Fault Current Limiter Testing Requirements

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An Assessment of Fault Current Limiter Testing Requirements

Prepared for

U.S. Department of Energy
Office of Electricity Delivery and Energy Reliability

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EXECUTIVE SUMMARY

The U.S. Department of Energy's (DOE) Office of Electricity Delivery and Energy Reliability (OE) is conducting research and development (R&D) on next-generation electricity delivery equipment including fault current limiters (FCLs). Prototype FCL devices are undergoing testing with the aim of market-ready devices making their debut in the transmission and distribution (T&D) system in the next five years. As these devices move through the research, development, and demonstration process, there are questions about whether or not the capabilities of commercial T&D equipment testing facilities are adequate to meet technology- and market-readiness goals.

The purposes of this report are to:
- Identify the specific testing requirements for the different FCL designs;
- Assess the capabilities of testing facilities in the U.S. and internationally;
- Perform an analysis to determine where existing testing capabilities and facilities fall short of meeting the testing requirements.

The scope of the project focused on solid-state and superconducting FCLs. Additionally, because testing requirements at lower-level current and voltage levels are relatively well understood, this report focuses on testing requirements and capabilities at higher current and voltage levels as these will be the conditions under which the equipment will operate once they are installed in the electric system.

Major Findings

- T&D equipment testing facilities can provide voltage and current to adequately test FCLs at the distribution level, but there is no place that has the capabilities to test FCLs at transmission-level current and voltage levels simultaneously. This is a concern because the superconducting FCL projects plan to produce devices that will operate at transmission-level voltages. While there is a need to conduct high voltage-current tests, there are a number of experts that believe it may be possible to substitute modeling and simulation for actual tests. Furthermore, so called "synthetic tests", which are common practice for circuit breaker testing may be developed for FCLs. If true, such concepts would hold for other advanced devices that are expected to be used in the transmission system such as next generation cables, transformers, and switchgear.

- Commercial T&D equipment testing facilities are not always conducive for advanced design and prototype testing for R&D projects. There are approximately 90 testing facilities around the world and these are equipped and managed to conduct routine tests of existing or market-ready devices to meet known standards and protocols. Those seeking to test advanced R&D designs and prototypes often encounter problems in using these facilities, including a lack of responsiveness in setting up specialized testing equipment (e.g., those tests that require cryogenic testing), which they do not have. In addition, while commercial facilities can be accommodating for R&D testing, they tend to be costly, busy, and difficult to schedule.

- There are not currently “standards” for testing prototype high-temperature superconducting (HTS) and solid-state FCLs and for integrating these devices with the electric system. Testing procedures have been and will continue to be developed by FCL device manufacturers and their utility R&D partners and will vary depending on the design of the equipment and the application. This lack of standards complicates the testing process as each trip to the testing facility has unique requirements, protocols, and procedures. The existence of standards could help expedite and accelerate the testing process.

- If utilities allow FCLs to be installed on their own systems as part of the testing process, they will have to take steps to ensure that a fault of the type for which the device was designed actually occurs. If not, the device might experience lower level faults only, or none at all, and it could take months, years, or they might never experience the maximum fault level. This is exactly what occurred with the CURL 10 FCL project in Germany.

Conclusions

- In order to achieve technology- and market-readiness goals there is a need for testing facilities that have the flexibility to respond to the special needs of R&D projects, prototype devices, and advanced designs based on novel materials or innovative concepts. The lack of such facilities causes longer than necessary design phases, slows down the commercialization process, and increases the development cost.

- Testing FCLs currently involves a collaborative approach involving equipment manufacturers, power companies, national laboratories, and universities. Given the unique capabilities of fault current limiters, and the specific grid applications in which they are expected to be used, there is an expectation that utilities will allow FCLs to be installed and tested on their own systems, before they have been simultaneously tested for high current and high voltage. If such testing is planned properly, it may preclude the need for testing facilities that can accomplish high voltage and high current simultaneously.

- There is no agreement on whether standards for fault current limiters should precede the design or if the devices need to be designed before standards can be developed. This is because there are a number of different designs and the testing requirements differ for each. Additionally, there is no agreement on the number and type of test standards that are needed for FCLs.

ACKNOWLEDGEMENTS

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TABLE OF CONTENTS

APPENDICES

1.0 INTRODUCTION

The U.S. electric grid is an essential part of American life. However, there is a well-recognized need to modernize America's electric grid, and the development and deployment of "next generation" electric transmission and distribution (T&D) equipment is a key part of this. With the limited investment in research and development (R&D) to create and test advanced electricity-delivery technologies, grid modernization will be a more difficult goal to attain.

Testing of Zenergy's FCL device

For example, most of the existing T&D infrastructure is reaching the end of its useful life, and coupled with steady growth in electricity demand there is increasing electricity congestion and reduced electric reliability in several areas of the country. To help address these problems, with R&D funding from the U.S. Department of Energy (DOE), equipment manufacturers, electric utilities, and researchers from private industry, universities, and national laboratories are teaming up to spur innovation and develop new technologies, tools, and techniques. Because of these efforts, the future electric grid will likely incorporate technologies very different from those that have been traditionally installed.

Some examples of these new technologies include solid-state and superconducting equipment, which are already making their way into the T&D system. Testing new T&D equipment is generally required by utilities to ensure that new devices being introduced in the grid will perform as expected and not have adverse effects on the electric system. The standards and protocols for testing conventional T&D equipment are well known and are referenced routinely. The Institute of Electrical and Electronics Engineers (IEEE) and the National Electrical Manufacturers Association (NEMA), each promulgate standards for electric power sector equipment. IEEE's members are electrical engineers; NEMA's members are firms that manufacture equipment. Another organization, American National Standards Institute (ANSI), does not promulgate standards but adopts standards from organizations such as IEEE or NEMA. Several international standards groups include the International Electrotechnical Commission (IEC) and the International Organization for Standards (ISO). CIGRE, the International Council on Large Electrical Systems, formed the A3.10 working group and published a technical brochure in 2003 which included a very limited set of recommendations for testing fault current limiters in medium- and high-voltage systems.[1] CIGRE Working Group A3.23 was created in 2008 and is working on the application and feasibility of fault current limiters in power systems. IEEE is currently working on establishing a task force on FCL testing.

However, there are currently not any standards for testing high-temperature superconducting (HTS) and solid-state fault current limiters and integrating the device with the electric system. These devices are too new and are still in the research and

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[1] CIGRE Brochure 239, *Fault current limiters in electrical medium and high voltage systems*

development phase. Testing recommendations have been developed by utilities and device manufacturers on a case-by-case basis. Once these devices are scaled up and ready to be fully tested, there are questions about whether or not the facilities exist to test them properly.

This situation is problematic because there is a growing need for fault current limiters (FCLs) on the electric grid, and inadequate facilities and testing standards could delay their deployment. Superconducting power equipment could be an important element in the effort to modernize the electric grid and promote grid security and efficiency. A considerable amount of R&D progress has been made in the last few years, and several electric utilities are beginning to include superconducting cables in their planning horizon. The U.S. Department of Energy is currently supporting solid-state and high-temperature superconducting (HTS) fault current limiter demonstration projects. As data from these projects become available, and as utilities begin to consider where and how to use them, there will be a growing need for standardized testing of these components.

The Electric Power Research Institute sponsored a workshop on September 21, 2007 in Hauppauge, N.Y. which was co-hosted by LIPA to discuss the needs for standards and specifications for testing superconducting power equipment. Stakeholders, including developers, equipment manufacturers, and electric utilities were invited to attend the discussions that were arranged in a semi-formal setting to promote open dialogue.[2]

Purpose and Scope

The purposes of this project are to:

- Identify the specific testing requirements for advanced electricity-delivery devices such as fault current limiters;
- Make an assessment of the existing capabilities of testing facilities in the U.S. and internationally;
- Perform a gap analysis to determine where existing testing capabilities and facilities fall short.

