ELECTRIC POWER RESEARCH INSTITUTE

Superconducting Fault Current Limiters

Technology Watch 2008

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PRODUCT DESCRIPTION

This report contains a technical overview of superconducting fault limiter (SFCL) technologies currently under development. It summarizes the benefits associated with SFCL technology and compares them to a list of ideal FCL characteristics that have been outlined by several electric utilities. Brief summaries of ongoing efforts to develop and deploy SFCL devices into the U.S. electric grid are also provided.

Results and Findings

SFCL devices have desirable attributes that make them attractive for grid deployment if their cost and reliability meet acceptable levels. There are also other characteristics that SFCL development teams strive to improve in order to more closely approach the ideal case. In the United States, development teams and the U.S. Department of Energy are developing SFCL prototypes for grid deployment within the next few years.

Challenges and Objectives

The content of this report has been arranged for those with interest in SFCL technologies that are seeking updated information about technical progress and status of ongoing projects. The information regarding ongoing U.S. projects in the report will make it useful for those who wish to stay informed about new developments while the overview of SFCL operation will provide beneficial introductory information for the layman. The target audience of this report is primarily utility personnel, managers, and planners that have an interest in the concept of SFCLs and wish to observe the technological progress toward commercial viability.

Applications, Values, and Use

The information contained in the report will be updated and expanded through the compilation of future technical updates on the subject. For instance, the next report will contain status updates on the U.S. projects summarized in this report and expand upon these updates to include SFCL projects worldwide.

EPRI Perspective

SFCL projects continue to make progress toward commercialization as power utilities worldwide deal with the issue of increasing fault current levels resulting from load growth. Working to find new ways to mitigate increased fault current magnitudes, utility planners have shown interest in fault current limiter technologies including those using superconducting materials. This technical update provides information about the operation of SFCLs along with summaries of ongoing developmental efforts.

Approach

The project team collected descriptions of SFCL technologies and summaries of ongoing projects from literature and direct interaction with project teams. The team provided brief technical descriptions of SFCL technologies and summarized their beneficial characteristics. The team also describes efforts underway to improve SFCL technology to increase their viability for use in commercial power systems.

Keywords
Superconducting fault current limiter
Fault current limiter
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CONTENTS

1
INTRODUCTION

Power grids are expanding their generation and transmission assets in an effort to meet growing demands. This expansion brings with it the potential for increasing fault current magnitudes that can have a damaging effect on grid equipment and even exceed the existing capabilities of conventional interruption devices. The trend towards renewable energy sources, distributed generation, and strong interconnection systems, also contribute to the increase in fault current levels. Novel fault current limiter (FCL) technologies present a possible solution and are of growing interest because of their potential to replace existing (and increasingly often unsatisfactory) methods of fault current protection. The superconducting FCL (SFCL) is one such technology. SFCLs attracted interest soon after the discovery of high temperature superconducting (HTS) materials but have only lately been seriously considered as it became apparent that coated conductors have potential to approach cost and performance levels desired by electric utilities.

High fault current levels can have a damaging effect on power system components both from the standpoint of electromagnetic forces and thermal stresses. It is therefore necessary to remove power system devices susceptible to damage from the immediate path of a fault until the system returns to an operating state that is safe for normal operation. Circuit breakers traditionally have had the task of providing this isolation. Although circuit breakers do their job well, they are limited by the rating of their mechanical contacts to magnitudes of 60 kA_{rms} or less. While higher capacity circuit breakers (up to 80 kA_{rms}) are now available, their high cost and large footprint make them a difficult retrofit option. Devices like fuses and disconnect switches also play a role in protection, but they require human intervention for reset and prove to be costly from the standpoint of labor and lost operating hours. Therefore, fuses and disconnect switches are used primarily for back-up and long-term isolation.

Figure 1-1
SuperLimiter™ SFCL Concept

(Source: and In-Grid Demonstration of a Transmission Voltage SuperLimiter™ Fault Current Limiter, 2008 DOE Peer Review, Washington, D.C.)

The case can be made that SFCLs are an attractive option for the mitigation of fault currents in future grid applications as they possess characteristics that make them invisible to a power system until their services are needed. The invisibility characteristic combined with the fast response and environmentally safe operation can potentially make SFCL technology viable for grid deployment assuming cost and reliability meet acceptable levels. The following chapters will discuss the benefits associated with SFCL technologies and summarize areas where additional improvement is needed. Ongoing projects to develop and deploy SFCLs within the United States are also summarized.

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WHY SUPERCONDUCTING FCLS?

Generally, SFCLs are passive devices that operate using the dynamic resistance of superconductors to limit fault current magnitudes to manageable levels. During nominal grid operating conditions, an SFCL exhibits virtually zero impedance on the power system. At the onset of a fault event, the electrical resistance of the superconducting components in the SFCL (typically superconducting wire or bulk material conductors) increases exponentially in response to elevated fault current levels (as well as the associated magnetic fields and temperature increase). This property is the basis for the SFCL's ability to limit current, either directly or indirectly depending on device design. The inherent behavior of SFCLs makes them attractive because they can react quickly and generally do not operate on the basis of sophisticated control electronics, switching algorithms, or mechanical switches.

