryogenic compressors and chiller, making it a rolling test bed (Figure 14).

Figure 10: Comparison of the Compact Prototype Models (L to R) 6x1, 3x2, 2x1

Figure 11: Full-Scale 6x1 Prototype under Test at Powertech Labs

Figure 12: Full-Scale 3x2 Prototype under Test at Powertech Labs

Figure 13: Full-Scale 2x1 Prototype under Test at Powertech Labs

Figure 14: Zenergy Trailer Setup as Rolling Test Bed at Powertech Labs

3.2.6 Powertech Compact FCL Test Results

The test results at Powertech conclusively proved the viability of the compact design FCL. While the testing was shortened due to equipment problems, enough data was taken to correlate the test data to the predicted performance. As an example, the fault current limiting results of the 6x1 are shown in Figures 15 and 16. Note the predicted and measured currents are almost identical and that the graph traces nearly overlap. These tests proved conclusively the efficacy of the compact FCL design and the accuracy of the design algorithms that had been developed to engineer the FCL to meet specific performance targets.

Figure 15: Measured versus Calculated 15 kA Prospective and Limited Fault Current – 6x1 FCL

Figure 16: Measured versus Calculated 15 kA Prospective and Limited Fault Current – 6x1 FCL

3.2.7 Powertech Testing Conclusions

The goal of the experimental work was to validate ZP's design tools and to conduct sufficient empirical work to optimize the fault-limiting behavior, the steady-state voltage drop, and the size of the Compact FCL prototypes. The units performed extremely well during testing at steady-state and under the application of sequences involving load and fault current periods. In several of the configurations, they showed exceptionally low insertion impedance at maximum load currents and significant fault current limiting capability. For example, the 6x1 design showed less than 70 Volts (1%) insertion voltage drop at 1.2 kA load current and a fault limiting capability of 46% at 25 kA prospective fault current. For comparison, the 3x2 design showed 40% clipping for the same 25 kA prospective fault current, but slightly higher insertion impedance at the same load currents. The back emf during faults showed peak values of the order of 4,000-6,000 Volts with no signs of reverse saturation. This indicates that the magnetic cores and the number of AC turns for the DC bias magnetic flux available were properly sized. Most of the tests were run with the HTS coils at 120 A DC bias current, and very minimum coupling was observed during 20-cycle faults at various fault current levels. There were no mechanical/electrical/thermal issues with the HTS coils during the short-circuit tests. The power supply and protection circuit performed well, as expected.

While the extensive planned test program was curtailed due to the onset of ground currents in the AC tanks before the complete test plan was finished, enough data was collected to satisfy the program objectives and to validate the

FCL design methodologies. Results pointed clearly to the importance of the AC ampere-turns during the fault condition adequately de-saturating the core and suggested that the FCL design protocols may over emphasize the core area parameter. Also, a fourth prototype not included in the set of DOE units was “yoked” (meaning that the two core half-phases were joined magnetically in a closed-loop by transformer steel). This was done in an effort to improve the ability of the HTS coils to saturate the iron cores in order to help reduce the steady-state voltage drop. Analysis of the data and comparison of the performance of the yoked design with the DOE unyoked designs suggest that “yoking” does improve the DC magnetic flux saturation of the core, but it also reduces the ability of the AC coils and the fault current to de-saturate the core. These observations must be taken into account under particular requirements involving a large impedance change with a relatively low change in current from a high steady-state current and a low fault current.

ZP believes that the experimental work conclusively validated the FCL design protocols and that it is possible to optimize the trade-offs between fault clipping, steady-state voltage drop, and FCL size. The main parameter governing such trade-offs would be the maximum steady-state load current voltage drop that can be tolerated and the rate at which the steady-state voltage drop could be allowed to increase at given load currents.

In conclusion, ZP proved that the Compact FCL design is a sound concept and that ZP should pursue the design of a Transmission Class FCL to fulfill the intent of the DOE project.

3.3 Special 2G Wire Test

The limited availability and high cost of 2G wire made the construction of a 2G magnet system for an FCL impossible. ZP had an open order for a 500-meter length of 2G wire with a manufacturer that went unfilled for almost two years during the FCL program, and which was canceled when the FCL project was terminated. A special report testing the applicability of 2G wire in an HTS coil was approved by DOE to fulfill the 2G coil requirement. (10.2.1)

3.3.1 2G Wire Report Summary

A test coil was made from a 12 mm wide 2G HTS wire. The manufacturer of the 2G wire was SuperPower, Inc. (US). The test coil was wound onto a 150 mm diameter GFRP former as a solenoid with 8 layers and 35 turns. The winding was done without problems, even though the HTS wire is quite wide for a solenoid winding with a small diameter. The coil was placed in a cryostat and cooled by a single-stage cryogenic cooler. During cool-down, the transition to superconductivity was found at about 90 K, as expected.

Up to 330 A pulse current was applied to the coil at low (28 K) and medium (45 K) temperatures without significant voltage drops over the coil being measured. This showed there was no major degradation of the superconductor due to manufacturing and testing. The coil operation was stable at these currents. At high temperatures (78 K coil, 87.5 K current lead), a voltage drop in the HTS wire was detected at about 100A, and the voltage did rise with time indicating an unstable operating point. No fast quenching was detected during the tests done, and no burn out of the wire was found, which was promising for larger coils, and which suggested that 2G wire might be appropriate for FCL magnet applications in the future.

The critical current at different temperatures could not be determined exactly due to limits of the test setup. An improvement of the thermal anchoring of the current leads would be required before the critical current of the coil can be determined exactly. Because of the high critical current of the wire and the small self-field of the test coil, the expected critical currents at low temperatures are very high.

3.3.2 2G Wire Coil

Using SCS12050 wire, a test coil was designed and manufactured. The coil was designed for 8 layers, which is the same number of layers employed in a former FCL magnet (the magnet for the CEC/SCE device). The arrangement of the test coil is shown in Figure 17 below.

A layer winding was chosen for the test coil, as the previous magnets were also made as layer windings. As the former outer diameter is quite small and the 2G wire is quite wide, it was more difficult to do layer winding.

