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Survey of Fault Current Limiter (FCL) Technologies – Update

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Technical Update, August 2008

EPRI Project Manager

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PRODUCT DESCRIPTION

As power systems grow and become more interconnected, fault current levels can increase beyond the capabilities of the existing equipment. Currently available solutions are very expensive and often come with significant operational disadvantages, such as increased impedance or outage time for fuse replacements. Power system operators have long needed a means of reducing fault current levels while retaining system stiffness and continuous operability. For many decades, EPRI R&D projects have tried to develop technically feasible and economically viable new technologies to build fault current limiters (FCLs). This technical update compiles a comprehensive collection of currently pursued FCL technologies—including resistive type superconducting, solid-state type, and hybrid type FCL projects—and compares them against each other to the best extent possible with data available through open literature and from individual developers.

Results and Findings

This update of the previous FCL technology survey, EPRI report 1010760, clearly indicates significant advances in conditional-impedance-increase type FCLs, which is reflected in greater interest in these devices in the utility realm. Significant progress in technology development resulted in the first commercially available high-temperature superconductor-based resistive FCL for medium voltage levels. Such developments may indicate a paradigm shift in the utility industry. Limitation of fault currents through condition-based impedance increase of inherently resettable devices—a common practice in low-voltage systems—may become the state of the art in medium- and high-voltage systems within a decade or so. This development may be as important for fault current management as the introduction of overvoltage protection through metal oxide varistor (MOV) surge arrestors was for insulation coordination. Successful demonstration projects have proven the technical feasibility of FCL devices into the 15-kV voltage class with three-phase power ratings up to 12 MVA.

Challenges and Objectives

For utility personnel tasked with the long-term planning of future infrastructure improvements in order to cope with increasingly higher fault currents, one major challenge is to follow and compare the various ongoing FCL technology R&D efforts. The objective of this report is to provide an overview of existing FCL technologies, with a focus on novel devices based on superconducting fault current limiters (SCFCLs).

Applications, Values, and Use

Significant research is needed into not only into how to build novel FCL devices, but also into how they operate in the system under various conditions. Particular emphasis should be given in proper modeling for simulating the inherent transients associated with faults limited by these novel technologies. Effects of large penetration of FCLs in transmission and distribution (T&D) networks should also be studied.

The lack of standard testing procedures for FCLs is reflected in the lack of standard specifications. FCLs can cover a wide range of response characteristics that are currently very difficult to specify by the utility end user. In order for utilities to feel more comfortable in applying novel FCL devices in the future, it will be important to establish working groups for developing FCL specification guidelines. Finally, it is important to monitor future developments of the various FCL technologies and compare their performance. At the publication of this report, none of the technologies investigated herein appear to take a clear lead over others.

EPRI Perspective

In June 2007, the U.S. Department of Energy announced a total funding of US$19.5 million for three projects in pursuit of developing SCFCLs for high-voltage applications. This follows the recent increase in demand by utilities for better means to cope with increasing fault current levels in distribution and subtransmission systems as a result of system upgrades and interconnection requirements for distributed generation. From a technical point of view, the major next step for SCFCL development is to extend the voltage range into the 110-kV class (and above) in order to be applicable for utilities to solve fault current problems. Most attractive for utilities are applications where either no adequate solution is available (for example, no breaker of required rating exists) or where FCLs can substantially enhance system operation due to the near-zero normal impedance. This technical update documents developments that offer a good chance of yielding economically viable FCL devices needed to satisfy the ever-growing demand for transmission-voltage-level applications.

Approach

Generic information about the existence of a new FCL project is relatively easy to access through press releases, publications and presentations, and expert knowledge by the authors. However, obtaining more specific technical information on FCL technology development projects in order to compare them in a meaningful way is not trivial, since much of this information is deemed proprietary and only little to nothing is publicly available through literature. Therefore, the approach adopted in producing this report was to contact the various project managers directly and ask for specific information. As an incentive for the potential participants of this survey to provide significant information, not necessarily to be found elsewhere, a copy of this report was offered in return. Participants were given the opportunity to comment on the specific content regarding their FCL technology before publication of this report to ensure that mistakes in describing these technologies, or misinterpretation of data provided, could be avoided.

Keywords

Fault Current Limiter (FCL)
Electrical Fault Currents
Circuit Breakers
Superconductors
Substations

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Furthermore, we want to thank all the contributors listed in Table 2 1 - Table 2 3 for their support by providing the data given in the comparison tables in Section 4.

CONTENTS

1 INTRODUCTION

In June 2007 the US Department of Energy (DOE) announced a total funding of US$19.5 million for three projects in pursuit of developing a superconducting Fault Current Limiter (FCLs) for high voltage applications [1]. This follows the recent increase in demand by utilities for better means to cope with increasing fault current levels in distribution and sub-transmission systems as a result of system upgrades and interconnection requirements for distributed generation (DG). In addition, three major technology developments fostered the increase in FCL activities:

- Refinement of production process of YBCO based superconductors for coated conductors (2G wire) with sufficient yield at acceptable cost (or at least cost projections)
- Progress in development of Magnesium Diboride (MgB_2) superconductors wire designed specifically with FCL properties
- Progress in development of Silicon Carbide (SiC) power electronic devices

The development of novel FCL devices has made significant progress since the publication of the previous report on this subject by EPRI [2] in 2005. Therefore, this report provides an update on the previous study, revising data about projects reported therein, as well as incorporating data about newly emerging projects.

2
METHODOLOGY

Generic information about the existence of a new FCL project is relatively easy to access through press releases, publications and presentations, and expert knowledge by the authors. However, obtaining more specific technical information on FCL technology development projects in order to compare them in a meaningful way is not trivial since much of this information is deemed proprietary and only little to nothing is publicly available through literature. Therefore, the approach adopted to produce this report was to contact the various projects directly and ask for specific information. As an incentive for the potential participants of this survey to provide significant information, not necessarily to be found elsewhere, a copy of this report was offered in return. Each participant was given the opportunity to comment on the specific content regarding their FCL technology before publication of this report to ensure that mistakes in describing these technologies, or misinterpretation of data provided, could be avoided.

Tables 2-1 through Table 2-3 list all the FCL projects from which contributions to the technology comparison presented in Section 4 have been received. The tables provide contact information for each project and reflect the three major categories of FCL devices currently pursued by R&D activities worldwide:

- Superconducting FCLs (SCFCLs),
- Solid-state FCLs (SSFCLs), and
- Hybrid arrangements which employ more than one key technology to achieve FCL functionality.

Table 2-4 lists additional FCL projects which could not be contacted, did not respond to inquiries, or specifically declined contribution of data for this report.

In the previous report [2] the following projects have been identified as requiring closer investigations in the future.

1. “Smart wires” by Georgia Tech – NEETRAC [3]
2. “Liquid metal FCL” by ABB Switzerland [4]
3. “Multi-Mode Static Series Compensator” by Mitsubishi Electric
4. “Saturated core type SCFCL” by SC Power Systems [5], [6]
5. “SCCL – a new FACTS-based fault current limiter” by SIEMENS [7]

While serious attempts were made to obtain this additional information we received data for the comparison matrix only on the “Liquid metal FCL”. In addition we clarified through personal communication with Prof. Deepak Divan from Georgia Tech that the “Smart wires” technology is not intended to function as a fault current limiter.