In recent years, electric power utilities have shown interest in novel FCL concepts as a means to help mitigate increasing fault current levels in their power systems. Electric utilities and research teams have already identified several needs (both present and forthcoming) for FCLs in commercial power systems and have characterized the nature of an ideal FCL device. Based on their unique operating characteristics, SFCL technologies present an attractive option as they meet several of the desired criteria.

Utility Considerations for FCL Technologies

A survey was conducted by EPRI in 2004 that involved 28 U.S. utility companies in an effort to better understand the level of interest utilities have toward novel FCL devices, and if they would consider procurement of such equipment. The survey revealed a number of key points:

- Utilities are making a reassessment of fault current mitigation methods and taking a serious look at needs and technologies. Novel FCLs are considered a vital alternative, but a greater understanding of design perspectives and grid validation is needed.
- There may be a modest market for novel FCL solutions for circuit breaker replacement in the next decade (assuming that FCL technologies are equivalent to circuit breakers in terms of reliability, compatibility with protection, ease of installation, O&M, etc…).
- Half of the survey respondents indicated that they would strongly consider the purchase of an FCL whose cost was 1-5 times the cost of a circuit breaker, especially in cases where circuit breakers of the desired ratings are not available. Another possibility is applications where the fault current levels are excessive and require more capacity than a circuit breaker upgrade alone can handle.
- The use of HTS cables will increase the need for FCLs, particularly in transmission applications. Combined HTS cable-FCLs should be investigated more thoroughly since a majority of the respondents indicated they would consider such cables as an alternative to increase transmission capacity and mitigate transmission bottlenecks.
- Utility companies need technical evaluations of novel FCL technologies that focus on specific applications and the impact of the FCL on the grid. This would help to increase

acceptance of the new equipment and methods. It may be beneficial to initiate representative case studies for different types of FCL applications.

The survey respondents indicated that there may be a market for FCL technologies if costs, reliability, and performance meet acceptable levels. The survey also revealed that utilities expecting increased levels of circuit breaker replacement within the next ten years are more likely to consider the deployment of FCL devices. It is worth noting that the survey may have not adequately considered the impact of independent power producers or distributed generators on the grid. Through proper consideration of these two points, it is likely that this survey would have indicated an even greater interest for FCL devices.

Desirable Characteristics of FCLs

In addition to limiting fault current magnitudes to manageable levels for conventional protection equipment, FCL devices within the utility grid (whether superconducting or not) will need to achieve several performance and reliability criteria to increase their viability within commercial power systems. Specific examples of the desired criteria or characteristics are summarized in Table 2-1. While these characteristics in whole represent the ideal case and cannot be completely realized in application, FCL development teams will strive to achieve designs that approach the ideal case.

Table 2-1
Summary of Desired Characteristics for FCLs

Characteristic	Summary
Zero Line Impedance	• Introduces no series impedance on a network during nominal operating conditions.
Fast Reaction	• Limit the fault current to below desired thresholds in the first quarter cycle of a fault.
Discern between fault and temporary over-current	• Be able to discern between an actual fault and a temporary over-current scenario. • Temporary over-current may be due to overloading, a case where it is not desired for fault current limiting to occur.
Allowance of some follow current	• While limiting fault current to manageable levels, allow enough of the current through to engage protection scheme. • If the protection relays do not sense a fault because an FCL is limiting the current to below sensing thresholds, the FCL will be required to hold off the fault current for extended periods of time.

Table 2-1 (Continued)
Summary of Desired Characteristics for FCLs

Characteristic	Summary
Maintains voltage rise to within operating limits	• During a fault, the voltage on an FCL will increase as the resistance increases. • An FCL must be able to operate without the voltage increasing to levels greater than the ratings of the electrical insulation.
Immediate Recovery	• After the fault clears, the FCL is immediately able to return to operation when the system is restored.
Redundancy	• If primary limiting mechanism fails, an FCL can still provide some limiting capability through its back-up scheme. • If an FCL fails to limit, then breakers and other equipment can be damaged.

Additionally, there are some characteristics of interest when dealing with the realities of FCLs in terms of substation assets. These secondary characteristics include but are not limited to:

- Footprint within substation (low footprint desired)
- Maintenance issues (low maintenance is desired)
- Small number of ancillary devices
- High reliability

This secondary set of characteristics impacts the operation and maintenance (O&M) activities required to support the FCL. Although utilities will likely equip themselves with properly trained personnel to accommodate FCLs in their substations, the extent of this build-up is dependant on the reliability of the devices, modularity (ease of repair/maintenance), and number of devices deployed.