Test Coil Data:

HTS Wire: SCS12050 (SuperPower)

ID Winding: 150 mm

Former: GFRP Tube

Winding: Layer

No. of Layers: 8

Length: About 50 mm (winding height)

No. of Turns: 35 (in total)

HTS Wire Length: Approximately 16.5 m

Inductance: Approximately 0.236 mH

Center Field: 0.27 mT/A

Perpendicular Field: Approximately 0.62 mT/A Perpendicular Field at Ends of Solenoid

Figure 17: Test Coil before Impregnation with Resin

Figure 18: 2G Test Coil Mounted in Cryostat

3.3.3 2G Test Results

A series of measurements were taken at the lowest recorded operating temperature of 28 K.

Without heating the cold-head, the coil reached a lowest recorder temperature of about 28 K without application of current to the test coil. The temperature of the current connection near to the coil was slightly above 35 K. Pulsed current, up to about 300A, was applied to the coil at a base temperature of about 28K as shown in Figure 19 below.

During current ramp-up and ramp-down a lot of noise was seen in the voltage signals, as the wires picked up the inductive components. The pick-up depended on the number of turns enclosed in the measuring loop and it was lowest for the sensors measuring the contacts (UK-1, 8-OK). Despite the noise, clear trends can be seen of the voltage and current changes over the test time.

With constant current, the approximate voltage-drop over the coil could be determined. This was compared to a voltage criterion, e.g. $0.1 \mu\text{V}/\text{cm}$ for 16.5 m of HTS wire ($\rightarrow U_c=165 \mu\text{V}$).

The measured current lead contact voltages were about $175 \mu\text{V}$ at 300 A each (UK-1 and 8-OK). The voltage drop over the HTS layers (1-8) was smaller.

No fast quenching was detected during the tests, and no burn-out of the wire was observed, which suggests a stable transition voltage regime, considerable margin in the critical current operating reserve, homogenous wire quality, and the potential for a predictable and measureable transition to quench, all of which is favorable for larger coils.

The critical current at different temperatures could not be determined exactly due to limits of the test setup. An improvement of the thermal anchoring of the current leads would have been required before the critical current of the coil can be determined exactly. Because of the high critical current of the wire and the small self-field of the test coil the expected critical currents at low temperatures are very high.

3.3.4 Conclusions – Improvements – Next Steps

- Improve the thermal anchoring of the current leads to the HTS Coil
- Install compensation coil(s) to reduce inductive voltages during current ramps
- Install a second feed-through for signal wires
- Perform additional measurements at different temperatures and greater accuracy
- Increase the magnet field strength for higher-field measurements
- Perform measurements during quench heater operation

3.4 Budget Period 2

The success of the distribution-class FCL in the SCE Avanti grid and the successful testing of the distribution-class compact designs at Powertech led ZP to propose accelerating the project and using the next budget period, Budget Period 2, for building the transmission-class FCL. With the design equations for iron mass, and copper coils well understood and the benefits of the ZP design approach of separating the high voltage AC from the HTS wire component of the FCL thoroughly established, ZP embarked on the transmission-class FCL design where the greatest risk was the electrostatic design of the FCL to meet the BIL requirements. To mitigate the BIL risk, ZP contracted with several experienced transformer designers to solidify the design. A contract with American Electric Power (AEP) was signed to install the transmission class FCL in their 138 kV grid at the Tidd substation in Brilliant, Ohio. Simultaneously Pennsylvania Transformer Technology Inc. in Canonsburg, Pennsylvania was selected as the contract manufacturer to build the transmission class FCL due to their prior HV experience and manufacturing capability.

3.4.1 138 kV Transmission Class FCL Design

AEP presented ZP with these design parameters for the 138 kV FCL

Requirements Summary

- 138 kV
- 1300 A_{rms}
- ~ 20 kA_{rms} prospective fault
- Reduce fault by 43%
- Recovery under load required

These parameters were then transcribed into a ZP specification (Table 2) with a few modifications:

Parameter	Data
Name of project for communication purposes	AEP Tidd
Location of project: city/state/country	Brilliant, Ohio USA
Rated Voltage	138 kV
Line Frequency	60 Hz
Lightning Impulse Voltage Withstand Level	650 kV
Power Frequency Voltage Withstand Level	310 kV (1 minute dry), 275 kV (10 seconds wet). See footnote
Continuous Normal Current	1300 A-rms
Maximum Normal Current (Magnitude and Duration)	1300 A-rms
Symmetrical Current through FCL for 3-Phase Fault at 138 kV & X/R for Total Fault	13,775 A-rms & 31.65 ANSI (without the series 2% reactor)
Symmetrical Current through FCL for L-G Fault at 138 kV & X/R for Total Fault	18,805 A-rms & 119.26 ANSI (without the series 2% reactor)
Symmetrical Current through FCL for 3-Phase Fault at 138 kV & X/R for Total Fault	8,090 A-rms & 33.60 ANSI (with the series 2% reactor)
Symmetrical Current through FCL for L-G Fault at 138 kV & X/R for Total Fault	9,831 A-rms & 21 ANSI (with the series 2% reactor)
Thevenin System Equivalent at 138 kV Side Z1, Z2, Z0 (Ohms)	0.31343+j2.56709 0.31345+j2.56713 1.68751+j7.46171 (Ohms)
Series Reactor at 138 kV Side = 2% on 100 MVA	3.81 (Ohms)
Thevenin System Equivalent at 345kV Side Z1, Z2, Z0 (Ohms)	0.34019+j5.46865 0.34044+j5.46871 0.57858+j6.00828 (Ohms)
Transformer Test Report Data: Rated H/M/T: 339/137.5/13.8 kV 450/450/100 MVA OFAF	Z H-M = 10.84 % @ 450 MVA ZM-L = 16.58 % @ 100 MVA Z H-L = 29.08 % @ 100 MVA
Transformer B	Is kept disconnected

Table 2: AEP Tidd Substation FCL Parameters

An important concept learned from testing the compact FCL full-scale prototypes was that round construction was better than square construction. Round HTS coils have less of a problem with delamination from the induced stresses during a fault, and round cryostats are easier to manufacture. Typically, transformer manufacturers build stepped round iron cores that have helical copper coils carrying the AC current. In an attempt to follow industry standards with round construction, the initial design analyses for the transmission-class FCL led to a design having a round horizontal FCL with round cryostats over the AC tank. One “AC tank” per phase would be used due to the transportation weight and height restrictions, making for a total of three AC tanks for a three-phase system. The configuration chosen was a 1x2 (two layers each with a single core) with the stepped round cores axially aligned.