The scope of the project includes solid-state and superconducting-based fault current limiters and focuses on projects sponsored by the U. S. Department of Energy.

Methodology

The “logic flow” of the methodology used to complete this project is shown in Figure 1. The project included interviews with experts from equipment manufacturers, electric utilities, universities, consultancies, and national laboratories on their experience with testing various T&D equipment and identifying testing requirements[3]. In parallel, research was conducted to evaluate the capabilities of existing testing facilities in the U.S. and around the world. A gap analysis was performed based on the testing needs and test facility capabilities.

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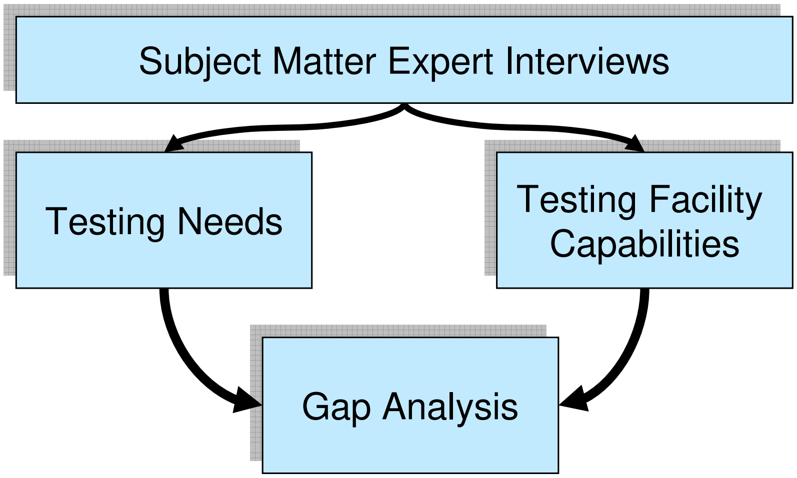
[2] More information about this workshop can be found at www.EPRI.com, report number 1016928, "Specifying and Testing Superconducting Power Equipment: Joint EPRI/DOE Workshop”

[3] See Appendix B: List of Experts

Figure 1. Methodology Flow Chart



Organization of the Report

The testing procedures and brief project status reports can be found in Chapter 2. During the interviews, the experts were also asked about the testing facilities with which they had experience. Based on these responses, an evaluation was conducted of the high-current and high-voltage facilities in the U.S. and abroad. The evaluation also involved discussions with representatives of the test facilities and a literature search. This information can be found in Chapter 3. After the interviews were conducted, a gap analysis was performed, which can be found in Chapter 4. Chapter 5 contains an assessment of the options for next steps in the development of testing facilities.

Appendix A contains a list of references used in the report. The list of experts can be found in Appendix B. Appendices C, D, E, and F contain testing information from the various Department of Energy-sponsored fault current limiter projects.

2.0 TESTING PROCEDURES FOR FAULT CURRENT LIMITERS

FCL Testing Procedures

DOE is conducting three high-temperature superconducting (HTS) and one solid-state fault current limiter projects. The three HTS projects involve the following companies: American Superconductor Corporation, SuperPower Incorporated, and Zenergy Power. The solid-state fault current limiter project involves the Electric Power Research Institute (EPRI) and the Silicon Power Corporation (hereafter referred to as Silicon Power). Additional information about each of these projects is contained in the text below and in Table 1.

Currently testing for fault current limiters is based on a hybrid test procedure for various existing equipment. For instance, the National Electric Energy Testing, Research and Applications Center (NEETRAC) worked with several manufacturers to develop testing procedures to validate their fault current limiter concept. Test procedures were derived from protocols for testing breakers, transformers, and reactors. Testing requirements need to be compatible with existing standards, taking into account the unique characteristics of the FCL.

The most important benefit of FCL in utility systems is the possibility to upgrade the electric grid to higher transmission capabilities while maintaining existing fault current limits for transformers and circuit breakers. This could save utilities money because they will no longer have to upgrade or retrofit existing equipment on their lines when they want to increase their transmission ratings. One of the delays to the faster adoption of FCLs is that currently, there are no standardized testing procedures in place for fault current limiters. While R&D efforts have been advancing, the current testing protocols are still very preliminary, and they have been set up based on each manufacturer's and hosting utility's specifications.

Because all four DOE projects are still prototypes, manufacturers are still conducting R&D testing and not type testing[4]. Testing of commercial-ready transmission class devices is still approximately 5 years away. R&D tests allow the manufacturers to explore the different parameters of the device being developed, such as the number of conductors needed or the size of the FCL coil to improve their design. These tests allow each parameter to be changed several times to validate different FCL functions. Type tests involve the evaluation of the device's functions, such as the time it takes to limit a fault or the maximum current and voltage that the device can withstand. It is important to note that as of today, there are no guidelines for type testing. From the ongoing R&D projects, and the rating that they are targeting, we can identify likely scenarios that a type test will include.

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[4] Type testing refers to testing commercial scale devices

While R&D tests are currently possible because all the manufacturers have prototype modules at lower voltage levels, FCL type tests will be more challenging because devices will need to be tested at high current and voltage simultaneously, and only a few laboratories have the capabilities to do high-power tests in the world. A discussion of testing facility capabilities can be found in the next chapter.

Table 1. Specifications for DOE's Fault Current Limiter Projects

Specification	American Superconductor	Silicon Power	SuperPower	Zenergy (formerly SC Power Systems)
Name	Super Limiter™	Solid-State Current Limiter	Superconducting Fault Current Limiter (SFCL)	Fault Current Controller (FCC)
Installed Location for Device	• First HV component testing December 2008 • Commissioning at SCE in 2012	• Design verification testing in 2Q09 at Test Lab	Plan to install and test at AEP's TIDD substation in Ohio	Plan to install and test in a utility grid, currently negotiating with a major utility. Separate project with California Energy Commission will test a similar 15-kV class FCL with SCE.
Design	• Resistive FCL • 3-phase, transmission level voltage • Low-inductance bifilar coil switching module technology using 2G wire	• Uses high power semiconductors Super-gate turn-off thyristor (SGTO)	• Resistive FCL • Matrix design has parallel, 2G HTS elements and conventional coils	• DC-based iron core • One DC first-generation HTS coil for a three-phase AC FCL • Saturable reactor-type FCL • Suitable for 2G materials, when available
Ratings (final design)	Voltage: 138 kV, 2000 A Class 115 kV, 1200 A at SCE site	Voltage: 69 kV Amps: 1,000 A	Voltage: 138 kV Amps: 1200 A	Targeting a three-phase transmission-level device at: Voltage: 138 kV Amps: 2,000 to 4,000 steady-state
Fault Current Reduction	20–50% Reduction – 37 % at SCE (63 kA to 40 kA)	50%-60% reduction	20%–50% reduction	20% to 40% reduction of a 60 kA to 80 kA fault
Testing Protocol Basis	Cable, Transformer	Transformer, Reactor, and Circuit Breaker	Transformer, Reactor, and Circuit Breaker	Transformer and Series Reactor

Because all the projects are at the R&D stage, testing procedures are very dependant on the FCL's design. Zenergy's FCC is very similar to a transformer; therefore, its testing protocols are based on transformer testing standards. Silicon Power's Solid-State Current Limiter follows circuit breaker testing standards due to its design specifications.

The following paragraphs discuss the different FCL type tests that we foresee once manufacturers have commercial devices based on CIGRE recommendations and discussions with industry experts.

Voltage Testing

Power Frequency Overvoltage and Partial Discharge Tests (Dielectric Tests)

This test is a series of experiments conducted at much higher than rated nameplate voltage to determine the effectiveness of insulating materials and electrical components and ensure that they do not deteriorate or do not flash over. It is performed in AC or DC with voltages varying from some hundred volts to several Megavolts. The choice of the nature and value of the test voltage is determined by standards that apply to the product tested. In the absence of standards, the following rule of thumb is used: The test is always performed with a frequency similar to the one under which the sample operates.