Finally, the project named "Inherently fault current limiting cable" has been started only very recently by American Superconductor (AMSC) and ConEd (New York) [8]. No information on this project could be gathered and incorporated before finalizing this report

Table 2-1
Resistive type Superconducting FCL projects contacted for detailed technical input to this report

Project leader	Country	Technology	Contact information
NEXANS	Germany	BSCCO-2212 bulk	Florian Steinmeyer Florian.Steinmeyer@nexans.com
CESI-RICERCA	Italy	MgB2 tape and BSCCO-2223 tape	Luciano Martini luciano.martini@cesiricerca.it
Siemens & AMSC[1]	Germany/USA	YBCO, tape	Hans-Peter Kraemer Hans-peter.kraemer@siemens.com
KEPRI	South Korea	Combination of fast mechanical switch and superconductor	Ok-Bae Hyun hyun@kepri.re.kr
SuperPower	USA	YBCO, tape	Chuck Weber cweber@superpower-inc.com

Table 2-2
Solid-State type FCL projects contacted for detailed technical input to this report

Project leader	Country	Technology	Contact information
Powell	USA	Silicon thyristor controlled breaker type	Jim Thomas Jim.Thomas@powellind.com
SPCO	USA	Silicon SuperGTO controlled switched reactor type	Mahesh Gandhi Mahesh_Gandhi@siliconpower.com
APEI Inc., University of Arkansas	USA	Silicon Carbide thyristor controlled breaker type	Alan Mantooth mantooth@uark.edu

Table 2-3
Hybrid type FCL projects considered contacted for detailed technical input to this report

Project leader	Country	Technology	Contact information
ABB	Switzerland	Liquid metal	Stephan Schoft stephan.schoft@ch.abb.com
AREVA	France	Combination of solid-state witch and fast mechanical switch	Georges Montillet georges.montillet@areva-td.com

[1] Siemens, Germany, is in a strategic alliance with American Superconductor (AMSC), USA.

Table 2-4
Additional FCL projects not contacted or not responding to inquiries

Project leader	Country	Technology	Comment
Hyundai Heavy Industries	South Korea	Superconducting, resistive, YBCO, tape	Design similar to Siemens/AMSC device using the same AMSC 344S conductor
Zhejiang University & Zhejiang Sanbian Sci-Tech Corporation	China	Silicon thyristor controlled inductor type, transformer coupled	
CAS	China	Silicon diode bridge with BSCCO-2223 tape superconducting inductor	
Nagoya University	Japan	FCL transformer, YBCO, tape	
AREVA	France	FCL transformer, YBCO or BSCCO-2223, tape	
AMSC & Southwirec	USA	Inherently fault current limiting cable	Project initiated spring 2007 funded by the US Department of Homeland Security (DHS)
Mitsubishi	Japan	Silicon IGBT controlled series compensator	
SC Power Systems (ZENERGY)	USA	Saturated iron core reactor with superconducting bias coil	Declined contribution of specific data requested
Ricor	Israel	Saturated iron core reactor with superconducting bias coil	No response to inquiries per email
Rolls-Royce	UK	Superconducting, resistive type, MgB2 tape	Declined contribution of specific data requested
Siemens	Germany	Silicon thyristor controlled series compensator (TCSC)	FCL functionality is a by-product of TCSC

3
UPDATE TO FAULT CURRENT LIMITING TECHNOLOGIES

This report is an update to the previous report on this subject matter published by EPRI in 2005 [2]. This chapter only provides updates to material presented in the previous report augmented with new material provided through contributors who submitted input to the comparison tables in chapter 4. Therefore, the sections on various FCL technologies are rather brief in some cases. Finally, this report only investigates new developments regarding "novel" FCL concepts as defined in Figure 3-1 (adopted from [2]). No major developments can be reported on any of the conventional (i.e. non-novel) methods listed in Figure 3-1.

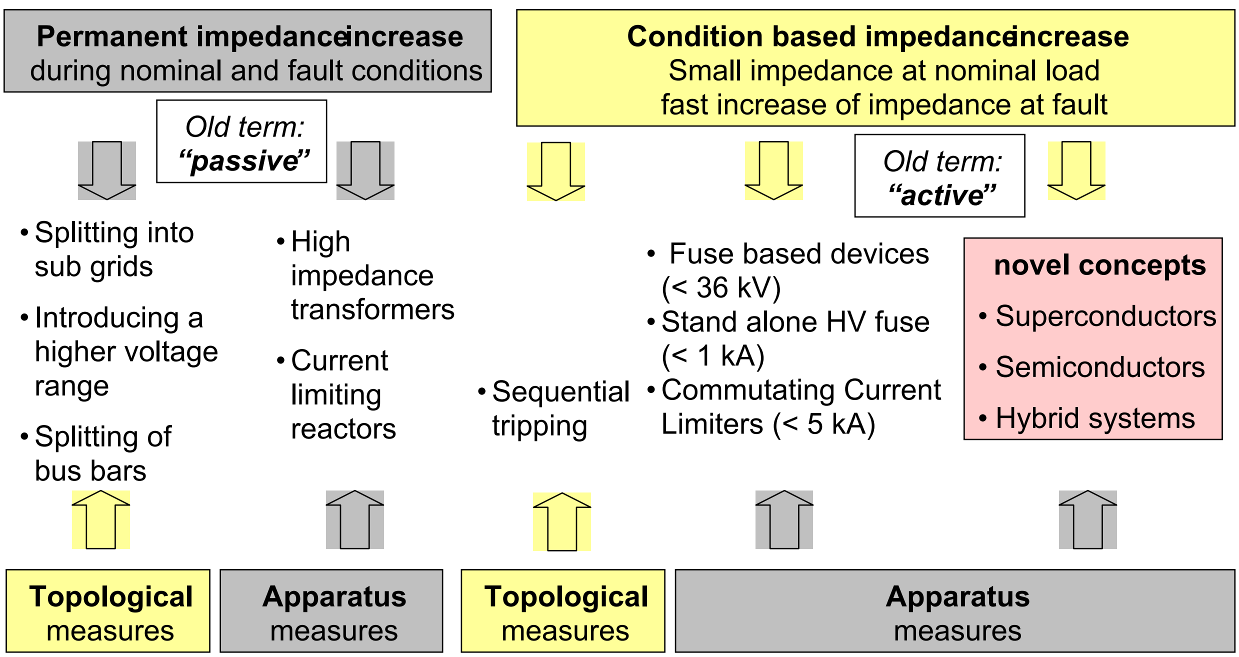


Figure 3-1
FCL systematic (adopted from [2])

Novel concepts based on superconductors (SCFCLs)

We take the opportunity to clarify a statement we made in [2] on page 4-5 regarding the utilization of superconductors in some SCFCL devices "as conductor of a DC magnet system". This statement included the usage of superconductors to wind a coil serving as the

- inductor in a diode-bridge type SCFCL [9]-[11]
- DC magnet to bias the iron in a "saturated iron core" type SCFCL [5].

In both cases, the key is that the superconductor will only be subjected to DC current during normal operation and will not quench during the fault current limiting event. This significantly reduces the losses in the superconductor and the corresponding cryogenic system.

It shall be noted that while YBCO coated conductors have become significantly important for novel SCFCL designs, the YBCO thin film technology, expected to become key for compact SCFCLs a few years back, has been completely abandoned by all major SCFCL projects (there were three projects reported with YBCO thin films in [2]). The reason is that while the switching performance of YBCO thin film is excellent, the manufacturing process is prohibitively expensive [12].