3.4.2 138 kV Design Challenges

Figure 21: Initial 1x2 FCL Concept for AEP Tidd 138 kV FCL

Figure 21 shows an original concept for the 1x2 single phase FCL for the Tidd location. To reduce the technical risk, several prototypes of varying scale were built in Australia by Zenergy Power Pty Ltd.

The first prototype of the initial design, as tested at the Australian national Lane Cove test facility, is shown in Figure 23.

Figure 23: Initial Approximately Half-Scale Prototype of 1x2 Design at Lane Cove Test Facility

As it turned out, during a design review, the DOE Readiness Review Team (RRT) correctly questioned the performance of the 1x2 design. During the earlier Powertech compact FCL developmental testing, the 3x2 compact prototype (which has similar construction) did not perform as well as expected. There were also questions raised regarding whether or not the large voltages induced by the flux into the HTS coils from the fault current would cancel to acceptable values due to the non-symmetric nature of the 1x2 design. To answer the questions, a half-scale model was designed, built, and tested by ZP Pty Ltd. Figures 23-25 show the results of the 1x2 prototype testing at the Lane Cove test facility for the 138 kV prototype test.

Figure 24: Excellent 1x2 Lane Cove Testing Results for Limiting the Fault Current

Figure 25: Arcing of 1x2 Compact FCL Prototype during Test

As predicted by the DOE RRT, the asymmetric design of the 1x2 device experienced imbalances in the electromechanical and electromagnetic forces induced in the device under fault conditions, which lead to particularly high induced voltages in the DC coils. This led ZP to rethink its design approach. A summary of the Lane Cove testing results is presented below; the test results from Lane Cove clearly demonstrated that:

- The proposed 1x2 device was not optimal
- While feasible, it could not be implemented easily
- The design was inherently unbalanced electromagnetically
- It displayed large mechanical forces, high variable AC flux outside device envelope, pronounced shielding effect, and high induced voltages under maximum fault conditions

The axially aligned cores and AC coils in series did not have the cancellation of flux and induced voltages as demonstrated in the 2xX designs. Flashovers occurred on the DC windings during the testing and made the 1x2 design unsuitable for the FCL. Consequently, ZP concluded from its Lane Cove testing of the 1x2 design that, while the 1x2 design was chosen originally for perceived manufacturing ease due to the incorporation of round cores with round coils on round formers in round tanks, a radical shift in the design approach was needed. This shift led to the adoption of a “new” 2x1 design that would place two electrical half-phases alongside each other in one AC tank to make a HV single-phase device. This arrangement, referred to as a 2x1, was previously tested at Powertech in July 2009 during the compact FCL prototype development testing. Test results suggested the 2x1 design should be more balanced, and should yield reduced shielding and minimize induced voltage effects. Extensive FEA modeling of the design predicted significantly improved performance, with the electrical half-phases, which are located side-by-side, significantly canceling each other's effects, thereby reducing the induced DC coil voltage and current transients and significantly reducing the AC flux variations outside of device envelope. The “cost” for this improved performance was an AC tank structure that would be more complicated to build, with “D-shaped” AC cores and coils inside a round dielectric tank.

Subsequent formal design evaluation meetings led to a change in the project baseline FCL configuration in agreement with the DOE RRT.

A new 2x1 FCL design was chosen as new project baseline, and a large-scale prototype (Figure 26) was slated for testing at Lane Cove in July 2010. Plans called for a high-voltage (138 kV L-G) single-phase HTS prototype to be tested. An AC “test tank” was to be built using production device techniques, and it was to be configured for testing using HTS magnets from another project (a commercial project that was scheduled to deliver a 1250-amperes, 11 kV three-phase FCL to Applied Superconductors Limited for installation at CE Electric in the UK). If completed, this test would have resulted in an approximately full-scale (ASL is 3- θ at 11 kV versus 1- θ at 138 kV) testing of a near-commercial device. Testing was scheduled for the KEMA facility in Chalfont, PA during November 2010, and a preliminary 2x1 design was completed. The electrostatic analyses were compatible with largest Zenenergy production magnet, and the project device performance was consistent with the RRT's recommendations.

Figure 26: Model of AEP 2x1 Prototype FCL

While the original plan was to quickly build an AC HV “test tank” and test at KEMA, Chalfont, PA, using a “borrowed” set of round magnets from the ASL CE Electric project, rapidly evolving schedule divergences affected the timing of the two projects and did not allow this to happen. ZP subsequently elected to build another large-scale prototype (Figure 27) and to test it at the Lane Cove test facility to validate the design approach. The AEP project continued independently into the design stage of an FCL specific for AEP’s Tidd substation, which was to be modeled and verified based upon the Lane Cove test results. Figure 28 shows some of the test results from the Lane Cove experiments, which were very encouraging. Taken with other results, which demonstrated greatly reduced current and voltage transients on the DC coils, the Lane Cove experiments validated the 2x1 design concept for the AEP project.

The Lane Cove large-scale prototype testing led to a significant set of accomplishments including:

- Down-selection of the 2x1 format as the design of choice for all future single-phase HV FCL applications
- Demonstration of the potential for fault-limiting capabilities in excess of 50% of the peak prospective fault current values
- Demonstration of a balanced design with low mechanical stresses and low induced voltages on the DC circuit
- Exhibition of repeatable fault current limiting performance that tracked well with FEA predictions
- Support from the RRT for a decision to proceed with full-scale 138 kV single-phase design for TIDD substation in which the first test phase would also be the first phase of the commercial installation

The 2x1 design concept was then applied to the specifications of the AEP Tidd station and the resultant fault current reduction was calculated as 43.5% (Figure 29). The required iron core mass and AC coils were then designed to fit within the constraints of the AC tank diameter which was designed to fit within the “warm bore” of the largest HTS magnets that ZP was then able to produce. The HTS magnet “warm bore” size (open center space of the cryostat) was limited by the manufacturing VPI oven used to cure the HTS wire on the GFRP former.

As previously discussed, the Lane Cove tests of the 2x1 prototype demonstrated the expected voltage cancelling in the DC coils, and the FCL transmission-class FCL design was changed to two AC cores and coils, side-by-side, in one layer oriented vertically. The problem was now constructing two cores and coils in a rounded enclosure to operate with the electrostatic gradients required for 138 kV. The solution was to design a “D-shaped” core with “D-shaped” coils as in the prototype. The concept was presented to PTTI and a small prototype “D-shaped” AC coil was built (Figure. 30) to verify the manufacturability of the concept and the ability to wind the “D-shaped” coils with an appropriately-rated copper CTC conductor.