Consideration of Superconducting FCLs

While the perfect FCL design may not be possible to achieve in the ideal sense, SFCLs come close to achieving the ideal case for many of the characteristics outlined in Table 2-1. One of the most attractive attributes of SFCLs is that they exhibit virtually zero impedance on a power system when operating under nominal conditions (no fault current). Also, their passive nature and reliance on physical material properties rather than the electronic processing of control algorithms allow most SFCLs to respond more quickly to fault events than actively controlled devices. The operating premise of SFCLs (dynamic resistance) allows for relatively simple operation without the need for switches or mechanical parts that can potentially fail during a limiting operation. Environmental impacts are also beneficial as the liquid nitrogen (LN_2) required to cool the superconductor also serves as an environmentally benign dielectric fluid. Generally, all high voltage FCL designs will require a fluid dielectric of some sort whether it is oil, a synthetic, or LN_2.

Development teams continue work to achieve close conformity to the desirable characteristics. One area of research and development is in achieving faster recovery time. Because superconductors heat-up during quench, they must be re-cooled to their nominal operating temperature before performing additional limiting operations. For some SFCL designs, the relatively slow process of heat transfer from the superconductor to the cryogenic coolant (LN_2) means that recovery times are relatively slow when compared to some other FCL designs, both superconducting and non-superconducting. However, methods have been developed to speed up the recovery times of these slower designs and/or allow multiple current limiting operations in succession. SFCLs also operate within a fixed current window of operation that is determined by the critical current level of the superconducting component. This characteristic allows the overcurrent or through current levels to be set only in the design phase. FCL designs that depend on control algorithms may better accommodate these parameters if variability is required.

The ability of SFCLs to provide virtually zero grid impedance and rapid response make them feasible for grid deployment if cost and reliability meet adequate levels. At the present time the cost of superconducting materials is quite high, but is expected to fall as the market develops and as methods to fabricate them continue to improve. Reliability is still unproven in the field as an actual SFCL has not yet been deployed into the grid. However, efforts to develop and deploy SFCLs into the U.S. grid are underway as discussed in Chapter 3. There are also significant field demonstrations planned in other countries, which will be highlighted in future technical updates.

How do SFCLs Work?

In general, SFCLs take advantage of the highly non-linear resistance characteristic of superconductors to change resistive states quickly during a fault event. A superconductor remains superconducting only as long as the thresholds of three parameters are not exceeded: current, temperature, and magnetic field. Under nominal operating conditions, the superconductor provides almost zero resistance to the flow of current. However, once the current reaches a maximum current threshold (the critical current), the superconductor begins to transition to a highly resistive state through a process commonly referred to as a "quench" (shown in Figure 2-1). Upon quench, the superconductor achieves its highly resistive state at an exponential rate as the temperature is driven up by the impeding current. Current induced magnetic fields, if higher than the maximum field threshold, may also contribute to quench. Since the critical current threshold is directly proportional to temperature, the quench process can easily lead to a runaway situation if an alternative current path is not available. Once the superconducting material is re-cooled to its operating level, a state of "zero resistance" is returned.

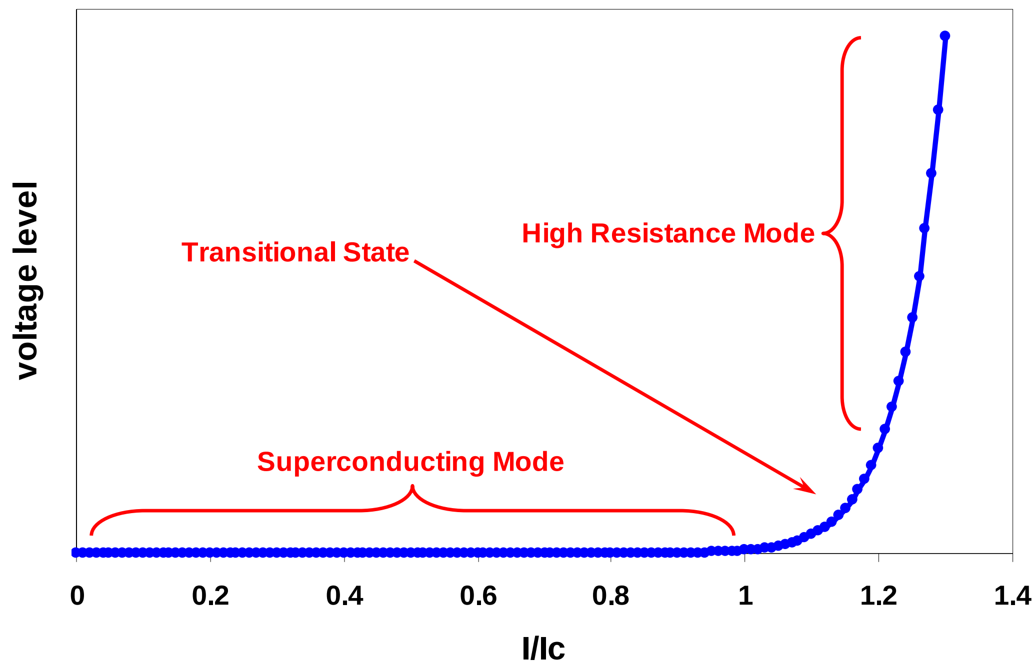

Figure 2-1
Conceptual Representation of a V-I Characteristic Curve for a Superconducting Material Showing the Transition to the High Resistance Mode

Most, but not all, SFCLs under development today are designed such that the superconductor is connected in series with the line current. Under nominal operating conditions, the line current flows through the device unimpeded until a fault occurs and the superconductor undergoes a quench. The high resistance path of the quenched superconductor then causes the fault current to take an alternate flow path through a shunt as shown in Figure 2-2.