The following sections provide updates on the SCFCL technologies in the same order as they have been discussed in [2].

Shielded core type

As stated in [2], there are still a few small, mostly university based academic projects active that utilize the "shielded core" type. However, the prospect of this type of SC limiter to be economically competitive is very low. Therefore, this type will not be discussed further in this report.

Resistive type

With the introduction of YBCO as the second generation of High-Tc superconductors and the development of YBCO elements and tapes suitable for FCL devices several projects have now adopted YBCO for their SCFCL projects. Compared with BSCCO (both bulk and tape) YBCO has fundamentally different quench properties, primarily due to the critical current density and the higher n-value. This property results in a much steeper increase in electric field with current which in return causes less sensitivity of the quench time with the rate of rise of the current during a fault. Therefore, YBCO based resistive type SCFCLs quench typically around three to four times the rated current, very much independent of the initial rate-of-rise (di/dt) of the fault current.

Nevertheless, the first two major SCFCL project discussed below continue to use BSCCO 2212 bulk material, primarily because of advances in manufacturing the necessary BSCCO elements and experiences gained through filed tests with the CURL10 device.

Finally, Magnesium Diboride (MgB_2) has emerged as a suitable candidate material for FCL devices. The major advantages of this material is its inexpensiveness, hence utilizing MgB_2 is expected to reduce the cost for superconducting material used in the SCFCL. However, the disadvantage of MgB_2 is the need to operate it at temperatures below its critical temperature of 39 K. This increases the effort to cool the superconductor and hence potentially increases the cost for the cryogenic system. If liquid cryogens are adopted for rapid re-cooling of a quenched SCFCL liquid nitrogen (LN_2) cannot be used in MgB_2–based SCFCLs. In such cases they require liquid Neon LNe_2 which has a liquefaction temperature of around 28 K.

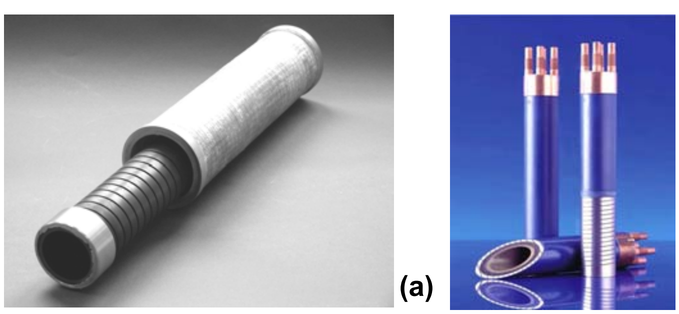
The following sections present updates and new projects listed by the names of the respective project leads.

Nexans SuperConductors

A decade after the first field test of a SCFCL by ABB [13], which was of the shielded core type, the CURL10 device was the first 3-phase High-Tc resistive SCFCL tested in the field in a real utility application [14] between 2004 and 2005. This device was a very successful demonstration of this technology at the distribution level voltage level (15 kV class). After the field test, the CURL10 device was transferred to the Karlsruhe Research Center (FZK) in Karlsruhe, Germany, for additional long term tests which were completed in mid 2007.

A single phase unit of an update to the original CURL10 design, which uses monofilar BSCCO 2212 bulk material coils for the HTS elements, as opposed to the bifilar coils previously used in the original device, has been tested successfully at 14.4 kV in Korea in 2007. This improvement is the basis for the first 15 kV class SCFCL devices now commercially available from Nexans SuperConductors (Nexans SC) in Germany [15].

A new R&D project, led by Nexans SC, and aimed to develop a 110 kV SCFCL has started 2005 in Germany [16]. The partners in this project are Nexans SC, Karlsruhe Research Center (FZK), Nexans NDI, Rheinisch Westfälische Energiewerke (RWE), and the University of Hannover. Like the predecessor device, the CURL 10, the CULT 110 adopts BSCCO 2212 bulk material for the HTS elements. Similarly, the CULT 110 elements are tubes which are machined into coils. For quench assistance a normal conducting metal coil is positioned coaxially around the tubes and connected electrically in parallel to them. The parallel coil also serves as electrical shunt to protect the HTS elements. The shunt coil carries the major portion of the current during the fault limiting phase when the SCFCL is activated and the HTS elements are quenched. The limiting performance of such components is excellent [17] but up to now the reproducibility of the manufacturing process is still insufficient [15], [17]. Figure 3-2 shows one of the fault current limiting elements designed for the CULT110 device. This coil-in-coil component features an inner superconducting coil and an outer normal conducting trigger coil. Both are electrically connected in parallel, with only a weak thermal coupling through the electrical connection [17]. For comparison, Figure 3-2 also shows the element used in the CURL10 device [2]. As opposed to the CULT110 element a metallic shunt is applied along the length of the superconductor in thermal contact with it.



(a) (b)

Figure 3-2
CULT110 elements (a) (from [17]), versus CURL10 HTS elements (b) (from [2])

A major challenge in this project is the design of the dielectric insulation system to withstand the high voltage stress in the cryogenic environment. Especially during quenching gaseous N_2 from the LN_2 boil off is expected to reduce the dielectric strength of the LN_2 insulation. Therefore, the cryostat for the CULT 110 prototype has been designed solely based on the dielectric properties of gaseous N_2, not taking advantage of the better insulation properties of LN_2 at all. First full scale testing of the CULT 110 is expected in 2010.

ABB

As stated in [2], no major developments on SCFCLs have been reported by ABB since 2001.

American Superconductor and SIEMENS

Siemens has previously pursued an SCFCL design based on YBCO thin film HTS elements. However, the high costs for these elements make this technology economically unattractive [12]. Therefore, Siemens has recently entered a strategic alliance with American Superconductor (AMSC) to co-develop a resistive type SCFCL based on the new AMSC stainless steel coated conductor technology (344S Superconductor) [18]. The partners in this project are AMSC, Siemens, Nexans, University of Houston, Southern California Edison, and the Los Alamos National Laboratory (LANL). The 5-year project aims to develop and test a 115 kV, 1200 A rated SCFCL which shall reduce the fault current in a given location from 80 kA to 55 kA [19].

The concept features a parallel arrangement of the superconducting FCL and a normal conducting current limiting reactor outside the cryogenic environment as illustrated in Figure 3-3. During normal operation, the fast (mechanical) switch is closed and the HTS switching module carries the load current, thereby bypassing the parallel shunt reactor. In case of a short circuit in the power system, the HTS element quench due to the increased current, consequently transferring the major portion of the fault current into the bypass reactor. The fast switch opens with minimum delay (currently, the SCFCL design requires a 3-cycle response of the switch) and disconnects the HTS module from the system, thereby allowing it to start the recovery process for re-closing. From tests conducted by SIEMENS and presented in [19] it appears that recovery of the HTS elements may be possible within a 2.5 s time window. Additional information about the tests can be found in [20].