Figure 30: Short Test AC Coil Wound with CTC Wire on "D-Shaped" Former at PTTI

The next major step was to design for the electrostatic clearances required for 138 kV. With a fixed "warm bore" of the large cryostats, the challenge was to design as much iron core into the AC tank as can be accommodated with the helical copper coils and still maintain the required 138 kV electrostatic clearances. Through many weeks of iteration and the collegial design of three experts in the field, the electrostatic design was finished. Figure 31 shows the electrostatic design of the "D-shaped" core design in the tank. Figure 32 shows the electrostatic analysis of the final design. However, to obtain the clearances for 138 kV and maximize the iron core mass available to "toggle" through the magnetically-biased saturated and unsaturated conditions, the design grew very tall. Several design proposals were evaluated to incorporate a removable top section housing the bushings that would be removed during shipping. Top section removal still made the single-phase device too tall for easy transport vertically (the preferred orientation for the strength and stability of the FCL). A check with the Ohio Department of Transportation revealed that the transport limiting height was 13.5 ft due to the bridge overhead clearances into Brilliant, Ohio. The vertical operating position was very desirable for the magnets for the cold heads were designed to function more efficiently vertically oriented. The solution was to design the interior of the tank such that the frame interior would support the core and coils for horizontal shipment; however, the final operating position was to be vertical. Calculations showed

the iron core and AC coil compression and construction would provide the necessary support for horizontal shipment. The key factor would be to design the manufacturing fixtures to rotate the cores from horizontal to vertical during assembly of the FCL.

3.4.3 HTS Magnet Design

Zenergy Power GmbH was to be the turn key supplier for the HTS magnets. To mitigate the risk of building a sub-par performance magnet, ZP GmbH designed a half scale magnet based on copper wire rather than HTS. The prototype DC coil was built on a G10 former with copper cold conduction plates to emulate the final HTS design. The copper coil was placed in a laboratory cryostat to evaluate the cold bus design. Figure 33 shows the copper coil used to verify the thermal design and performance of the magnet. The copper magnet was tested in a laboratory cryostat with a production cold-head to verify the performance of the coil and the thermal bus design (Figure 34).

Figure 33: Copper Coil on G10 Former used as Test Coil for Heat Transfer Verification

Extensive testing was conducted over several weeks to evaluate the test coil. The test routines included several cool-down and heat-up cycles and evaluations of the temperature distributions around the coil and thermal bus in relation to the cold-head connection. The copper magnet experiment yielded significant test results that validated the thermal design, including:

- A half-scale (0.7 m) copper coil constructed and tested
- The “Dry” (conductive) cooling thermal design was optimized (cold-finger location, spacing, dimensions and shape) and validated for the production magnet
- Performance evaluation included the use of resistive heaters installed at coil edge to simulate AC losses, and ambient heat input from the DC bias current leads
- A novel, shock-resistant copper cold-bus implemented
- Testing was completed in a cryostat with production cold-heads
- Heat transfer models developed and validated for correlation with the full-scale FCL

Results of the copper magnet test are shown in Figure 35. The correlation of the predicted to actual temperature is very close for both temperature locations on the coil.

3.4.3.1 HTS Coil and Cryostat

The HTS magnet coil was wound with the specification that the OD have a maximum of 1700 mm and the inner “warm bore” of the cryostat to be a minimum of 1500 mm. The HTS magnet was designed with conductive cooling utilizing a copper bus connected between the HTS wire and the redundant cold heads that cool the HTS wire to less than 20 degrees K. Figure 36 shows the magnet covered with super insulation ready to be installed in the cryostat. The magnets were designed with a thick top plate to which all components (cold heads, lifting hooks, mounting pads, and electrical connections) are mounted, see Figure 37. With the mounting pads on the top surface of the cryostat, the magnets are then suspended from the mounting structure keeping the cold heads upright. The structure holding the magnets is to be built with substantial integrity to withstand the 40,000 pound attractive force between the two magnets when in use.

Figure 36: AEP Magnet with Super-Insulation Ready to be Mounted in Cryostat

Figure 37: AEP Assembled Cryostat with Components Mounted to Top Plate.

Figure 38: Assembled Cryostat with Weather-Resistant Housing over Cold-Heads.

The cryostat assembly has a weather resistant enclosure protecting the cold-heads, see Figure 38. All interconnecting wires are cabled with plug-in connectors for interfacing to the auxiliary enclosure, which houses the monitor and control instrumentation, and the auxiliary power supplies. The interconnecting wires and cables were designed on a “plug and play” basis in which the cryostat side of the cables and the auxiliary enclosure side of the cables were marked and matched to corresponding weatherproof multi-pin connectors on cryostat and the exterior of the auxiliary enclosure. This reduced the number of connections that needed to be made, improved their integrity and reliability, and reduced the potential for installation and connection errors.

Figure 39: Cold-Heads Connected to Cryogenic Compressors through Conduit with Plug Connectors

As shown in Figure 39, the two cold heads in the weather resistant housing are connected to their respective cryogenic compressors with helium pressure lines and electrical control cables. A closed loop water chiller is required to provide cooling for the cryogenic compressors. In the final field installation, two units are provided for redundancy; for shop testing, a portable unit (the large dark grey metal box in the right of the picture) was employed.

Figure 40: Cryostat Cool-Down to 25 deg K with One Cold-Head

3.4.3.2 Cryostat Cold Performance

Figure 40 documents the excellent cool-down performance of the magnets. The first magnet was assembled and cooled down to 25 degree K. The process took 3.5 days as only one cold-head could be turned on at a time and turning on the cryogenic compressor of the second cold-head exceeded the capacity of the portable chiller, and the over-temperature conditions would shut down the compressors). Two cold-heads were able to be operated in parallel for short periods of time, and an additional incremental drop in temperature less than 20 K was noted. The jagged line on the right side of Figure 40 at ~23 K shows the multiple events in which both cold-heads were cycled and the resulting temperature decreases and increases.