For instance, a dielectric test will use DC voltages for batteries and AC voltages for transformers.

Basic Lightning Impulse Insulation and Switching Impulse Level Tests

Outdoor electrical T&D systems are subject to lightning surges. Even if the lightning strikes the line some distance from the FCL, voltage surges can travel down the line and into the FCL. High-voltage switches and circuit breakers can also create similar voltage surges when they are opened and closed. Both types of surges have steep waveforms and can be very damaging to electrical equipment. To minimize the effects of these surges, the electrical system is protected by lighting arresters, but they do not completely eliminate the surge from reaching the FCL. The basic insulation level (BIL) or switching impulse level (BSL) of the FCL measures its ability to withstand these surges.

Current Testing

Continuous Current Test

This test runs the FCL at its rated current for several hours to ensure that it reaches thermal equilibrium. The goal is to demonstrate that the device can operate under full-load current. Manufacturers want to make sure that all connections with the FCL withstand continuous current flow thermally. Any weak connection will result in a rise in temperature or pressure build up.

Short-Time Withstand Current Tests

There are two types of short-time withstand current tests: 1) electrodynamic and 2) thermal capability. The goal of the electrodynamic test is to determine whether the device can withstand electrodynamic forces and the mechanical integrity of the device. If there is a loop or a bend in the conductor, outward mechanical forces try to expand the loop. A straight conductor would not experience these kinds of forces. The thermal capability test evaluates whether the device withstands the heat from high current and high voltage.

Breaking / Making Test

Breaking / making tests are circuit breaker (CB) tests. They only apply to FCLs that have CB functionality built into them, such as the Silicon Power and SuperPower devices. Breaking/making tests measure circuit breaker capabilities such as the integrated protection systems, which come with some breakers at low and medium voltages. One subset of this test is the maximum rated breaking current test. It is an FCL limitation test. The manufacturer tests at different current levels above rated current and up to the full rated fault current. If there is a rated load current value, multiples of that would be tested, and the maximum prospective fault current for the circuit for which the FCL is designed.

Fundamental Performance Testing

Recovery under Load

This is a new type of test that is specific to FCLs and not for circuit breakers, transformers, and other conventional devices. The reason is that superconducting FCLs need to cool down the superconductor before the device can experience another fault. The value of a FCL to the utility customer is greatly enhanced by the voltage class of the device and its ability to handle multiple faults without having to be removed from service. The latter requires that the device be able to recover to its pre-fault condition while still carrying normal load current and voltage. Load current flows through superconductor and any shunt circuitry simultaneously, while the superconductor cools down from prior heating during the fault current transient(s).

Fault Current Limitation

This test evaluates at each perspective current level how long it takes for the FCL to develop significant impedance, which in turn causes the desired voltage drop across the device, how large this voltage drop is, and whether the FCL can sustain the voltage for the specific time needed to open a breaker. Solid-state FCLs may have a feature to actively control current (similarly to household dimmer switches), which is not available with HTS FCLs; however, they both need to pass the current-limitation test.

Electromagnetic Compatibility Test

This test determines whether the device can withstand with electromagnetic interference and the amount of electromagnetic radiation it emits when it functions.

Utility Commissioning Tests

There are currently no guidelines on how utilities need to specify FCLs; therefore an FCL might be specified based on its applications. Some examples of applications include a bus tie FCL, a feeder FCL, or a generator tie FCL. For instance, a bus tie FCL might not need to recover under load; however, a feeder FCL will have tight specifications on how fast it needs to recover under load. Utilities may also have different requirements on how many faults FCLs can sustain before they can trip out or how long can they take to recover.

It is important to recognize that the most critical regime for the FCL is when it is limiting a fault current. The device has to internally develop high voltage levels while limiting large amounts of current, and there are no test sites around the world available to provide such large power levels for testing. For example, if an FCL experiences a 40 kA fault in a three-phase system rated at at 138 kV, the FCL needs to develop 40 kV across its terminals[5] to reduce the fault level to 20 kA. The reason for this is that a 50% reduction in fault current requires the FCL to develop the same amount of impedance as the source provides. Hence, 50% of system line-neutral voltage drops at the source impedance and 50% at the FCL. Therefore, the manufacturer will need to test the device with a 4 GVA power source. Furthermore, if this FCL is dominantly resistive the source must also provide real power of approximately the same magnitude. Testing laboratories are not yet able to offer such high power levels for testing. However, it shall be pointed out that certain SCFCL concepts, such as the one presented by AMSC/Siemens utilize an external shunt reactor to carry the major portion of the fault current. Hence, the superconducting portion of the system may be tested separately without the external shunt requiring significantly less current than the complete system.

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[5] This calculation assumes that the FCL drops 50% of the $138/\sqrt{3} = 80$ kV system line-to-neutral voltage to reduce the fault current by 50%.

Another note is that solid-state FCLs will not have to be tested for partial faults of reduced magnitude, but HTS FCLs would need to be tested for this. The reason for this is that there is potential for thermal runaway, which could degrade the superconductor and cause it to fail. HTS FCLs should work as specified under full load, but partial load may be problematic.

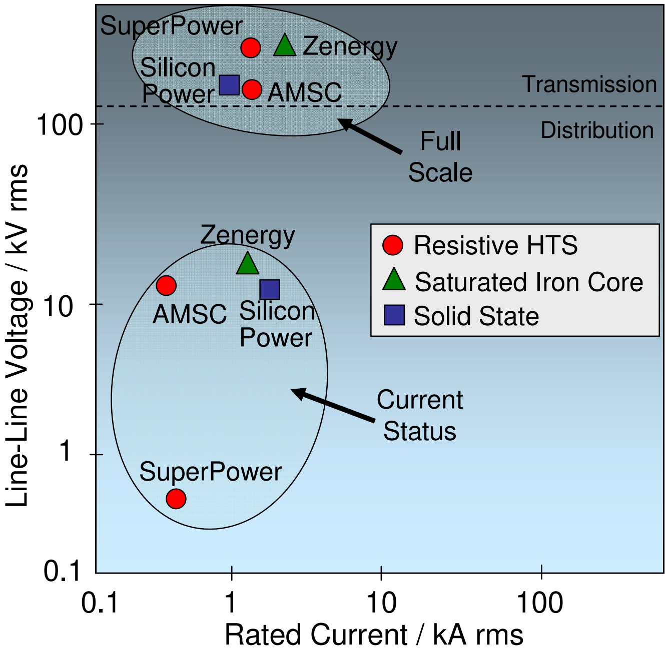
A CB duty test is a test to see how many times it is able to open and close before the energy-storage system of the device is exhausted and it no longer functions properly. A similar kind of test should be considered for FCLs. However, the reason for any limitation in the number of close-open-close cycles a FCL can perform may be different, depending on the FCL technology employed.

One important conclusion is that even though R&D testing procedures for FCLs have typically been based on transformer, reactor, or breaker standards it is crucial to address the differences between FCLs and those devices before adopting final testing procedures. Finally, the tests used in the R&D stage change depending on how far along the device is and testing labs are not set up to show such flexibility in their work because they were designed to test conventional devices with well known standards.

Status of DOE FCL Projects

The four DOE projects have testing requirements that differ by design and installed location. Some of the projects are still negotiating the testing requirements. Figure 2 shows the current and voltage of the devices as they stand right now and also when they are at full scale. The figure also indicates the type of device for each fault current limiter.

Figure 2. Current and Voltage ratings for the FCL projects[6][7]



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[6] Adopted from a presentation given by M. Steurer at the EPRI Superconductivity Conference, September 2007

[7] Details of the FCL R&D testing can be found in the appendices

AMSC's FCL module

American Superconductor Corporation's (AMSC) Fault Current Limiter

AMSC has the lead to develop and demonstrate in-grid testing of a commercially viable three phase transmission voltage superconducting FCL. Phase 1 of the project will involve development of the core technology followed by a demonstration of a single phase FCL in the beginning of 2010. Phase 2 of the project will include the construction, test and in-grid operation of a full three phase 115 kV SuperLimiter FCL by the end of 2012.