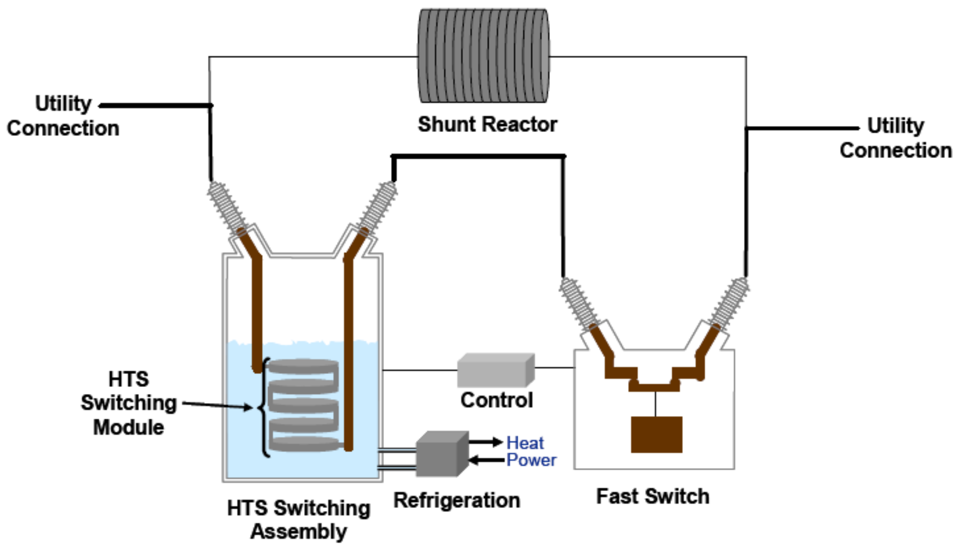


Figure 3-3
Siemens/AMSC SCFCL concept for high voltage applications (from [19])

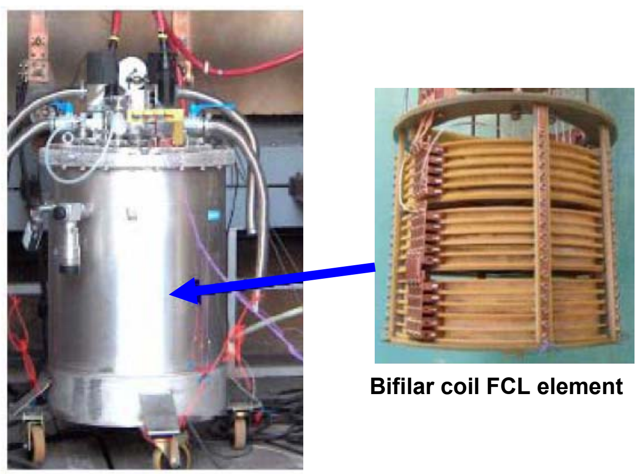


Figure 3-4
Siemens/AMSC 2.25 MVA/1-phase resistive SCFCL testing unit (from [19])

SuperPower

In 2006, the original project labeled Matrix Fault Current Limiter (MFCL) was held for approximately one year and resumed in 2007 with a somewhat modified HTS element design. It now specifically utilizes SuperPower's 2G wire for the HTS elements, whereas the previous design was based on BSCCO 2212 bulk material from Nexans SC [21]. The goal of the project remained: to develop a 138 kV class SCFCL that allows to avoid expensive upgrades of circuit breakers to 80 kA interrupting capability at locations where utilities face the challenge of fault current levels increasing beyond the current 40 kA or 63 kA ratings. The first target for field testing has been identified as a dedicated substation within the American Electric Power (AEP) grid. The target ratings are 138 kV, 1200 A continuous current, and 26 kA_{RMS} fault current. A major challenge this project tries to overcome is the requirement by many utilities that the FCL shall be able to recover under load. For SCFCLs this means that the heat generated in the device within the current limiting phase during and after the quench as to be extracted out of the cryogenic environment quickly to allow a rapid re-cooling of the HTS elements while the nominal load current continues to flow through the device. SuperPower reported recovery under load within time scales of approximately 12 s from experiments with relatively short HTS elements in parallel to their respective shunt elements (peak voltage around 1 V with currents around 60 A).

Hyundai Heavy Industries

Hyundai Heavy Industries Co., Ltd. (HHI) since 2004, in partnership with Yonsei University, embarked on the development of SCFCLs for distribution system using YBCO coated conductor (CC) wire as a part of the 21C frontier R&D program. As a result, HHI successfully developed and tested a non-inductive winding resistive type 13.2 kV / 630 A SCFCL demonstrator using superconducting coils with AMSC's 344S YBCO CC wire [22]. While the voltage and current ratings of the tested device are higher than the AMSC/SIEMENS device [19], [20] it operates on the same principle and utilizes the same wire. Since no data about this test was made available, this project could not be included in the comparison Table 4-1 - Table 4-3.

Korea Electric Power Research Institute

The second SCFCL project in South Korea funded under the under the 21C Frontier R&D program has been a collaborative work by Korea Electric Power Research Institute (KEPRI) and LS Industrial Systems (LSIS) [23]. It utilizes a hybrid (parallel) arrangement of similar concept as described in [24]. However, instead of a semiconductor switch, the series connection of a superconducting element from YBCO coated conductor and an ultra-fast opening mechanical switch provides sufficient voltage build-up after the quench to commutate the major portion of the fault current into a parallel path. Therefore, this SCFCL is still of the resistive type as it utilizes the quench of the HTS element (in this case only for initiating the current limiting phase).

As shown in Figure 3-5, the current path parallel to the HTS element consists of another ultra-fast closing mechanical switch (auxiliary contact) in series with a parallel arrangement of a fast acting fuse and a current limiting reactor. The goal of this arrangement, which requires significantly more components than regular resistive type SCFCLs, is to reduce the amount of superconductor material, and thereby cost, hence potentially increasing the economic feasibility. This is accomplished by placing the major voltage stress during the current limiting phase onto the fast acting fuse. The superconducting element only exhibited 215 V when operated in the single-phase experimental device tested at 14 kV. In this SCFCL the required YBCO films are only 2.5 % (108 YBCO stripes) or less of those required for a regular resistive SCFCL (4320 stripes) described earlier. While this device is self triggering (no external trigger circuit required) it bares the disadvantage that the fast acting fuse requires replacement after every fault event, just like the fuse in the commonly used explosive trigger based FCL called the Is-limiter [25].

Under the hybrid SFCL concept, KEPRI & LSIS have successfully fabricated and short-circuit-tested a three phase FCL at 22.9 kV and 630 A (25 MVA). KEPRI and LSIS now prepare a field test at a Korean Electric Power Corporation (KEPCO) testing yard at 22.9 kV. Major research targets are reliability tests and protection coordination studies. The installation is planned for early 2008 and with subsequent fault test planned for the early summer 2008.

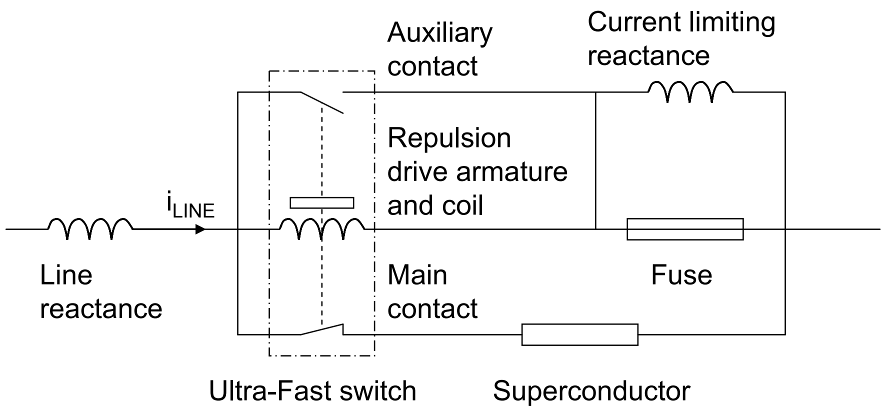


Figure 3-5
Hybrid type SCFCL by KEPRI and LSIS (adopted from [23])

CESI RICERCA

While all the previous resistive type SCFCL projects fully utilize the resistive regime of the superconductor after the quench to maximize the electric filed in order to minimize the required superconducting material, the resistive type SCFCLs developed at CESI RICERCA in Milano, Italy, utilize mostly the flux-flow regime for electric field build-up [26]. This “long-length” principle is illustrated in Figure 3-6 in comparison with the “short-length” used in all other projects. During the limiting phase of the “short-length” principle the superconductor not only enters the resistive regime but heats up significantly, in some cases above room temperature.