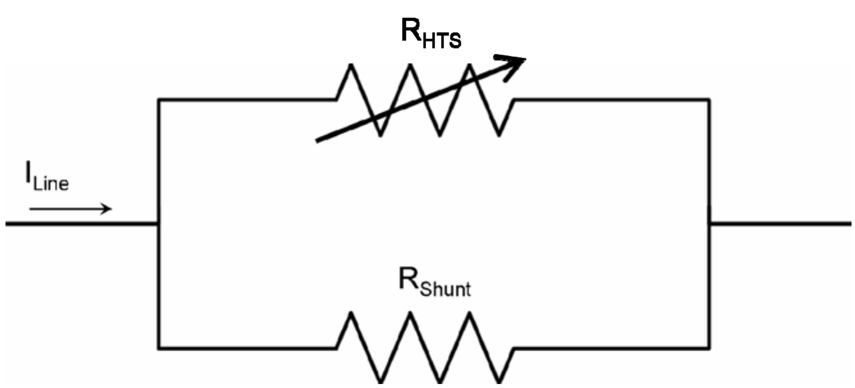

Figure 2-2
General Operating Premise of a Shunt Type SFCL

The shunt (which may be an inductive or resistive path) exhibits a relatively large impedance in a power system under nominal conditions, but is relatively low compared to the highly resistive state of the quenched superconductor. Therefore, the line current will flow through the superconducting path under nominal conditions and through the shunt during a fault event. This operation makes it possible for the superconducting path to remain undamaged by the post quench current.

Another SFCL design being developed operates on a different principle than that described above. In the so-called “saturable core reactor” a magnetizable iron core is saturated by applying a DC bias field originating from DC current flowing in a separate (superconducting) coil. Figure 2-3 shows an equivalent circuit of a generalized saturated iron core FCL. Due to the DC field, the respective AC coil (which is wound on the same core) exhibits low differential inductances for small AC current magnitudes (i.e. below the trigger threshold, typically a few times the rated current of the device). That is, the iron core is driven into saturation by the DC current, resulting in a very small inductance (essentially the coil inductance without the iron). Thus, the apparent SCFCL impedance is also low. For additional information, see the EPRI report referenced in Figure 2-3.

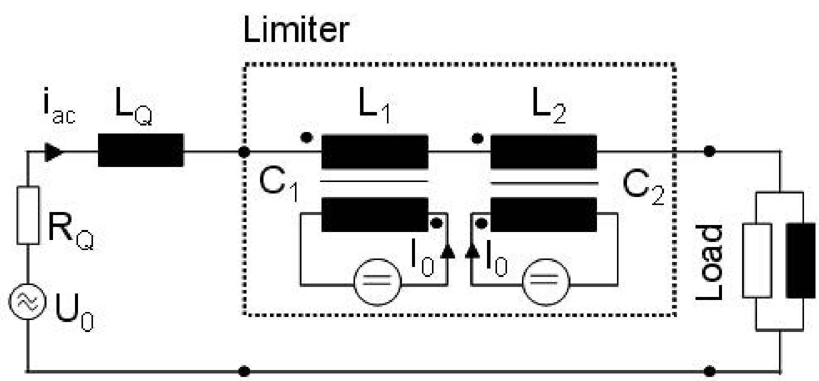

Figure 2-3
Equivalent Circuit of the Saturated Iron Core FCL

(Source: Survey of Fault Current Limiter (FCL) Technologies – Update. *EPRI, Palo Alto, CA: 2008. 1016389)*

3
DEMONSTRATION PROJECTS IN THE UNITED STATES

SFCL activities within the United States are moving in the direction of grid-deployed demonstration projects. Currently, there are four SFCL demonstration projects (Table 3-1) in progress that use various design schemes to achieve fault current limitation. The U.S. DOE (U.S. Department of Energy) is sponsoring three standalone SFCL projects via their Superconducting Power Equipment (SPE) Program, designed to provide financial support for the development and commercialization of superconducting devices for power grid use. The fourth project is an inherently fault current limiting HTS cable that is sponsored by the U.S. Department of Homeland Security (DHS).

Table 3-1
SFCL Projects Within the United States

Prime Contractor	Type	Conductor	Nominal Voltage	Comments
SuperPower	Resistive	YBCO	138 kV	• In-grid demonstration at an AEP substation in Ohio.
Zenergy	Saturable Core	BSCCO	26 kV	• Utilizes a DC biasing coil constructed from HTS material. • Project team has identified a host utility, but information is unavailable at this time.
Siemens/American Superconductor	Resistive	YBCO	115 kV	• In-grid demonstration near Riverside, CA. in a Southern California Edison substation.
American Superconductor	Resistive	YBCO	13.8 kV	• A 200-300 m long HTS cable with inherent FCL capability. • Project funded by the US Department of Homeland Security. • In-grid demonstration that will link two ConEd substations in Manhattan, NY.