AMSC has conducted testing with their partner, Siemens, on a single-phase device with a rated current of 300 A rms and a rated voltage of 7.6 kV, which corresponds to a nominal apparent power of 2.25 MVA. The testing was conducted in January 2007 at the IPH-Berlin test facility. This module corresponds to a 13-kV class three-phase module. The test demonstrated that the module could reduce a short-circuit current from 28 kA to 3 kA. AMSC and Siemens conducted R&D testing on their FCL module to validate its design and provide data for scaling up to a higher voltage class. R&D testing information for this module can be found in Appendix C.

At this time, the utility testing requirements for AMSC's full-scale FCL are still under negotiation with SCE. The device is rated at 138 kV, but will operate at 115 kV in the Southern California Edison territory due to an absence of 138kV substations. Part of the design criteria for the device is to reduce a fault from 63 kA to 40 kA. The design is also modular so that coils may be added or removed in series and in parallel. In the way, the design may be extended to virtually any steady state current or limiting requirement. Also, by employing an external reactor, some flexibility is retained even in an existing installation to respond to system growth or change. The device is planned to be tested in accordance with IEEE and IEC specifications for 138 kV rated cable accessories and transformers.

SuperPower's Fault Current Limiter

SuperPower has the lead to develop a superconducting FCL for operation at 138 kV. The device will utilize a matrix design consisting of parallel 2G HTS elements and conventional shunt coils. The program will include the fabrication and testing of three prototypes, a single phase proof-of-concept prototype, a single phase alpha prototype and a three phase beta prototype. The first prototype unit has been tested in a laboratory and the second prototype will also be tested off grid. The final beta prototype is to be installed and operated in the American Electric Power (AEP) grid.

Testing one of SuperPower's FCL modules

SuperPower tested two alpha prototype single phase modules from 100 to 400 volts with 1.2 kA continuous current and 37 kA peak fault. They have successfully proved the concept of recovery under load for AEP's reclosure sequence. This sequence can be found in Appendix D. SuperPower is still optimizing the design so that it is more compact while still having the same functionality. Their final design is trying to reduce fault currents by 20-50%.

Zenergy Power's Fault Current Controller

Zenergy has the lead to design, build, and test a saturable iron-core superconducting FCL that is a prototype for a commercial product suitable for operating at a typical 138 kV transmission grid substation. One of their devices will operate at distribution voltage (less than 69 kV) and another will operate at a transmission voltage of at least 138 kV.

Zenergy's Fault Current Limiter

Zenergy's FCL prototype completed its first R&D tests at 480 V and 460 A in October 2007 at Pacific Gas & Electric (San Ramon, CA). They also tested a three phase 13.1 kV device at 10 kA and 16 kA fault levels at the PowerTech Laboratory in British Columbia, Canada. The device was able to reduce the 16 kA fault by (39 kA peak) 23%. It completed its first FCL performance test and was exposed to real-life grid operating conditions in December 2007. Zenergy is designing a 26 kV device for installation in Seattle City Light's electrical grid by mid 2010. The device is being designed to reduce a prospective fault by 50%. Their final 138 kV device will reduce a 60 kA to 80 kA fault by 20% to 40%. Additional information on the testing procedure conducted at PowerTech can be found in Appendix E.

Standard Building Block Assembly for the Silicon Power FCL

Silicon Power's Solid-State Current Limiter

Silicon Power has built a 6-kV building block device rated at 3 kA. Silicon Power evaluated various semi-conductor technologies before deciding on the Super Gate Turn-off Thyristor. They plan to design, build, and test a single-phase 69-kV device rated at 1 kA. The R&D testing recommendations for this device can be found in Appendix F.

Additional Examples of FCL Testing

CURL 10 Fault Current Limiter

There are several additional domestic and international examples of FCLs.[8] One project, sponsored by the German Ministry of Education and Research, warrants mention and is called CURL 10. The CURL10 FCL was a 10-kV, 10-MVA device with a continuous current rating of 600 A. It was the first field test of a resistive HTS FCL and was installed in

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[8] http://www.iop.org/EJ/abstract/0953-2048/20/3/R01

Germany's RWE Energie utility grid in 2004. It underwent a series of tests depicted in Table 2. In the laboratory, it limited a prospective short-circuit current from 18 kA to 7.2 kA. It operated in the electric grid for nine months, and while it experienced several lesser faults, it did not experience a design fault. A design fault is the maximum fault level the device can limit given its internal characteristics. This is of significance because it shows that even if a device is placed in a real-world scenario, it may not undergo the worst-case scenario fault during the test period. This could mean that utilities may need additional data to prove that the device functions properly, which could take several years of additional testing or it may not occur at all. If the design fault is never reached, then other utilities that are interested in fault current limiters may delay their purchase of the devices.

Table 2. Major Tests for the CURL 10 FCL

Major Tests	Purpose of Test
Single component and model tests	to verify component insulation and to qualify components
Testing on three "components" (2002)	to verify voltage distribution
Testing on nine "components" (2003)	to prove surge voltage suitability and voltage distribution
10 MVA test (2003)	to prove all HV aspects for the demonstrator
Field test (2004)	to prove long-term operation

3.0 TEST FACILITIES AND CHARACTERISTICS

The growth in world electricity demand has created resource adequacy problems in many regions along with needs for new knowledge and equipment in all aspects of the supply chain. Meeting this need requires adequate facilities for designing and testing new equipment. This chapter provides a brief overview of the testing facilities and their capabilities for evaluating advanced devices, including FCLs.

Typically, there is a distinction made between *high-voltage* and *high-power* facilities. The testing programs at a high-voltage laboratory are concerned with properties of dielectrics (both solid and gas) at very high voltages, the design and performance of conductor lines for high voltage transmission lines, etc. A high-power laboratory provides an opportunity for studying the characteristics of high-power systems and the behavior of components under real-world or simulated high-power conditions. Test facilities are typically not referred to as high-current facilities because this capability is implied in the capabilities of high-power facilities.

T&D device testing is being conducted internally at the manufacturer's facility, one of its partner facilities, universities, government facilities, independent testing facilities, or a combination of them. The manufacturer's facility is typically limited in the capabilities they have, but some can do initial screening testing. The partner facilities along with universities and government facilities typically have high-voltage facilities but limited power capabilities. Government facilities require upgrades and modifications in order to provide adequate testing. Independent test facilities often have the test capabilities, including power and fault capabilities, but are available at a high cost. Table 3 depicts several examples of test facilities and their capabilities. The column headings for the table are explained below.

Testing facilities have a wide range of capabilities to test voltage, current, and power. The voltage-testing capability can be broken into three types of tests: AC source, impulse, and DC source. AC source voltage is the maximum voltage capability that the facility can provide at steady-state. Impulse voltage is the maximum amount of voltage that the facility can provide for milliseconds or to simulate a lightning strike. The DC source voltage is the maximum about of voltage that can be provided by a DC source.

Current testing can be done at very high levels but only for several seconds or less at low voltage. Some facilities are capable of very high voltage testing but not capable of very high current testing such as NEETRAC and Mississippi State. High power testing is available at a very limited number of facilities in the world. In North America, the KEMA facility in Chalfont, Pennsylvania and the Power Tech facility in Vancouver, Canada are the two primary test facilities with high-power capabilities. Three of the four FCL projects have used these facilities to conduct testing. The KEMA facility in Arnhem, The Netherlands, has the highest power test capability in the world.