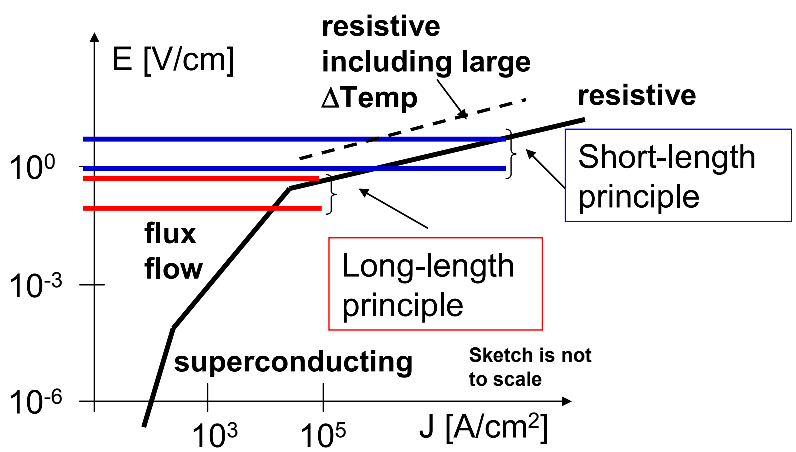


Figure 3-6
Two principles for resistive type SCFCLs

The “long-length” concept has the advantage that due to the significantly reduced energy density in the superconductor the re-cooling times, even under load conditions, are much shorter. In fact, data from experiments given in [27] demonstrates that immediate recovery under load cuCrent is possible with this approach. The disadvantage is that significantly more superconductor material is required because, as illustrated in Figure 3-6, both the electric field E and the current density J at which this E occurs are smaller. Therefore, more length and cross section is required compared to the “short-length” concept to achieve the same voltage drop across the SCFCL device at the same through current. In fact, the CESI RICERCA design for resistive-type SCFCL is based on the use of typical BSCCO-2223 tapes having a large fraction of silver-alloy matrix and it takes into account the difficulty to reach electric fields higher than (0.15…0.2) V/cm in such conductors without facing severe burn-out problems. By using 2G YBCO conductors with highly resistive matrix, this design will automatically turn into the “short-length” principle.

According to CESI RICERCA experience an overall current density (HTS plus metallic matrix) as high as $J \cong 3 \cdot 10^5$ A/cm^2 can easily be reached. Of course, at such high J values the HTS contribution (at least for BSCCO-2223 tapes) is significant only at the very beginning of the fault transient but becomes negligible after 2-3 cycles. For silver (Ag) sheathed BSCCO-2223 the slope of the flux-flow curve is less steep than for other HTS conductors. Therefore, $E \cong 0.2$ V/cm for $J \cong 3 \cdot 10^5$ A/cm^2 are typical values for such materials as indicated in Figure 3-6. For BSCCO tapes with Ag sheath CESI RICERCA selects an appropriate length to ensure that during the most severe short circuit events the conductor temperature rise is less than $\Delta T \cong 150$ K to avoid any possible HTS degradation or failure.

Most recently, CESI RICERCA also developed a SCFCL demonstrator based on MgB_2 [28] tapes with non magnetic high-resistive metallic matrix suitable for SCFCL applications.

Rolls-Royce

Rolls-Royce in the United Kingdom (UK) has a project called Superconducting Fault Current Limiter for Electrical Marine Propulsion (SuFCLEMP). According to [29], partners in this project are the Marine Division of Rolls-Royce, Diboride Conductors Ltd, and the University of Cambridge, both in Cambridge, UK. The project was conducted over 4 years, ending in 2007. The goal was to design an SCFCL for marine applications on ships. The project was supported 50% by the UK government. As a result, a 1-phase MgB_2 based SCFCL demonstrator was built and tested at full current but reduced voltage level. It used round wire 1 mm and 2 mm in diameter with 316L stainless steel sheath, manufactured at MICC Ltd. in Newcastle, UK in a full-sized wire plant through a monocore, powder-in-tube (PIT) process from commercially supplied ex-situ MgB_2 powder. Besides the usage of the potentially inexpensive MgB_2 as the HTS material the second key technology employed for this resistive type SCFCL is a proprietary thermal design for operation of the device at 28 K. As described in [29] the MgB_2 samples utilized in the demonstrator achieved 0.6 V/cm at approximately 270 A. However, no further data was made available for usage in this report (see comment in Table 2-4). Therefore, this project could not be included in the comparison Table 4-1–Table 4-3.

A new project labeled “MANtIS” has been initiated in 2007 which aims to develop a 3-phase MgB2 based resistive type SCFCL for utility applications by 2010. The utility partner in this project is Scottish Power. Again, no technical details about the ratings of the proposed device were made available for this report.

Saturable Magnetic Core FCL

In comparison to the resistive type SCFCL, the saturable magnetic core FCL is a truly inductive FCL. The principle is to saturate two magnetizable iron cores by applying DC bias fields originating from DC current flowing in separate coils. Figure 3-7 shows the equivalent circuit of the saturated iron core FCL [30]. Due to the DC field from each DC coil (C_1 and $C_{2)}$ the respective AC coils (L^1 and L_2) which are wound on the same core exhibit low differential inductances for small AC current magnitudes (i.e. below the trigger threshold, typically a few times the rated current of the device). As illustrated in Figure 3-8 (from [30]), both iron cores are driven into saturation by the DC currents i_{DC1} and i_{DC2} which cause the magnetic circuits to operate around the DC bias magnetic fields H_{DC1} and H_{DC2}, respectively. There, the inductances L_1 and L_2 are very small and essentially the coil inductances without the iron. The apparent SCFCL impedance is also low and consists of the sum of the two coil resistances and their power frequency reactances.

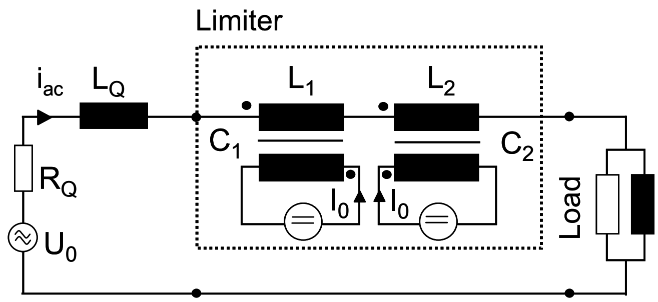


Figure 3-7
Equivalent circuit of the saturated iron core FCL (from [30])

During normal operation, the AC current i_{ac} is low enough to keep the cores fully saturated which maintain the low impedance state of the SCFCL. In the case of a fault, the large AC current will alternately drive the two coils out of saturation and into the region of high permeability on the magnetization curve resulting in a significant increase of the apparent coil inductance. The consequence is a large increase in voltage drop across the SCFCL which in turn clips the fault current. The simulated waveforms shown in Figure 3-8 are typical for a fault occurring at the peak of the source voltage with a purely inductive pre-fault load current. The SCFCL model and parameters used in this simulation are according to [31].