3.4.3.3 AC Losses in HTS Wire

The unknown factor when calculating the performance of the magnet and the amount of cooling required was the AC losses of the HTS coil during normal operating condition with maximum normal AC load current. AC currents in the HTS coil result from weak coupling from the flux of the AC current through the AC coils and cause heating of the HTS coil. In addition to ambient heat leakage from convection and radiation, and conductive inputs from current leads and direct inputs from DC bias current, the induced AC heat load must also be removed by the cold-heads or the magnet

temperature would increase. The extent of these AC losses was unknown for 2G wire. Robert Duckworth of ONL was asked to perform several experiments to determine the AC loss for future 2G wire designs.

3.4.3.4 Importance of Knowing AC Loss

Due to the efficiencies that result from operating HTS wire at temperatures significantly below transition temperatures and due to the high cost of HTS, ZP chose to design and operate its HTS magnets at extremely low temperatures. The objectives of this strategy were to reduce the total cost of HTS conductor used in a FCL system and to increase the margin to quench by taking advantage of the significantly higher magnetic field performance and I_c (critical current) available at reduced temperatures. But, operating at reduced temperatures significantly increased the demand on the cryogenic systems and the thermal design of the HTS magnets – among other things, the thermal lift or cooling capacity of the Cryomech AL-325 cryogenic compressors were reduced by more than two-thirds when operating at 20K versus 77K. These severe refrigeration requirements made understanding the AC losses of the FCL magnets extremely important. Among other things:

- Fringing ac fields generate losses in HTS dc coil
- Losses must be characterized and accommodated in thermal design
- Estimates range from 10's to 100's of watts per coil – this spread unacceptably complicated the thermal design
- Measurements were needed instead of calculations, because established analytic methods were known to be inaccurate
- Losses concentrated on coil edge; not uniformly distributed (see Figure 41)

3.4.3.5 Excerpts from the Robert Duckworth Report - Executive Summary

As part of the ZP FCL project design, it was determined that the AC losses generated in the DC bias coil from the fields that were produced by the room temperature AC components of the three-phase FCL circuit were significant. These AC fields, which were calculated as having values up to 25 mT, would impart a dynamic resistance on different portions of the DC bias coil, which would in turn generate heat during normal operation. Since the DC bias coil has regions which operate at different percentages of DC transport current in relation to the local critical current and DC fields up to 2 T, knowledge of the dependence of the dynamic resistance on these factors would help to determine the appropriate refrigeration load for the system.

While dynamic resistance has been examined in 1G BSCCO conductors at these operating conditions, 2G YBCO coated conductors have not been characterized as extensively. Expressions for dynamic resistance that have been previously used may require some revision due to the difference in aspect ratio between 1G and 2G conductors and the composition of 2G YBCO coated conductors compared to 1G BSCCO conductors. Dynamic resistance measurements were carried out at 77 K on an as-manufactured AMSC 2G YBCO coated conductor as a function of DC transport current with applied DC background fields up to 2 T and applied AC magnetic fields up to 20 mT. These results were compared to existing dynamic resistance theories to determine best expressions to represent dynamic resistance for 2G YBCO coated conductors.

With respect to tape orientation, there was a clear difference in the dynamic resistance dependence. The dynamic resistance due to an applied AC field perpendicular to the tape face is nearly two orders of magnitude higher than the dynamic resistance with the AC field parallel to the tape face. For the case of AC field parallel to the tape face, no measurable voltage was observed at applied AC fields up to 25 mT below 85% of the sample critical current. For a resistance greater than $1 \times 10^{-5} \Omega/\text{m}$ with the AC field perpendicular to the tape face, the dynamic resistance had a linear dependence on the applied AC field. As the fraction of the DC transport current to the sample critical current was increased, the resistance increased and threshold field where the dynamic resistance appeared decreased. These functional behaviors of the dynamic resistance were consistent with existing theories; however there was sufficient difference in the absolute values to suggest refinement of the theories to better represent YBCO coated conductors.

When DC background fields perpendicular to the tape face were applied, the functional dependence of the dynamic resistance with respect to applied AC fields and fraction of DC transport current to sample critical current did not change. The applied DC field did change the dependence of the threshold field with respect to the fraction of DC transport current to sample critical current. This dependence was consistent with the change in critical current of the sample due to applied DC field. It was concluded that additional work with AC and DC fields parallel to the tape face would be beneficial.

3.4.3.6 ORNL Experiment

The extensive characterization experiments of 1G and 2G wires carried out ORNL were performed under the following conditions:

- AC field (0-20 mT)
- DC field (0 – 2 T)
- Parallel / Perpendicular field orientations
- DC current (0-100% I_c)
- Data collection at 77 K initially, then repeated at 30 K

Additional experimentation at other temperatures (20K, 25K, 35K, 40K, 50K and 60K) was suggested for possible future work. Figure 42 shows one of the test rigs and sample arrangements that were used for collecting data. A direct refrigeration system was used for data collection at 30K, but the magnetic flux orientations remained consistent with those shown in Figure 42.

Figure 42: Voltage Arrangement used to Measure Dynamic Resistance in HTS Samples

Figure 43 shows a typical data set that was collected. With a perpendicular AC magnetic field from 0-25 mT losses were measured at transport currents ranging from 50% to 90% of critical current. As expected, losses increased as transport current increased as a percentage of critical current and AC perpendicular magnetic field increased, but a consistent range of increase of about 300% from 50% to 90% of critical current was identified. As a result of the ORNL experiments, ZP concluded that:

- While AC losses increased as I_{op} / I_c and background perpendicular magnetic fields increased, they were tolerable for the proposed project
- ZP would have been able to optimize HTS magnet design for wire cost versus cryogenics cost
- Using 77 K data, loss from dynamic resistance is between 0.1 mW/m to 15 mW/m for the regimes contemplated
- Operation of HTS coil at 30 to 50 K would significantly increase the critical current, which would in turn increase the threshold current
- Measurements on a 1G wire done at 77 K on a cryogenic system matched reasonably well with the preliminary 2G data and confirmed the first-order approximations of magnet system AC losses
- The custom equipment developed by ORNL was uniquely suited for the purpose and provided 2G wire performance data that had never before been collected.

3.4.4 FCL Auxiliary Enclosure

An auxiliary enclosure (Figure 46) was designed to house the cryogenic compressors, DC power supplies, and PLC monitoring equipment and computer/SCADA interface. The HTS FCL components required monitoring to ensure that they were operating efficiently and that all components were operating properly. The FCL system was designed to be built with redundant components to ensure consistently high operational duty cycles and to improve the reliability of the FCL system.