Table 3. Examples of Test Facilities and Capabilities

Name	Location	Insulation Test (MV) at "zero" current			Current Test (kA) at "zero" voltage		High-Power Test		Kind of Source(s) for the Lab	How Can the Facility Be Accessed?
		AC 50/60 Hz	Lightning Impulse 1/2/50μs	DC	Fault	No-load voltage (kV)	Maximum (Surge) Power Rating (MVA)	Continuous Power (MVA) @ nominal voltage (kV)		
KEMA[9]	Chalfont, PA	0.55	0.80	0.10	50 for 1 s 63 for 0.5 s.	13.8	3250	N/A	Short-circuit generators rated for 1,000 and 2,250 MVA parallel operation possible	Private facility -- approx $10k/day
KEMA[10]	Arnhem, The Netherlands	1.00	2.60	1.00	390 for 0.42 s.	15 @50Hz 17@60Hz	8400	N/A	4 short-circuit generators, 2,100 MVA each	Private facility
Power Tech[11]	Vancouver, Canada	0.80	3.00	1.00	110 for 3 s.	13.6	1500	N/A	Power system grid (12,000 MVA)	Private facility -- approx $10k/day
ORNL	Oak Ridge, TN	0.2	0.8	0.3	50	0.3 (0.6 with upgrade)	N/A	N/A	DC and AC power supplies	Available to DOE funded partners
LANL	Los Alamos, NM	0.138 (with upgrade)	N/A	0.025	4 (100 for ~1 sec. with upgrade)		1400	5 @ 13.4 400 for 1 s	13.4-kV power grid; 1.4 GVA generator	Available to DOE funded partners
Bonneville Power Administration[12]	Vancouver, WA	1.1 @ 0.75A	2.0 indoor 5.6 outdoor	1.0 @ 10 mA	200	0.35	TBD	5 @ 13.2	60 Hz power system grid fed from 13.2 or 115 kV, OR 60/400Hz motor generator at 2.4 kV	Dept. of Energy
NEETRAC[13]	Atlanta, GA	1.00	2.20	1.00	25 for 2 s	.12	N/A	N/A	2.2 MV, 220 kJ Impulse generator 1MV Cascade Transformer	University-based Independent test laboratory
Florida State University-CAPS[14]	Tallahassee, FL	0.1	0.14	0.14	84 13 7	0.385 0.48 4.16	130	7.5 @ 4.16 1.5 @ 0.48	60 Hz power system grid fed from 12.47 kV	University-based Independent test laboratory
					1.7 13 4.8 (DC)	4.16 0.48 1.15 (DC)	N/A	6.2 @ 4.16 1.5 @ 0.48	Variable frequency and voltage converter[15]	

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[9] Personal communication with Rene Smeets, KEMA

[10] Personal communication with Rene Smeets, KEMA

[11] Personal communication with Jan Zawadski, Director of Power Laboratories

[12] Personal communication with Jeffrey Hildreth, BPA

[13] Personal communication with Frank Lambert, NEETRAC

[14] Personal communication with Michael "Mischa" Steurer, FSU-CAPS

[15] Worldwide unique installation which allows waveform control at a bandwidth of approx. 1.2 kHz fully integrated with a real-time simulator which enables power hardware in the loop simulations.

There are several ways that a facility can produce power for testing. Many facilities use a short-circuit generator. Some facilities are able to use the local electric grid as the power source. There are two perspectives on having power provided by rotating machinery or by a network. Rotating machinery provides greater utilization, greater availability, and greater flexibility; however, type and commissioning testing typically require connection to a network.

Accessibility is another criterion for testing facilities. Some facilities, such as the Power Tech and KEMA, are private and charge a daily fee for their testing services. Other facilities, such as those run by the Department of Energy's National Laboratories, are open to the partners of the funded projects.

High-temperature superconducting devices such as cables and fault current limiters require a cryogenics system to cool the devices to superconducting temperatures. However, cryogenic systems using liquid nitrogen, for instance, is not a standard system that all test facilities provide. Tests on superconducting FCLs and cables have been done at private test facilities and national laboratories because they can be adapted to accommodate liquid nitrogen tanks.

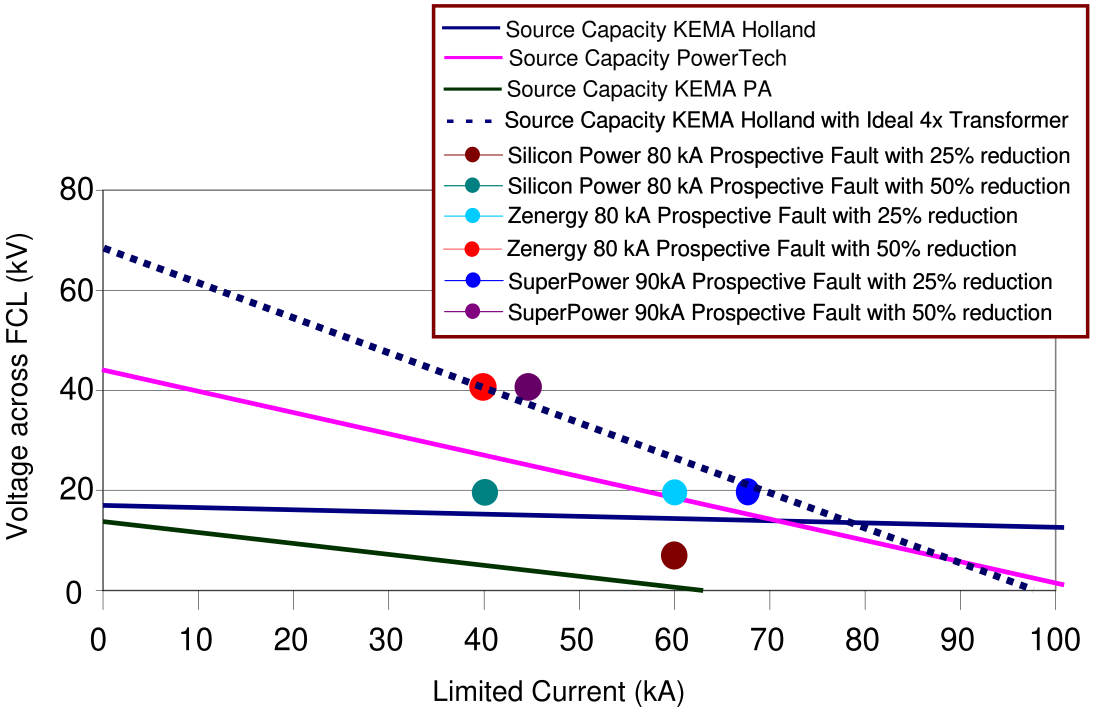
4.0 GAP ANALYSIS

Based on the information collected for assessing the testing requirements and the capabilities of the T&D equipment testing facilities, an analysis was performed to determine gaps.

Figure 3 below compares the testing requirements for the final designs of the DOE fault current limiter projects with the capabilities of the existing facilities. The figure shows the simplified source characteristics of three major testing facilities in comparison to the parameters required for testing four FCL projects. The lines for the source capacity were drawn using the data from Table 3 under the current test (kA) at “zero” voltage. For instance, the PowerTech facility can provide a no load voltage of 44.6 kV and a fault condition of 110 kA. By plotting 44.6 kV at zero kA and 110 kA at zero kV you can estimate the source capacity of the PowerTech facility.

The range of parameters stems from different current limiting requirements those FCLs may have to fulfill. For example, if the SuperPower device in its current target application (138 kV, 90 kA) has to reduce the fault current by 25% to 67.5 kA it will have to drop 20 kV across its terminals. If it should reduce the current by 50% the voltage would be double, or drop 40 kV across its terminals. As illustrated in Figure 3, none of these conditions can be fulfilled by any of the testing laboratories. While it is, in principle, possible to change the source characteristic of the facility by using a voltage step up transformer it seems only the KEMA facility in Holland could then cover some of the required testing parameters. For simplicity it was assumed that an ideal step up transformer was used, which does not add impedance. AMSC has indicated that the existing test facilities are adequate for their transmission level device configuration and that is why they do not appear on the graph.