One of the difficulties with this concept is the inherent magnetic coupling between the AC coils and the DC bias coils. During the fault current limiting phase, significant voltage may be coupled into the bias coils which in turn may challenge its dielectric insulation as well as the voltage withstand capability of the DC power supply. Either the physical arrangement of the DC bias coil reduces the magnetic coupling (i.e. entire core within one coil) or the DC bias coil is switched of and shunted quickly after the onset of the fault. The former method requires additional space (i.e. increases the size of the device) and the latter method requires fast switching devices and active triggering.

This concept does not utilize the quench of a superconductor as the non-linear element causing the condition based increase in impedance during the fault. Therefore, saturable magnetic core FCLs do not necessarily require superconductivity. However, it is highly advantageous to use HTS tapes for winding the DC bias coils to reduce conduction losses. The effort for cooling under normal operation is very small since the current is DC and no AC losses occur. This is the reason why this type of FCL is typically listed as a superconducting FCL (SCFCL).

An advantage of this concept is that the trigger threshold can be varied within a limited range, depending on the actual design. This feature may be used to adjust the SSCFL for different conditions caused by system reconfiguration. However, it has yet to be investigated how important such a capability really is in utility applications.

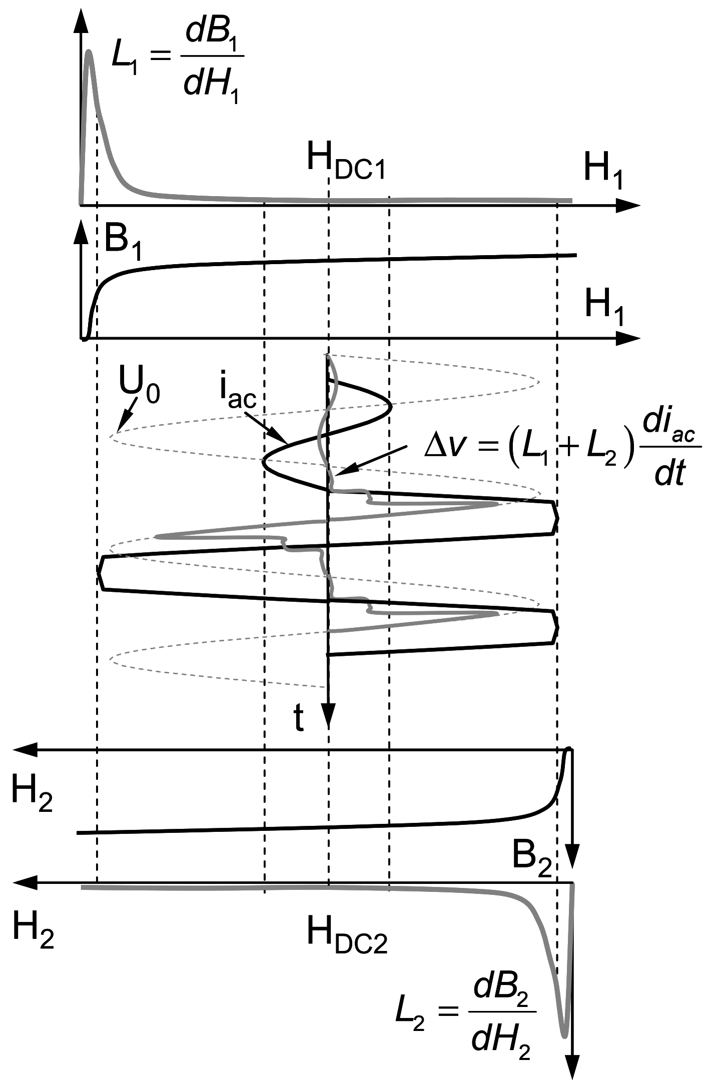


Figure 3-8
Principle of the saturated iron core FCL (from [30])

Saturated iron core with superconducting DC bias coil by SC Power Systems

SC Power Systems in California promotes a concept titled “Fault Current Controller” which utilizes the saturated iron core principle. While generally very little information is publicly available about the technical details of this device, Figure 3-9 (rendering from [32]) shows a conceptual drawing of the device. Ratings of 35 kV and 3 kA continuous current, designed to limit a 40 kA prospective fault current to 20 kA, are given in [32]. The 3-phase device utilizes 6 individual AC coils, two per phase mounted on their respective iron cores, 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 AC current flowing trough all three coil pairs the total of all the 6 fluxes in these cores sum to zero 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. While no values for the mass of the device could be obtained for this report the massive iron core significantly contributes to the overall weight of this design. No test results (tested voltage and current waveforms) could be obtained either.

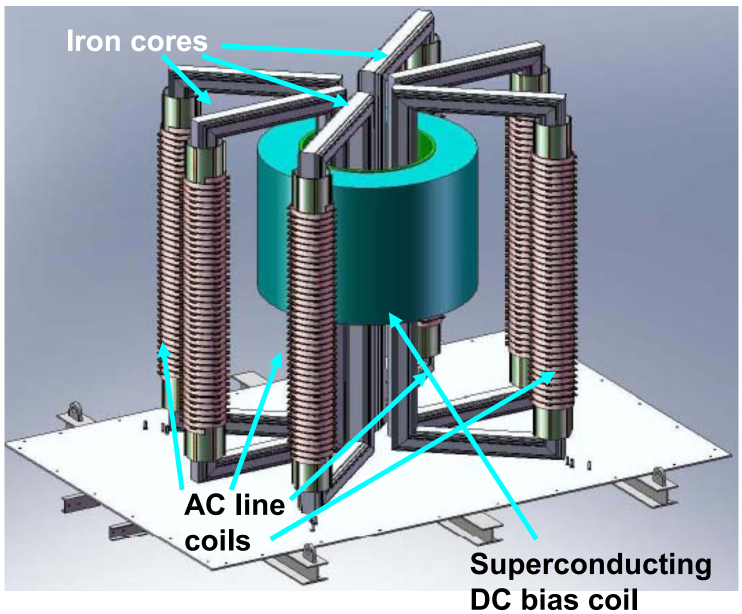


Figure 3-9
Conceptual design drawing of SC Power System's saturated iron core type SCFCL (adopted from [32])

Novel concepts not based on superconductors

This section describes novel FCL technologies which do not utilize superconductivity for their core functionality. The majority of projects in this category utilize semiconductor (solid state) switches as the non-linear elements causing the condition based increase in impedance during the fault. In particular the progress in development of Silicon Carbide (SiC) semiconductors as well as advances in Silicon (Si) based devices draws increase attention within the R&D community for utilization in FCL devices. Therefore, this section briefly summarizes results from some of the semiconductor development activities before describing major non-SC FCL projects.

Controlled LC resonance circuits (e.g. series compensators) and converter based FACTS devices may provide fault current limiting as a by-product of their primary functionality but are not considered here since they are not stand alone FCLs.