Demonstration of Standalone SFCLs

Standalone SFCLs are self-contained devices that have the sole purpose of limiting fault currents. The distinction is made because of recent activities to develop superconducting power cable systems that posses inherent fault current limiting capability. Unlike these HTS cable systems that serve the dual purpose of high capacity power transport and fault current limiter, standalone systems function only as fault current limiters in a power grid application.

Standalone SFCL systems within the U.S. are each being developed by project development teams that will realize the application from design, fabrication, eventual deployment, and finally operation. Funding for these projects is provided in large part by DOE, with additional funds provided by project team members, host utilities, and other local/federal government entities.

SuperPower Demonstration at American Electric Power

A project team managed by SuperPower is developing a transmission class (138 kV) Matrix SFCL for deployment into an AEP substation. The SuperPower SFCL project has the distinction of being the first HTS transmission-level power device to be proposed among the current crop of HTS devices being developed[1]. The design of the SuperPower SFCL prototype will limit fault currents up to 13.8 kA_{rms} (37 kA peak). The project team includes, but is not limited to, the participants described in Table 3-2. EPRI was the first institutional funder for this project and has remained a key project participant by providing both funding and technical expertise.

Figure 3-1 illustrates the SuperPower design concept. A prototype device was previously tested at 13 kV[2]. The prototype device has undergone significant design changes since 2004, including transition to YBCO superconductors. Scale-up of the design to 138 kV and qualification tests of the new superconductor have recently been accomplished. The SuperPower prototype will be installed into AEP's TIDD substation. It is expected that a single-phase "alpha" unit will be produced and tested by the end of 2009 with deployment at AEP occurring in 2010 or 2011.

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[1] A 138 kV HTS cable system was later proposed and deployed on Long Island.

[2] *High Temperature Superconducting Matrix Fault Current Limier: Proof-of-Concept Test Results.* EPRI, Palo Alto, CA, SuperPower, Inc., Schenectady, NY, and Nexans SuperConductors, Hürth, Germany: 2004. 1008697.

Table 3-2
SuperPower SFCL Project Team Summary

Participant	Project Role
SuperPower	• Project manager • Systems integration • SFCL matrix design and development • HTS conductor and matrix supplier • Prototype design, fabrication, & testing
AEP	• Host Utility • Site selection & specifications • Operational support: installation, commissioning, & monitoring
SEL **(Sumitomo Electric Industries)**	• Bushings & cryostat supplier
EPRI	• Initial funding • Technical Review
ORNL **(Oak Ridge National Laboratory)**	• High voltage dielectric development • Cryogenic consultation
LANL **(Los Alamos National Laboratory)**	• Conductor improvement • Support for matrix testing and design

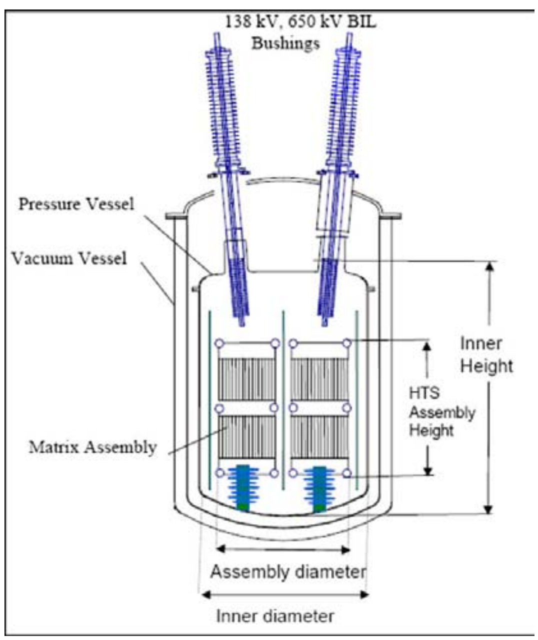

Figure 3-1
SuperPower Matrix SFCL Design

(Source: Transmission Level HTS Fault Current Limiter, 2008 DOE Peer Review, Washington, D.C.)

Zenergy Project

A manufacturer and developer of HTS commercial applications, Zenergy Power plc is in the process of developing a saturable-core FCL that utilizes a DC superconducting coil to saturate a specially designed high permeability core. Table 3-3 provides a summary of project team participants and roles.

The Zenergy limiter is basically a saturable-core reactor and that utilizes a specially designed high permeability core to exhibit a high inductive reactance on the AC line during fault events. HTS conductors are utilized for the DC coil to increase efficiency and to achieve high magnetic fields with small cross-section. Refer to Figure 3-2 and Figure 3-3 for simplified visuals of the operating concept. The 3-phase device utilizes 6 individual AC coils, two per phase mounted on their respective iron cores, and connected electrically such that their fluxes cancel out in the center. The cores are arranged in a star-like configuration with their magnetic return paths in the center of the arrangement. Under balanced 3-phase operation the AC current flowing through all three coil pairs results in zero flux in the cores at all times. Therefore, only one superconducting coil is required to bias all 6 cores in the required direction with respect to their AC coils. This unique arrangement significantly reduces the superconducting material required for this design.