Figure 3. Testing Requirements for FCLs and Existing Capabilities



Additional major findings from this gap analysis are found below.

Gap: Testing can be done at distribution voltage, but not transmission

There are four FCL projects sponsored by the DOE. Within the next five years, in order for these devices to be fully tested, they could need to undergo testing at 138 kV and at high fault current levels of 50 to 100 kA. The actual fault current levels depend on the characteristics and topology of the electric grid in which they will be applied and therefore vary from one service territory to another. FCLs can be tested today at distribution system-level voltages, but not for transmission-level voltages of 115kV and above. Utilities have expressed a need for 138-kV FCLs, and if there were higher-class devices available, they would be interested in using them.[16] These higher transmission class devices could potentially require higher voltage and current levels to adequately test their capabilities.

There are a number of facilities that have the capability to perform high-voltage testing at low current or high current at low voltage. This kind of testing can be used to test devices without using high power. Transmission level T&D equipment will need to be tested at high voltage and high current, and there are not adequate facilities to do this. Testing high voltage is relatively easy, and there are a number of facilities with this capability, but current and power testing are more difficult because a test facility must

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[16] *Impact of Fault Current Limiters on Existing Protection Schemes,* CIGRE Technical Brochure 339, Working Group A3.16

plug into the grid or have access to very large generators. The ability of a laboratory to provide adequate testing conditions is limited by local utility service restrictions, such as the incoming utility power being able to sustain repeated fault testing. However, in most cases, an even greater limitation is the test facility's need to protect its own test equipment.

Examples of high-power facilities that are being used today include Power Tech in British Columbia, Canada, and KEMA T&D Testing Services, which has locations in Chalfont, PA, and Arnhem, The Netherlands. While these facilities do have high-power testing capabilities, they would not be able to test, for example, a 138-kV fault current limiter with a 50-kA fault current. These facilities do not have any plans to upgrade their capabilities in the near future.

Gap: Facilities are not equipped for R&D project or type testing

Existing test facilities are not designed for meeting the testing needs of researchers investigating the performance limits and capabilities of advanced designs and prototypes. They are designed to test conventional devices that have well-known and prescribed testing standards and do not require support from engineering staff or technicians. When R&D projects undergo initial testing procedures, there are a number of modifications that need to be done as the devices are subjected for the first time to high power. When renting commercial testing facilities, costs can become prohibitive as researchers customize and retool their equipment and refine their testing protocols and procedures while in the test cell. For example, for FCLs based on high temperature superconducting designs, the cost of the renting the test cell, plus the cost of site labor, plus the cost of the cryogenics and rental equipment, can result in total costs that range from $10,000 to $15,000 per day, depending on the facility.

In addition to cost, there is also an issue of timing and scheduling. There are a limited number of facilities that have the capability to do testing, and device manufacturers may have to wait several months before they are able to schedule tests. This can cause delays because the R&D projects are typically under tight deadlines and requirements to show progress and meet performance targets for which DOE is accountable to the Office of Management and Budget and the U.S. Congress. If a series of tests are not completed according to plan, missed deadlines could delay commissioning dates and ultimately the technology- and market-readiness goals of the project. Delays also affect utility planning and could raise risks of their not being able to see projects through to their completion.

Customer service and worker safety are paramount in the electric power industry. As a result, Utilities generally are extremely cautious in their testing requirements, especially for next generation equipment based on advanced materials and designs. Testing therefore usually extends to actual grid installations, as is occurring with the high temperature superconducting cable demonstration projects. When utilities go through the process of testing advanced devices on their systems, it sometimes takes years to compile sufficient data to determine whether the device functions properly and as expected under the full range of possible conditions. There are instances where devices are tested outside of the U.S. to fulfill a utility's testing requirements, and testing in another country, which operates at voltage and frequency levels different for those used in North America, has its own set of logistical issues. Shipping devices long distances can add substantially to project testing costs, and delays can be experienced due to international trade and treaty issues.

Gap: Standards for testing FCLs do not exist

There are currently not any “standards” for testing fault current limiters and integrating the devices with the electric system. Testing recommendations and guidelines have been and will continue to be developed by FCL device manufacturers and their partners and will vary depending on the design of the equipment and the application. One of the issues with developing testing standards for FCLs is that the devices cover a wide range of response characteristics that are currently difficult to specify by utilities. For example, the characteristics for solid state FCLs are mostly similar to those of existing electric equipment such as transformers, circuit breakers, and reactors. Establishing working groups for developing FCL standards and specification guidelines could be a valuable step in helping utilities feel more comfortable with investing and applying these new devices on their systems.

There is disagreement among industry experts whether one standard should be developed for all FCLs or if several standards should be developed based on the design. FCL designs can vary greatly, and it may be necessary to develop a standard to be able to test each of these unique designs. However, from the utility’s perspective it may be simpler to have one standard by which to test all FCL devices because the design differences are much less important to them than the functionality the devices provide.

APPENDIX A. LIST OF REFERENCES

Noe, M. and Steurer, M., *High-temperature superconductor fault current limiters: concepts, applications, and development status*, Superconducting Science Technology 20 (2007) R15–R29 http://www.iop.org/EJ/abstract/0953-2048/20/3/R01

Kraemer, H-P, et al, *Test of a 2 MVA medium voltage HTS fault current limiter module made of YBCO coated conductors*, Journal of Physics: Conference Series 97 (2008) http://www.iop.org/EJ/abstract/1742-6596/97/1/012091

Schmitt, H, et al, *Impact of Fault Current Limiters on Existing Protection Schemes*, CIGRE Technical Brochure 339, Working Group A3.16

CIGRE Brochure 239, Fault current limiters in electrical medium and high voltage systems

APPENDIX B. LIST OF EXPERTS CONSULTED FOR THIS PROJECT

Table B-1. List of Experts Contacted

Name	Organization	Interview Date
Tom King	ORNL	11/27/07
Steve Ashworth	LANL	11/27/07
Pat Duggan	ConEd	12/5/07
Mahesh Gandhi	Silicon Power	12/7/07
Harshad Mehta	Silicon Power	12/7/07
Woody Gibson	Zenergy Power	12/11/07
Bert Nelson	Zenergy Power	12/11/07
Alanzo Rodriguez	California Institute of Technology	12/18/07
Syed Ahmed	SoCal Edison	1/4/08
Tom Tobin	S&C Electric	1/15/08
Frank Lambert	NEETRAC	1/15/08
Dale Bradshaw	Electrivation	1/16/08
Chris Rose	LANL	1/17/08
Mike Gouge	ORNL	1/17/08
Alex Malozemoff	AMSC	1/18/08
Drew Hazelton	SuperPower	1/24/08
Chuck Weber	SuperPower	1/24/08
Ashok Sundram	EPRI	1/31/08
Patrick Murphy	DHS	2/13/08
Alan Wolsky	ANL	5/16/08

APPENDIX C. AMSC R&D TESTING

Medium Voltage FCL Testing Procedures

AMSC and Siemens developed a one phase FCL module with a rated current of 300A and a rated voltage of 7.5 kV, which corresponds to a nominal apparent power of 2.25 MVA. The module underwent a series of tests including single coil tests, power tests of the FCL module, tests in standard configuration, tests in shunted configuration, recovery after a fault, and dielectric tests. Additional details from these tests can be found in an AMSC and Siemens document.[17]

Single coil tests

The AMSC FCL module is made of three stacks connected in series and each stack contains 5 coils connected in parallel. The single coils were checked for room temperature resistance and critical current to ensure the stability of the superconducting wire. The coils were then subjected to 20 switching tests at 2.3 kV, which was the maximum voltage available at the Siemens test laboratory. Because this voltage was lower than the maximum expected in the power test of the module the fault hold time was increased to simulate the thermal load. Extrapolating the results from these tests it was determined that the maximum average temperature fell within 115-125°C, which is a safe level compared to the melting point of the solder used in the wire.