Silicon versus Silicon Carbide

Silicon Carbide (SiC) has distinct advantages over Silicon for manufacturing semiconductor power devices. Table 3-1 gives a comparison of key physical properties of Si and 4H-SiC. There are over 200 known poly-types of SiC, but the data in Table 3-1 is for 4H-SiC, because it is being used by industry to manufacture power semiconductor devices. The higher band-gap of SiC translates into practically negligible junction leakage current at temperatures up to 600 ^{o}C, thus allowing for operation of devices at high temperatures. In fact, the thermal conductivity of SiC is comparable to that of metals at room temperature. Si is limited by a junction temperature of approximately 150 ^{o}C. This leads to an improvement by a factor of 10 in the power density if SiC is used for for power modules. If suitable heat removal strategies are implemented the sizes of heat sinks will be reduced and active cooling eliminated as compared to that needed for Si.

Table 3-1
Material properties of Silicon (si) and industrial Silicon Carbide (4H-SiC)

Parameter	Si	4H-SiC
Energy Band-gap (eV)	1.12	3.26
Electric Field Breakdown ($\times 10^6$ V/cm @ 1 kV operation)	0.25	2.2
Dielectric Constant	11.8	9.7
Intrinsic Carrier Concentration n_i (cm^{-3} @ room temperature)	10^{10}	8.2×10^{-9}
Electron Mobility, μ_e ($cm^2/V \cdot s$ @ room temperature)	1400	700-980
Hole Mobility, μ_h ($cm^2/V \cdot s$ @ room temperature)	450	120
Saturated Electron Drift ($\times 10^7$ cm/s @ $E > 2 \times 10^5$ V/cm)	1.0	2.0
CTE (ppm/K)	4.1	5.1
Young's Modulus (GPa)	156	400
Thermal Conductivity (W/m·K @ Room Temperature)	150	400
Density (g/cm^3)	2.3	3.2
High Breakdown Strength, (MV/cm·K)	1.5	4.9
Current Density (A/cm^2)	200	1000
	100 most commonly found	100 currently achieved, and 800 reported

The higher breakdown electric field of SiC allows the design of thinner and more highly doped voltage blocking layers. Combining these attributes in a majority carrier device, results in 100 times improvement in power density. For minority carrier devices, this translates to 100 times improvement in the switching speed. These faster switching speeds lead to a reduction in the size of passives required in accompanying circuitry. Table 3-2 summarizes the advantages of SiC over Si for power devices.

Table 3-2
Advantages of SiC over Si for power devices

Performance Metric	Causal Property Affecting Metric	Advantage
Blocking Voltage	Electric Field Breakdown	Higher blocking voltages (≅10 times)
Current Density	Saturated Electron Drift	Higher current density (≅5 times)
Volumetric Reduction	Electric Field Breakdown	Power density (≅100 times)
Switching Speed	Electric Field Breakdown	Faster speeds (≅100 times)
Operating Temperature	Energy Band-gap, Thermal Conductivity	Higher operating temperature (≅4 times)

All of these attributes allow SiC to compare to Si quite favorably in potential fault current limiter (FCL) applications once a certain voltage level is addressed. For example, the effective conduction loss of the SiC thyristor will be about twice that of a Si thyristor, due primarily to the wider band-gap of SiC. However, as application voltages reach the 15 kV class and beyond, it is possible that fewer enough devices are required for voltage blocking using SiC such that the conduction loss becomes equivalent (e.g., 6 series-connected 5 kV Si thyristors compared to 3 series-connected 10 kV SiC thyristors). Volumetric reduction of the FCL is achieved through several mechanisms:

I. fewer devices in a high voltage stack,

II. significantly simpler thermal management system, and

III. smaller commutating passives due to faster switching speeds. If SiC power devices will able to achieve current densities close to the theoretical limit in the future, further reduction in volume will be possible.

The basic facts about the two materials were known well for many years. However, only recently noticeable improvements to the manufacturing process led to feasible SiC semiconductor devices which demonstrate real potential for power applications.

Solid-State FCL by Arkansas Power Electronics International

Arkansas Power Electronics International (APEI) at the University of Arkansas has successfully developed a low power solid state FCL (SSFCL) test unit using SiC devices. While the power rating is still small (approximately 1 kW) this project is worth noting since this is the first SiC based FCL of this kind.

Figure 3-10 shows the basic equivalent circuit of this SSFCL. During normal operation current flows through the main thyristors (M1 and M2). When the system detects an increase in the line current above a specified threshold, one of the auxiliary thyristors (AUX1 or AUX2) is turned on long enough to force a current zero in the corresponding main thyristor (i.e. AUX1 turns off M1 and AUX2 turns off M2). In order to accomplish this action, the commutating capacitors (C1 and C2) have to be sized in order to hold a reverse-bias voltage across the main thyristors for a suitable period of time, known as the full reverse recovery time, so that they remain off while the current is redirected to the limiting element. Since the SiC thyristors (M1 and M2) cannot block reverse voltage diodes (D1 and D2) are connected in series. This is essentially the basic circuit used by all thyristor based FCLs with resonant (commuting) circuit for turn-off.

Depending on the desired type of SSFCL, a resistor, an inductor, or a surge arrestor of appropriate power rating can be placed between points A and B to allow follow current flow while all the semiconductor switches have turned off. In such cases a separate circuit breaker is required to turn off the line current. Alternatively, phase angle control can be applied to the main thyristors to allow a controlled follow current flow. In this case, the element between points A and B only provides energy absorption and hence over voltage protection during the first turn-off event but does not carry significant current thereafter.

Since SiC devices offer faster switching speeds than equivalent Si devices (equivalent in terms of blocking voltage), the commutating capacitors required are significantly smaller. Since SiC is capable of higher temperature operation than Si, the thermal management requirements are vastly reduced. These two factors synergistically lead to a substantially smaller footprint for a SiC solution as compared to the Si implementation.

In order to utilize all possible functionalities from such an arrangement an intelligent control algorithm has to be implemented to clear the power system from temporary faults (i.e. re-closing) or to shut it down for permanent faults.

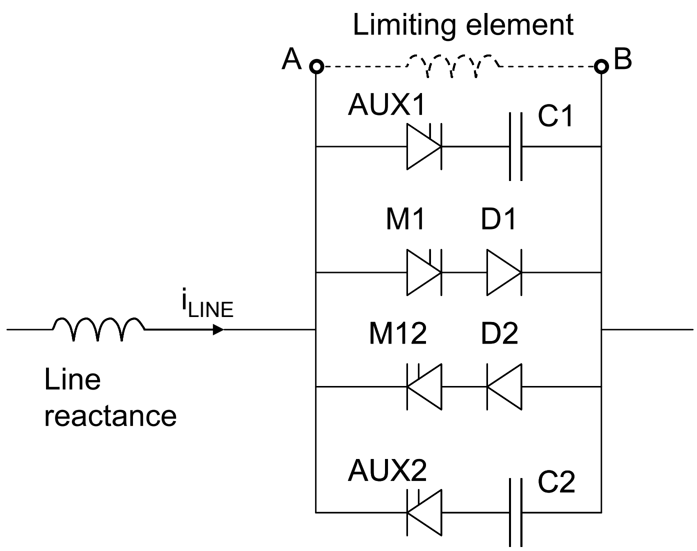


Figure 3-10
Basic equivalent circuit of the SiC based SSFCL

Solid-State FCL by Powell

The details of the SSFCL device developed jointly by EPRI and Powell Electronics Inc. were reported in [2]. No significant changes have been made to the design which would impact its fundamental functioning. The overall goal of the project is to eventually develop a 138 kV class device. The device uses standard Si thyristors and a resonant circuit as shown in Figure 3-11 for current turn-off in the main thyristor part [33]. A combination of resistors and varistors are used in parallel to the circuit for absorbing the energy dissipated during switching. The follow current is controlled by means of phase angel control without the use of a current limiting inductor. This allows the device to not only limit but also interrupt the current. A 15 kV / 1200 A class 3-phase device, shown in Figure 3-12, was successfully tested for current interruption in 2006 at KEMA Power Test Labs in Pennsylvania, USA. A detailed description of this device can be found in [33].