The Zenergy SFCL is currently in the fabrication phase with an acknowledgment from the project team that a prospective demonstration host utility has been identified. As more information becomes available as to the deployment schedule and status of the saturable-core prototype, it will be included in future technical updates.

Table 3-3
Zenergy SFCL Project Team Summary

Participant	Project Role
Zenergy Power	• Project manager • Systems integration • SFCL matrix design and development • HTS conductor and matrix supplier • Prototype design, fabrication, & testing
LANL **(Los Alamos National Laboratory)**	• Host Utility • Site selection & specifications • Operational support: installation, commissioning, & monitoring

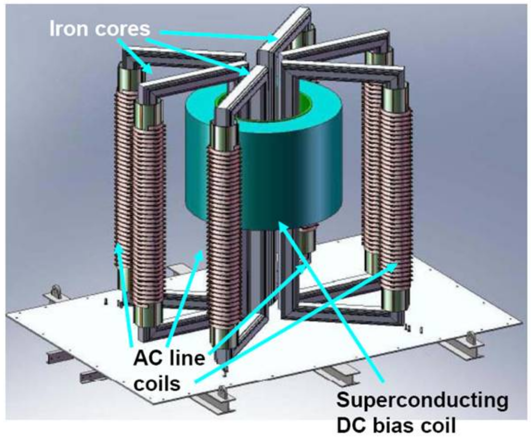

Figure 3-2
Zenergy Saturable Core FCL with HTS DC Saturating Coil

(Source: Survey of Fault Current Limiter (FCL) Technologies – Update*. EPRI, Palo Alto, CA: 2008. 1016389)*

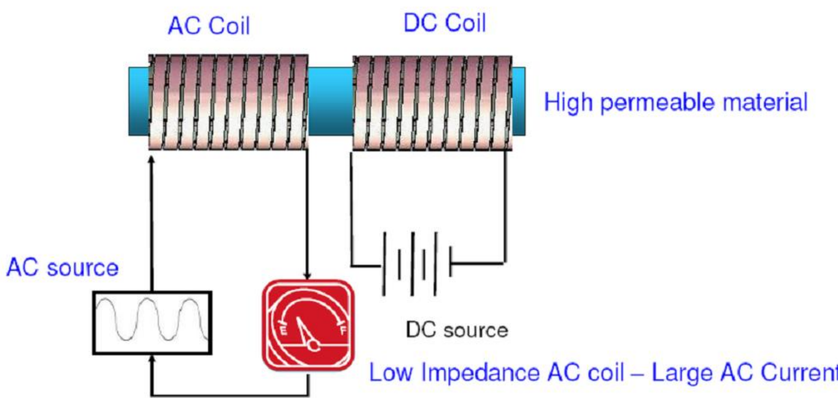

Figure 3-3
Zenergy Saturable Core FCL with HTS DC Saturating Coil

(Source: Design, Test and Demonstration of Saturable-Core Reactor HTS Fault Current Limiter, 2008 DOE Peer Review, Washington, D.C.)

SuperLimiter™ Demonstration at Southern California Edison

Siemens and AMSC are heading an effort to develop and deploy a 138 kV class SFCL termed "SuperLimiter™" for use in the Southern California Edison power network. The project is to develop a prototype that will limit up to 63 kA_{rms} for the demonstration and then further improve the design for commercial deployment that can limit fault currents greater than 80 kA_{rms}. The project team is outlined in Table 3-4 and a conceptual design diagram is presented in Figure 3-4.

Table 3-4
SuperLimiter™ SFCL Project Team Summary

Participant	Project Role
AMSC (American Superconductor Corporation)	• System engineering • HTS wire supplier
Siemens	• FCL module design & fabrication • System modeling
SCE (Southern California Edision)	• Host utility • System integration • Requirements/Specifications
Nexans	• Termination design/supplier • High voltage design
LANL (Los Alamos National Laboratory)	• AC loss measurements
TCSUH (Texas Center for Superconductivity at the University of Houston)	• Wire characterization