Power tests

The power tests of the module were tested at the IPH (Institut “Pruffeld fur elektrische Hochleistungstechnik”) facility in Berlin Germany. More than 40 power tests at voltages greater than 6.5 kV for 40 to 50 ms.

Tests in standard configuration

Two power tests were conducted at fault current of 10 kA and 28 kA with the FCL directly connected in series between the source and a shortened load, or in “standard configuration”.

Tests in shunted configuration

In a “shunted configuration” the FCL is in series with a circuit breaker and arranged in parallel to a current limiting shunt reactor. The results from this test proved that active part of the FCL can be designed to be significantly smaller if a shunt reactor is connected in parallel to the FCL.

Recovery after a fault

An important feature of a FCL is how long it takes to recover or cool down from a fault. If the current can be applied to the device without a measurable voltage drop across the switching elements, then the device has recovered to a superconducting state. Tests confirmed that the recovery time (2.4 s) was the same for the individual coils as it was for the entire module.

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[17] *Test of a 2 MVA medium voltage HTS fault current limiter module made of YBCO coated conductors*

Dielectric tests
Basic insulation level (BIL) tests of the standard rated lightning impulse and power frequency withstand voltages were tested at >95 kV and at >38 kV, respectively. These are the standard BIL levels for nominal voltages up to 17.5 kV.

Planned High Voltage FCL Testing Procedure

Development testing is being conducted on elements of this system.

This includes testing of each individual HTS coil produced. In this test, the coil is subjected to a representative overcurrent, transition to a normal state resistance, heating to above room temperature and recovery to a superconducting state.

Also, various elements of the high voltage dielectric design are being tested. This includes elements of the coil internal dielectric insulation and coil assembly to ground dielectric.

Furthermore, the device terminations have been fabricated and already successfully tested to required BIL and BSL levels in addition to power frequency overvoltage, partial discharge and extended operation at rated current.

A summary of the testing planned for the transmission level fault current limiter is summarized below. This will be performed on the superconducting assembly independent of the conventional circuit breaker and parallel reactor that are included in the complete installation.

- Cool and pressurize the system to subcooled operating temperature and pressure.
- Perform mega-ohmmeter, LCR and DC-Ic measurements of system.
- Pass rated current (nominally 1200A) through system for greater than 8 hours.
- Perform partial discharge test per requirements of IEC 60840, 12.3.4. In summary, test voltage is raised gradually to 140kV, held for 10s and slowly lowered to 114kV. There shall be no detectable discharge exceeding 5pC.
- Perform lightning impulse voltage test per requirements of IEC 60840. In summary, this is completed at 650kV with the standard BIL waveform repeated 10 times in both the positive and negative polarity. Also, this is repeated on each terminal of the system and with both terminals electrically connected.
- Perform switching impulse test per standard switching impulse waveform at 540kV level and similar to requirements of IEEE Std C57.16. However, C57.16 only requires positive polarity and 15 repetitions. This test shall be completed 5 times in both the positive and negative polarity. Also, it shall be repeated for each terminal and with the two terminals electrically connected.

- Perform power frequency voltage test per requirements of IEC 60840. In summary, connect 190kV, 60Hz AC to one terminal of the assembly for at least 15 minutes.
- Repeat partial discharge test.
- Repeat mega-ohmmeter, LCR, DC-ic tests.
- Perform power switching test. This is done by applying 20 to 30kV RMS, 60Hz to the terminals of the assembly for a fixed, short duration of 4 cycles. Repeat this test 5 times. Exact voltage, duration and phase angle of onset are to be determined prior to the test and as constrained by test facility capabilities.
- Repeat mega-ohmmeter, LCR, DC-ic and tests.
- Repeat partial discharge test.

APPENDIX D. SUPERPOWER R&D TESTING

NEETRAC began working with SuperPower in 2003 to familiarize utilities with the new high voltage superconducting fault current limiter technologies. Six member utilities from NEETRAC were visited during 2003 to understand the potential applications of the device. A project was launched in 2004 which was funded by NEETRAC utilities to develop a recommended acceptance dielectric test program. SuperPower formed a project advisory board including staff from American Electric Power, NEETRAC, and experts from the Department of Energy's National Laboratories. The FCL test program development process started with a review of the dielectric requirements of existing ANSI/IEEE standards for circuit breakers, transformers, and reactors. After a review of the standards it was determined the following three testing specifications would be used to design SuperPower's FCL device: ANSI/IEEE Circuit Breaker C37.06 Table 4, ANSI/IEEE Transformer C57.12.00 Table 6, and ANSI/IEEE Reactor C57.16 Table 5. An analysis was done to compare circuit breaker, transformer, and reactor standards to each other for several conditions.   Table D-1 summarizes the proposed FCL recommendations.

Table D-1. SuperPower's Proposed Fault Current Limiter Recommendations

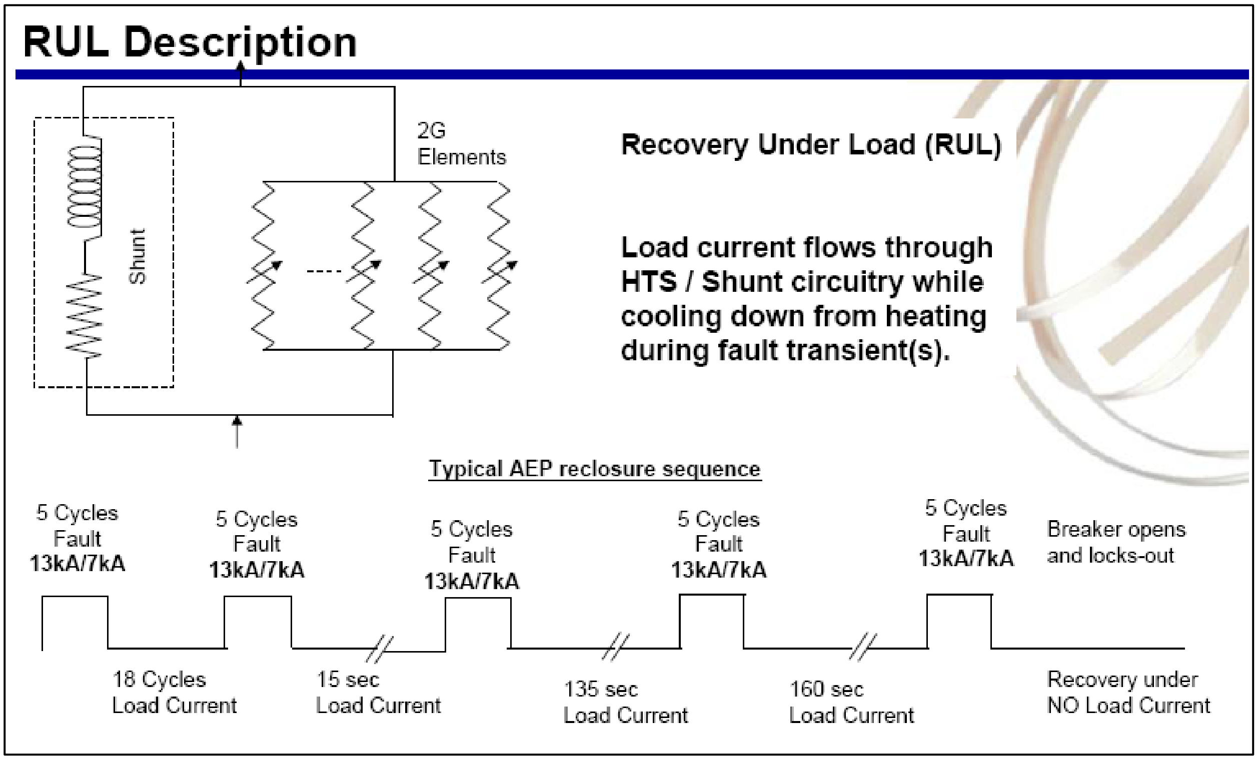
Tests to be Conducted	Proposed FCL Requirement
60Hz Withstand	Based on ANSI Circuit Breaker C37.06 Table 4
Partial Discharge	Based on ANSI Transformer C57.12.00 Table 6
BIL Lightning Impulse	Based on ANSI Reactor C57.16 Table 5
Chopped Wave	Based on ANSI Transformer C57.12.00 Table 6
Switching Impulse	Based on ANSI Transformer C57.12.00 Table 6

SuperPower's test program development for its single-phase Alpha FCL is shown in Table D-2. The typical AEP reclosure sequence can be found in Figure D-1, courtesy of SuperPower.