To ensure proper operation of the HTS FCL, key parameters on the FCL were to be monitored. Several of the monitoring points included: cryostat temperatures, chiller water temperatures, HTS magnet system DC currents, and ambient temperatures. Because of the system redundancy, almost one hundred channels of data were to be collected and monitored. With the goal of easy access in mind, the auxiliary enclosure was designed with several doors on the front and back. The heavy (500 pound) cryogenic compressors were to be located on the first level, and the electronics were to be located on the second level.

3.4.5 Zenergy FCL Software

Software used in the development of the HTS FCLs was standard off-the-shelf applications of ANSYS, FEA, and PSCAD where the variables were the parameters of the FCL. Software developed specifically for the FCL with cost-share funds was for the HMI monitoring of the FCL. The PLC control software was standard Siemens code, the Wonderware interface was developed with help from Serra an E&M Company. The process software was specifically designed for the Siemens PLC to operate the controls for the FCL. A Wonderware - Human Machine Interface (HMI) program running on a "Toughbook" communicated with the user to provide a graphical depiction of the levels present and switch positions and operating conditions of the FCL. While automatic control of the FCL was normally the mode of operation, manual control could be activated for servicing or testing the operation under various parameter changes. A SCADA data line was also output from the FCL which enabled an external monitor system to record and display the data at the utility operations center. Figure 44 shows the display of the HMI for configuring the set points, scan rates, and refresh rates. Figure 45 is an example of the actual computer screen with a graphical representation showing levels, switch positions, and numeric readouts.

Configuration 1

12/16/2009 1:12:51 PM

Installation 1 Configuration

SCADA Configuration

Upload log every: Hrs

On upload failure, retry every: Secs

Screen data stale after: Mins

Maximum allowed value for PS current: A

Minimum allowed value for PS current: A

Maximum allowed value for PS voltage: V

Minimum allowed value for PS voltage: V

Maximum allowed OVP value: V

Minimum allowed OVP value: V

Maximum allowed value for CH temperature: K

Minimum allowed value for CH temperature: K

On: start HMI here:

Clear location based startup screen selection list:

Temporary file directory (not the Historian Data Import directory):

Log block transaction timeout: Secs

Historian data file creation timeout: Secs

PLC connection timeout: Secs

PLC disconnection timeout: Secs

Send data transmission timeout: Secs

Send data shutdown timeout: Secs

User control session timeout: Mins

Number of displayed decimals for inputs:

Number of displayed decimals for outputs:

PLC Configuration

Cold head 1 high setpt: <input type="text" value="500"/> K	HTS auto voltage: <input type="text" value="2.5"/> V
Cold head 2 high setpt: <input type="text" value="500"/> K	HTS auto current: <input type="text" value="99.9"/> A
	HTS standby current: <input type="text" value="30"/> A
Cold head deadband: <input type="text" value="1"/> K	
Cold head warning temp: <input type="text" value="70"/> K	HTS minimum current: <input type="text" value="76"/> A
	HTS maximum voltage: <input type="text" value="2"/> V
LN2 warning level: <input type="text" value="60"/> cm	
LN2 warning pressure: <input type="text" value="610"/> Torr	HTS ramp down step: <input type="text" value="10"/> A
	HTS minimum voltage: <input type="text" value="-1"/> V
Top cover low alarm: <input type="text" value="15"/> C	
Top cover warning temp: <input type="text" value="18"/> C	HTS coil warning temp: <input type="text" value="75"/> K
Top cover deadband: <input type="text" value="1"/> C	HTS coil critical temp: <input type="text" value="78"/> K
UPS high voltage: <input type="text" value="28"/> V	
UPS low voltage: <input type="text" value="20"/> V	

Test Mode

Message Mode

Garbage Collection Mode

Retain Intermediate Log Files in Temporary Directory

Disable Data Import

Non standard disconnects

Figure 44: Wonderware Parameter Configuration Page

3.4.6 FCL Structure

The FCL structure was designed to support the magnets at the correct vertical distance around the AC tank. Figure 47 shows the general external arrangement of the FCL, which was considerably different than the earlier 11 kV FCL with a similar architecture that was manufactured for ASL and CE Electric in the UK. The 11 kV, two-magnet FCL used an external support structure to position the magnets. For the AEP device, the AC tank was to be a structural component in order to reduce the overall external dimensions of the FCL. In the AEP design, the bottom magnet was to be placed in its holder mounted to the foundation, and the tank inserted into the bottom magnet by a crane. The top magnet would have been attached to supports cantilevered off of the “top hat” portion of the AC tank prior to the entire assembly having been lowered into the bottom tank. The radiators would have been attached last. The AC

tank and cryostats were design for continuous outside exposure without an additional enclosure. The cold-heads were to be protected by a weatherproof housing, the interconnecting cables were to be sheathed in a conduit, and the electrical interfaces were to have weatherproof plug-in connections for ease of assembly.

Figure 46: Model of Auxiliary Enclosure for AEP FCL

Figure 47: AEP Single-Phase FCL Model

Figure 48: AEP FCL Overall Schematic

Figure 48 shows the overall dimensions and weights of a single-phase of the AEP FCL. Due to the finite and somewhat limited warm-bore radius of the cryostat, the active core area of the FCL was limited, and the FCL AC tank had to grow in length to meet the iron mass required for the fault reduction. The FCL height exceeded allowable road clearances, so the AC tank design was modified in order to allow the FCL to be shipped horizontally. While the AC tank design was proceeding, other vendors were contracted to design and build the auxiliary enclosure to house the cryogenic compressors, DC power supplies, and control electronics. ZP in Germany was building the two complete HTS magnet subsystems, and the first magnet had only been cryogenic tested when the project was terminated. Purchase orders were issued for the iron cores, CTC copper for the coils, and the insulation material for the coil winding.

3.4.7 Factors Affecting the FCL Timeline

Several factors influenced the timetable for the Transmission Class FCL. ZP was informed by PTTI, the manufacturing partner that had been selected for the project, that the manufacturing timetable would slip due to:

1. The loss of manufacturing engineers on the shop floor needed for the manufacturing improvements to handle the long horizontal cores and modifications to the coil winding lathe required to upgrade it to handle the long coils.