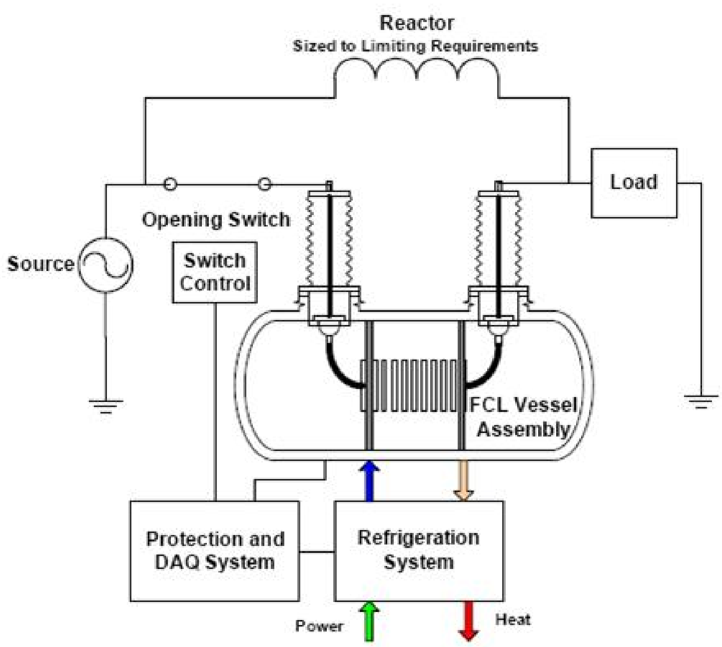

Figure 3-4
SuperLimiter™ System Design

(Source: Development and In-Grid Demonstration of a Transmission Voltage SuperLimiter™ Fault Current Limiter, 2008 DOE Peer Review, Washington, D.C.)

The operating concept of the SuperLimiter™ uses three stages to limit an incipient fault as explained below and shown in Figure 3-5.

1) Under nominal conditions, the superconductor conducts current with virtually zero impedance (green/grey colored arrows).

2) When a fault occurs, the superconductor becomes highly resistive to the current, as indicated in Figure 3-5 by the "normal state resistance." As well, a parallel reactor begins to pass current. These actions (red/dark colored arrows) decrease the fault current level by providing increased impedance to the power network.

3) Once the fault is limited, the superconducting and normal resistance branches are removed from the network by the physical switch to allow them to cool. The line reactor then dampens the residual fault current and allows time for protection relays to take action to clear the fault.

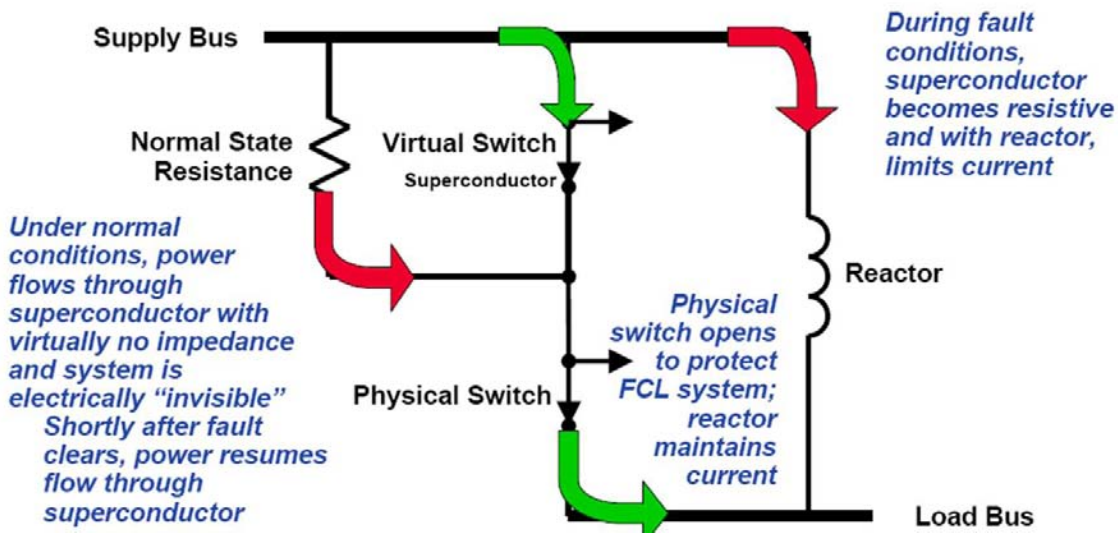

Figure 3-5
Operating Concept of the SuperLimiter™

(Source: Development and In-Grid Demonstration of a Transmission Voltage SuperLimiter™ Fault Current Limiter, 2008 DOE Peer Review, Washington, D.C.)

The SuperLimiter™ prototype will be installed into the SCE Valley substation near Riverside, California where it will service a bus tie. While information about the project schedule was not available during the compilation of this report, critical milestones and dates will be made available in future technical updates.

Demonstration of HTS Cable with Inherent FCL

The U.S. Department of Homeland Security and AMSC have championed a novel concept that integrates the limiting characteristics of standalone FCL systems into high capacity HTS cables. The concept will be tested in a demonstration project hosted by Consolidated Edison Company, named "Project HYDRA." The project team is identified in Table 3-5.

Table 3-5
Project HYDRA Team Summary

Participant	Project Role
AMSC **(American Superconductor Corporation)**	• System engineering • HTS wire supplier
Ultera	• FCL module design & fabrication • System modeling
Air Liquide	• Cryogenic Refrigeration System • Cryogenic System Monitoring
Consolidated Edison	• Host Utility • System planning and operation
ORNL **(Oak Ridge National Laboratory)**	• Engineering support • Prototype testing
DHS **(U.S. Department of Homeland Security)**	• Primary funder

Project HYDRA will demonstrate a high capacity substation intertie by linking an already operating 138/13.8 kV substation to a newly built substation of the same rating that will be located nearby. The two substations will be tied at their secondary (13 kV) voltage buses, thus eliminating the need for two additional transformers at the new substation that would normally be installed under Con Edison's N-2 contingency planning scenario. Because of the interconnection at each substation secondary, fault currents can be extremely high.