Table D-2. FCL Test Program Development for SuperPower

System Parameters	Rating
Voltage (kV rms)	80.0
Load Current (A rms)	1200.0
Short-Circuit Fault Current (kA rms)	14.0
Short-Circuit Fault Current (kA peak)	37.0
Fault Duration (cycles)	5.0

Figure D-1. FCL Test Program Development for SuperPower



RUL Description

Recovery Under Load (RUL)

Load current flows through HTS / Shunt circuitry while cooling down from heating during fault transient(s).

Typical AEP reclosure sequence

APPENDIX E. ZENERGY POWER'S TESTING

NEETRAC launched a project in 2006 to develop a recommended acceptance testing program for the 15-kV fault current limiter. The Zenergy Power FCL test program is a compilation of an existing ANSI/IEEE transformer standard and other tests as outlined below.

Future testing requirements are still being negotiated with the California Energy Commission and SCE. Zenergy Power may be able to do comprehensive full-load testing at distribution voltages and then extrapolate to higher voltages during more limited testing such as impulse tests. This kind of testing will prove that the device will not experience an electromechanical failure due to a fault.

The device is a saturable-core fault current controller (FCC)—15-kV class, three-phase device with a BIL of 110 kV and nominal current rating of 1,200 A. The unit will have dry-type AC windings similar to a dry-type transformer with porcelain external bushings in an NEMA 3R enclosure.

Existing U.S. and international standards for air core rectors, dry-type transformers, and circuit breakers and CIGRE Working Group's A3.10 report (December 2003), "Fault Current Limiters in Electrical Medium and High Voltage Systems," were reviewed for application to superconducting saturable-core fault current controllers.

Figure E-1 summarizes the overall design tests that the Zenergy Avanti FCL will be subjected to. It is important to note that when fault tests are conducted, tests 1 through 7 in table 1 will have been already completed at a different experimental facility. However, the preliminary test sequence on applied voltage and load current illustrated in Figure E-2 shall be applied as the first test to the FCL.

Figure E-1. Zenergy Power Test Summary

#	TEST	Location	Ref.(*)	Date	Observations
1	Winding Resistance	T&R Electric	IEEE Std C57.16-1996	9/23/08 to 9/30/08	
2	Impedance	T&R Electric	IEEE Std C57.16-1996	9/23/08 to 9/30/08	
3	Total loss	T&R Electric	IEEE Std C57.16-1996	9/23/08 to 9/30/08	
4	Temperature rise	T&R Electric	IEEE Std C57.16-1996	9/23/08 to 9/30/08	Must be carried out at rated current. Reduced voltage is allowed.
5	Applied voltage	T&R Electric	IEEE Std C57.16-1996	9/23/08 to 9/30/08	@34kV according to coil manufacturer and IEEE C57.12.01
6	Insulation power factor	T&R Electric	IEEE Std C57-12.01-2005	9/23/08 to 9/30/08	
7	Insulation resistance measurement	T&R Electric	IEEE Std C57-12.01-2005	9/23/08 to 9/30/08	
8	Fault current tests	Powertech	Engineering Spec. ZP-ES-08-05	10/14/08 to 10/17/08	
9	Turn-to-turn	Powertech	Engineering Spec. ZP-ES-08-05	10/20/08 to 10/21/08	
10	Lightning impulse @110 kV	Powertech	Engineering Spec. ZP-ES-08-05	10/20/08 to 10/21/08	
11	Chopped-wave impulse	Powertech	Engineering Spec. ZP-ES-08-05	10/20/08 to 10/21/08	
12	Audible sound	MFG or Shandin	Engineering Spec. ZP-ES-08-05	10/20/08 to 10/21/08	
13	Partial Discharge	Powertech	Engineering Spec. ZP-ES-08-05	10/20/08 to 10/21/08	
14	Radio influence voltage(RIV)test	Powertech	Engineering Spec. ZP-ES-08-05	10/20/08 to 10/21/08	

Figure E-2. Zenergy Power FCL Base Testing

Secondary Voltage of main transformer bank	Steady state current through FCL required	Load bank impedance on load side of FCL	Source limiting impedance	Time duration of steady state current	Cooling time
kV	A	Ω	Ω	s	min
12	200	As required	As required	100	<20
12	500	As required	As required	100	<20
12	750	As required	As required	100	<20
12	1200	As required	As required	100 max	20

Quantities to measure:

- Line current in the three phases
- Voltage on the source and load side of the FCL
- AC Coil temperature

Quantities to derive from measurements:

- FCL voltage drop

1. FCL impedance
2. Voltage and Current harmonics

APPENDIX F. TESTING RECOMMENDATIONS FOR SILICON POWER

The testing requirements for Silicon Power's 69 kV device are based on the circuit breaker specifications ANSI C37-04, ANSI C37-06, and ANSI C37-09.

For the 69 KV device there are 3 different dielectric tests:

- Power frequency voltage test: 160 kV power source applied to the FCL with respect to ground for 1 minute (there should not be any leakage current, or it should be in the milliamps range)
- Impulse test: to prove the dielectric component to withstand lighting: 350 KV (KEMA has done in the past up to 250 KV)
- Impulse test with chopped wave: test to prove dielectric against voltage spikes. 450kV for 2 microseconds width of the voltage spike

Temperature rise test or continuous current withstand test:
Silicon Power has to test at 3000 Amps, but does it at a lower voltage -- 200 Volts (because testing at full voltage requires 360 MVA). Silicon Power uses a number of thermocouples inside their equipment to monitor the temperature. Silicon Power is working on a second phase where they will try 4000 Amps in one year or 1.5 years. Silicon Power has coordinated with the KEMA test facility and determined they have this capability.

Fault current limiter testing:
Silicon Power will connect equipment with a source that can provide 80,000-100,000 amps for 100 microseconds, then 30,000 amps for 100 milliseconds. When the system has a fault, the FCL can see 80,000 amps and within the time range it is supposed to bring 80,000 amps down to 30,000 after 100 milliseconds.

Voltage waveform testing:
The voltage waveform testing will be done at 69kV with 3000 amps for 10-15 minutes. This will require approximately 360 MVA.

Silicon Power will do a reliability or lifecycle test, but they have not done it because it is hard to do them in a lab setting because it requires large power consumption.

A summary of Silicon Power's testing requirements are shown in Table 2.

Table F-1. Testing Requirements for the Silicon Power Current Limiter

Parameters	Rating
Rated Maximum Voltage	72.5 kV rms
Rated Continuous Current	3000 A rms
Rated Power Frequency	50/60
Rated Let-Through Current, kA rms (Customer Specified)	<20/31.5/40
Rated Let-Through Current Duration	30 Cycles
Power Frequency 1 min Dry	160 kV rms
Impulse, Full-Wave (1.2/50 μSec) Withstand	350 kV peak
Impulse, Chopped Wave (2 μSec) Withstand	452 kV peak
Ambient Operating Temp	-30 to +40 Degree C

Note: Ratings derived from ANSI Circuit Breaker C37-04.