2. The incompatibility of the software between ZP and PTT, which necessitated that printed manufacturing drawings would have to be produced in order to check tolerances and make judgments regarding the final manufacturability of the design.

ZP also met with AEP to finalize the planned interconnections with the grid and to review testing and installation requirements. The two-day meeting with AEP generated many questions and answers and much activity to close the gaps. However, the question of installation costs which had been determined at the beginning of the contract to be \$850,000 and were to be split by ZP and AEP had been revised by AEP to a figure of at least \$1.6 M, with additional costs possible and expected, and neither AEP nor ZP had sufficient budget to absorb the additional costs.

ZP had also determined that no power lab in North America could test the 138 kV FCL to its full limits at full voltage and full current. The only test facility able to test at full voltage and current was at KEMA in The Netherlands. KEMA in Chalfont, PA could perform limited current testing at reduced voltage, but the FCL would not receive the full stress under test conditions. AEP was concerned with placing the FCL into their grid, if it had not been tested to the full stress it could experience under maximum fault conditions. AEP asked that ZP discuss this matter with NEETRAC, DOE, and the Readiness Review Team. The RRT recommended that the FCL be installed with the air core reactors (ACRs) (which were already in place at the Tidd station) always in series with the FCL. The ACRs would insure that the FCL would not receive any greater stress than was experienced during the laboratory testing available at KEMA Chalfont, PA.

3.4.8 Zenenergy Power Change of Focus

A major change occurred in early September 2011 with this project. The ZP Australian team determined that with proper iron core and magnetic circuit design techniques, it would be possible to use only one superconductor magnet to saturate the iron cores of the FCL. Further investigation led to determining that further enhancements to the magnetic circuit design with judiciously placed iron would further reduce the number of Ampere-turns (ATs) required to saturate the iron core. The extension of this research concluded that the ATs required for saturation was within the capabilities of DC power supplies and conventional resistive copper DC coils. This profound realization was an epiphany for the inductive FCL technology, since suitable FCL performance could be achieved without the cost of the HTS wire, associated cryostats, cold-heads, cryogenic compressors, chillers, and the maintenance, training, cost to operate, and the poor reliability of these elements. While these conclusions were the result of an analytical study, there was no indication from a physics point of view that it would not work. A fast-paced test of the concept performed in mid October 2011 in Australia, verified the concept and proved the efficacy of the conventional DC magnet inductive FCL.

The ZP FCLs have been built with magnets made from 1G HTS wire since 2007. The plan was to utilize 2G HTS wire when the availability and cost made the switch feasible. Unfortunately 2G HTS conductor was not generally available in quantity during the performance of this project, nor did the price come down substantially from the initial short-length and test and qualification sample offerings from the 2008 and 2009 timeframe. ZP's FCL program was predicated on the availability 2G HTS conductor with greatly increased performance and reduced price that would bring the cost of saturated reactor FCLs more in line with the expectations of the utility companies.

Simon Cleaver, the CEO of Zenenergy Power, PLC (Zenenergy Power, Incorporated's parent company) recognized the business opportunity in a less expensive, HTS-free FCL and after careful consideration, choose to focus the company's Australian and United States teams toward making the non-HTS FCL a commercial success. ZP has built several FCLs, and through extensive testing, has proven the Saturable Reactor FCL concept. Having a FCL with no cryogenics, requiring far less maintenance, consuming less auxiliary power and with the appearance, reliability, functionality and maintenance profile of standard utility equipment will greatly ease the adoption of the saturated

reactor FCL by the utility industry. The FCLs will now fit seamlessly into utility substation configurations without any adjustment in utility operations and maintenance practices, or field maintenance and repair capabilities.

The ramifications of Mr. Cleaver's decision were several. First, all POs for the AEP project were put on hold and then subsequently cancelled, once DOE concurred with project termination. Fortunately the POs of the major components of iron, copper, and insulation materials were stopped in time to not incur any penalties. Second, DOE concurred with ZP's assessment, and through DOE Program Manager Mr. Don Geiling, ZP was given permission to terminate the project. Third, AEP was informed of the Zenergy Power decision and given several options for future FCLs.

The original goal for the DOE funding of the Zenergy Power project "Design, Test and Demonstration of Saturable Reactor High-Temperature Superconductor Fault Current Limiters" was to stimulate the HTS wire industry by developing commercial products which would consume massive quantities of, first 1G, then 2G, HTS conductor. Since the premise of the original funding was to stimulate the HTS wire industry, and since ZP had concluded that for the foreseeable future its saturated reactor FCL was not economically viable with HTS wire, the DOE and Zenergy Power mutually terminated the project.

4 Summary and Conclusions

Zenergy Power has successfully designed, built, tested, and installed in the US electrical grid a saturable reactor Fault Current Limiter. Beginning in 2007, first as SC Power Systems and from 2008 as Zenergy Power, Inc., ZP used DOE matching grant and ARRA funds to help refine the design of the saturated reactor fault current limiter. ZP ultimately perfected the design of the saturated reactor FCL to the point that ZP could reliably design a suitable FCL for most utility applications. Beginning with a very basic FCL design using 1G HTS for a coil housed in a LN₂ cryostat for the DC bias magnet, the technology progressed to a commercial system that was offered for sale internationally. Substantial progress was made in two areas. First, the cryogenics cooling system progressed from a sub-cooled liquid nitrogen container housing the HTS coils to cryostats utilizing dry conduction cooling and reaching temperatures down to less than 20 degrees K. Large, round cryostats with "warm bore" diameters of 1.7 meters enabled the design of large tanks to hold the AC components. Second, the design of the AC part of the FCL was refined from a six legged "spider" design to a more compact and lighter design with better fault current limiting capability. Further refinement of the flux path and core shape led to an efficient saturated reactor design requiring less Ampere-turns to saturate the core. In conclusion, the development of the saturable reactor FCL led to a more efficient design not requiring HTS magnets and their associated peripheral equipment, which yielded a more economical product in line with the electric utility industry expectations.