The 200-300 meter long "fault current limiting" HTS cable will be routed from the existing substation underneath a street and terminated at the new substation located approximately 450 ft away. The cable will be of the tri-axial configuration (three concentric electrical phases) and operate at 13.8 kV, 4 kA_{rms} (96 MVA) nominally – see Figure 3-6. The project is currently in the development, fabrication, and testing stage with installation slated for sometime in 2010.

The project team is developing an HTS cable that utilizes newly developed second generation superconducting tape that can achieve a resistive state under over current conditions very quickly. This is achieved by a special, high resistance stainless steel cladding over the superconducting wire that is used to wind the cable. Upon an incipient fault, the superconductor transitions to the resistive state so that the cladding begins to conduct the current, effectively acting as a shunt (see Figure 2-2). The shunt branch, composed of the stabilizing materials in the HTS tape, inserts more impedance to the network causing the fault level to decrease. (In Project HYDRA there will be a large parallel copper bus to interconnect the substations, which will also introduce an impedance to the fault current.)

Figure 3-6
Tri-axial HTS Cable Arrangement to be Used for Project HYDRA

(Source: High Temperature Superconducting Cable, 2008 DOE Peer Review, Washington, D.C.)

4
PROGRAM TO MONITOR DEMONSTRATION PROJECTS

Information regarding the technical concepts of SFCLs and the status of various SFCL-related projects can be difficult to maintain and understand given that it comes from multiple sources and in many cases from a scientific perspective rather than one of engineering/power systems. In order to provide utility personnel, managers, and supervisors with relevant and up-to-date information on the status of the technology, EPRI intends to produce a series of technical updates on SFCL systems.

Information to be Included

Each annual edition of the Technology Watch will cover SFCL technologies and projects from a power engineering and asset management standpoint. Results and status updates of in-grid demonstration projects will provide some indication as to the effects of SFCLs on a power network and provide a "lessons learned" approach with regards to maintaining the equipment and improving reliability for commercial use. The reports will also cover important planning and testing issues including but not limited to fabrication, installation, commissioning, and O&M.

SFCL projects worldwide will be covered in this program. Detailed summaries of each major project will be covered and then followed by annual updates as to their status. When available, relevant operating data and unusual occurrences will be reported as well as solutions to issues encountered during field trials and/or grid demonstrations.

Methodology

The information for these technical updates will assimilated from several sources including but not limited to the following:

- Literature search
- Direct interaction with project teams
- Discussions with utility personnel

A literature search will conducted to get the most relevant information regarding the basic design and compilation of superconducting FCL systems. Developers of the technology, which include physicists, engineers, and project managers, will be contacted to discuss possible issues with various FCL components and designs. These developers will also be contacted in order to request updates on the status of their respective projects. Electric utility personnel will also be contacted to acquire information regarding O&M issues and performance of the demonstration device(s) within their respective power systems.

5
ANNOTATED BIBLIOGRAPHY

The following references provide information pertaining to FCLs both superconducting and non-superconducting. Also provided are references to additional superconducting power equipment and ancillary systems.

(1) *Survey of Fault Current Limiter (FCL) Technologies*. EPRI, Palo Alto, CA: 2005. 1010760

Compiles a comprehensive collection of currently pursued FCL technologies and compares then against each other to the best extent possible with data available through open literature.

(2) *Fault Current Limiters – Utility Needs and Perspectives*. EPRI, Palo Alto, CA: 2004. 1008696

Presents a the formulation and results of a utility survey used to obtain an understanding of utility needs, perspectives, and perceptions with regard to novel FCL methods for both distributions and transmission systems.

(3) *Survey of Fault Current Limiter (FCL) Technologies – Update*. EPRI, Palo Alto, CA: 2008. 1016389

An update to document 1010760. Compiles a comprehensive collection of currently pursued FCL technologies – including resistive type superconducting, solid-state type, and hybrid type FCL projects – and compares then against each other to the best extent possible with data available through open literature and individual developers.

(4) *Cryogenics: A Utility Primer*, EPRI, Palo Alto, CA: 2006. 1010897

A Primer on Cryogenics intended to provide a sense of cryogenic technology, why it is needed, how it works, and a feeling of what it can and, to some extent, what it cannot accomplish. The intention is to present useful information to a diverse audience ranging from non-technical utility personnel to engineers trained in other technical areas.

(5) *Superconducting Power Cables: Technology Watch 2008.* EPRI, Palo Alto, CA: 2008. 1015988

Summarizes full-scale superconducting cable projects throughout the world ranging from full-scale test installations to utility demonstration projects. The report covers various aspects of each project from design to implementation; and to the extent that it is available, updated status regarding O&M is also presented.

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