The original goal for the DOE funding of the ZP project "Design, Test and Demonstration of Saturable Reactor High-Temperature Superconductor Fault Current Limiters" was to stimulate the HTS wire industry with, first 1G, then 2G, HTS wire applications. Over the approximately 5 years of ZP's product development program, the amount of HTS wire employed per FCL and its cost as a percentage of the total FCL product content had not dropped substantially from an unsustainable level of more than 50% of the total cost of the FCL, nor had the availability increased (today the availability of 2G wire for commercial applications outside of specific partnerships with the leading 2G wire manufacturers is extremely limited). ZP had projected a very significant commercial potential for FCLs with higher performance and lower costs compared to the initial models built with 1G wire, which would come about from the widespread availability of low-cost, high-performance 2G HTS wire. The potential for 2G wires at greatly reduced performance-based prices compared to 1G HTS conductor held out the potential for the commercial production of FCLs at price and performance levels attractive to the utility industry. However, the price of HTS wire did not drop as expected and today the available quantities of 2G wire are limited, and the price is higher than the currently available supplies of 1G wire. The commercial option for ZP to provide a reliable and reasonably priced FCL to the utility industry is to employ conventional resistive conductor DC electromagnets to bias the FCL. Since the premise of the

original funding was to stimulate the HTS wire industry and ZP concluded that copper-based magnets were more economical for the foreseeable future, DOE and ZP decided to mutually terminate the project.

5 Acknowledgements

ZP would like to recognize and thank the DOE Readiness Review Team for their support and contributions to the development of the saturable reactor FCL technology and Dr. Robert Duckworth of ORNL for his groundbreaking research in measuring and modeling the AC losses of 2G HTS conductor under a variety of operational environments.

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8 List of Acronyms and Definitions

8.1 Acronyms

ACR	Air Core Reactor
ARRA	American Recovery and Reinvestment Act
AT	Ampere Turn
BIL	Basic Insulation Level
BP	Budget Period
DOE	Department of Energy
FCL	Fault Current Limiter

HTS	High Temperature Superconductor
HVAC	Heating Ventilating and Cooling
LN ₂	Liquid Nitrogen
ONL	Oak Ridge National Laboratory
PLC	Programmable Logic Controller
PTTI	Pennsylvania Transformer Technology Inc.
RRT	Readiness Review Team
SCADA	Supervisory, Control and Data Acquisition
SCE	Southern California Edison
ZP	Zenergy Power, Inc

8.2 Definitions

None

9 References

1. Robert Duckworth, "Dynamic Resistance Measurement at 77 K of Zenergy FCL Project Update", January 2010
2. Robert Duckworth, "ORNL contribution to Zenergy FCL presentation" (2010 Peer Review), June 2010
3. Franco Moriconi, "High Voltage Testing", Powertech Labs, Surry, BC Canada, Dec 2007 (SCP/TR-07/03)

10 Appendix. Public Documents

10.1 Patents Granted or Applied For, Software Developed

1. Patent documentation submitted under Intellectual Property Provisions (CSB-1003)
Cooperative Agreement Research, Development, or Demonstration Domestic Small Businesses
2. Software for Wonderware HMI developed under this grant submitted under DOE Form 241.4

10.2 Publications

1. "2G HTS Wire Testing", Dr Jan Wiezoreck, for „Design Test and Demonstration of Saturable Reactor High-Temperature Superconducting Fault Current Limiters“ DE-FC26-07NT43242, 21 September 2009
2. "Analysis of the Effect of a Saturable-Core HTS Fault Current Limiter on the Circuit Breaker Transient Recovery Voltage", J. Lopez-Roldan, A. C. Price, F. De La Rosa, and F. Moriconi, 2011 IEEE PES General Meeting, Detroit, Michigan, July 24-29, 2011
3. "Modeling and Test Validation of a 15kV 24MVA Superconducting Fault Current Limiter", Franco Moriconi, Nick Koshnick, Francisco De La Rosa, and Amandeep Singh, 2010 IEEE T&D Conference, N. Orleans April 19-22, 2010.
4. "An Innovative Compact Saturable-Core HTS Fault Current Limiter - Development, Testing and Application to Transmission Class Networks", Franco Moriconi, Francisco De La Rosa, Amandeep Singh, Bill Chen, Marina Levitskaya, Albert Nelson, IEEE Transmission and Distribution, November 24, 2010, 2010 IEEE PES General Meeting, July 26-29, 2010, Minneapolis, Minnesota.
5. "Resonance of a Distribution Feeder with a Saturable Core Fault Current Limiter", Christopher R. Clarke, Franco Moriconi, Amandeep Singh, Ardalan Kamiab, Russ Neal, Alonso Rodriguez, Francisco De La Rosa, and Nick

Koshnick, IEEE Transmission and Distribution Conference and Exposition, November 24, 2010, N. Orleans April 19-22, 2010.

6. "Development and Deployment of Saturated-Core Fault Current Limiters in Distribution and Transmission Substations", Franco Moriconi, Francisco De La Rosa, Frank Darmann, Albert Nelson, and Larry Masur, Applied Superconductivity Conference August 2-6, 2010, Washington, DC, USA. Also published in Trans., on Applied Superconductivity, Vol. 21, Issue 3, pp 1288-1293, June 2011
7. "Saturated-Core Fault Current Limiter Field Experience at a Distribution Substation", Albert Nelson, Larry Masur, Franco Moriconi, Francisco De La Rosa, Detlev Kirsten, C I R E D, 21st International Conference on Electricity Distribution, Frankfurt, Germany, 6-9 June 2011
8. "Wind Power Plant Enhancement with a Fault-Current Limiter", E. Muljadi and V. Gevorgian, F. DeLaRosa, IEEE PES Annual Meeting, Detroit, Michigan, July 24-29, 2011

10.3 Technical Presentations

1. "Design, Test and Demonstration of Saturable-Core Reactor HTS Fault Current Limiter", Larry Masur, Frank Darmann, Robert Lombaerde, Presented at the U.S. Department of Energy Annual Peer Review, Crystal City, VA, July 31, 2008
2. "Design, Test and Demonstration of Saturable-Core Reactor HTS Fault Current Limiter", Franco Moriconi, Frank Darmann, Robert Lombaerde, U.S. Department of Energy Annual Peer Review, Alexandria, VA, Aug 4-6, 2009
3. "Design, Test and Demonstration of Saturable-Core Reactor HTS Fault Current Limiter", Albert Nelson, Franco Moriconi, Robert Lombaerde, U.S. Department of Energy Annual Peer Review, Alexandria, VA, June 29 – July 1, 2010
4. ASL 11 kV FCL for the CE Electric Grid, Newcastle, UK, Albert Nelson, Franco Moriconi, EPRI Superconductivity Conference, Tallahassee, Florida, October 12, 2011