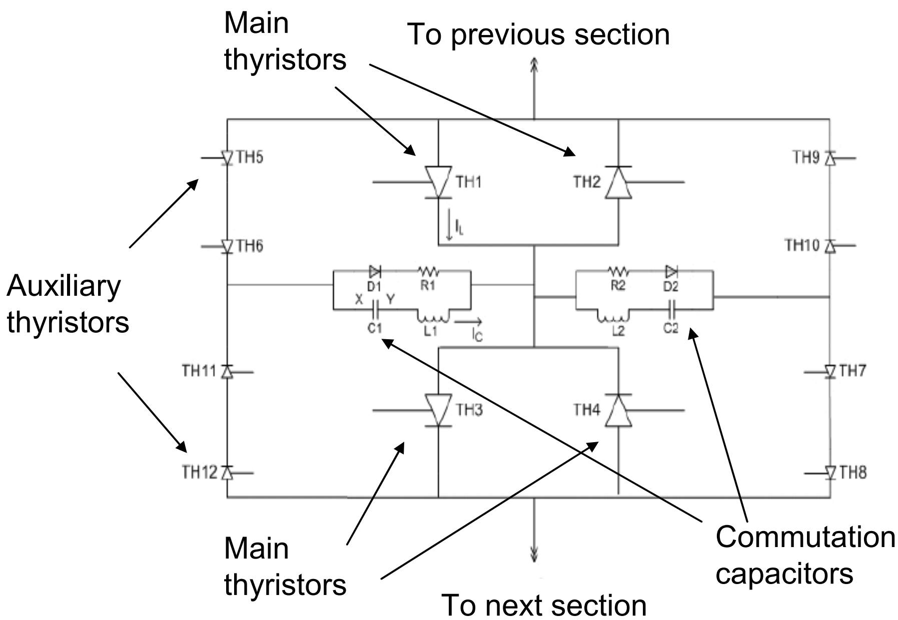


Figure 3-11
Powell's SSFCL circuit (circuit from [33])

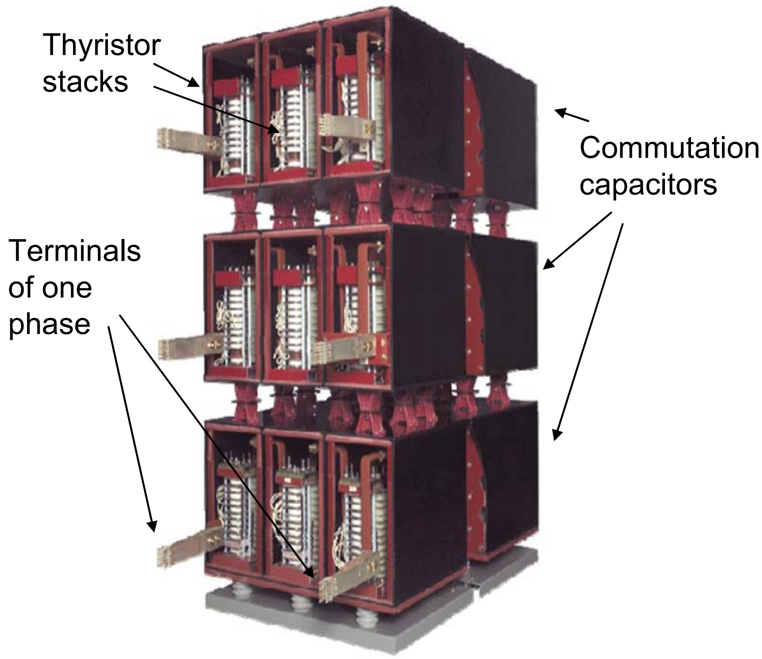


Figure 3-12
Powell's 3-phase SSFCL (photo from [33])

Solid-State FCL by Silicon Power Corporation (SPCO)

Several SSFCL projects are under way at Silicon Power Corporation (SPCO, USA, with partnership from EPRI. Two at the 15 kV class with nominal current ratings of 1200 A and 4000 A, and one at the 69 kV level with a 3000 A rating. They all utilize SPCO's proprietary Super-GTO (SGTO) device which, despite its name, at this time does not have hard turn-off capability. Development is under way to incorporate the hard-turn off capability in the SGTO device. In fact the device behaves in the circuit similarly to a standard thyristor, except for the significantly increased allowable rate of change of current (di/dt) and rate o change of voltage (dv/dt) during and after turn-off, respectively. This, together with the reduced recovery time of this device, allows a much faster turn off with a resonant circuit shown in Figure 3-13 than with standard thyristors. This in turn allows a significant reduction of the size of the components comprising the resonant circuit. Moreover, the SGTO exhibits less forward voltage drop and hence less on-state losses than a regular GTO or IGCT. However, the losses are still comparable to those of standard thyristors. All the circuits proposed for SPCO's SSFCLs feature a current limiting inductor as shown in Figure 3-13 to allow follow current flow.

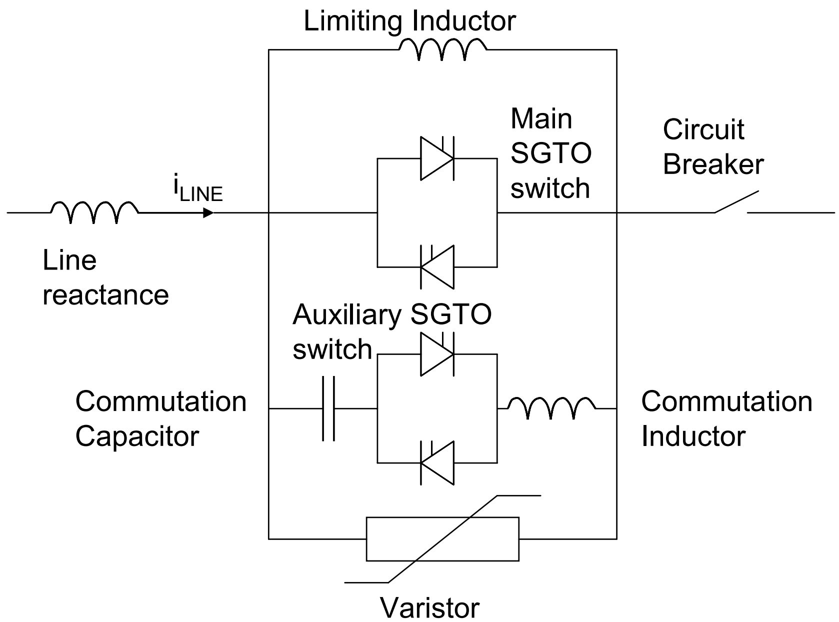


Figure 3-13
Basic equivalent circuit of the SSFCL by SPCO

Hybrid SSFCL by AREVA

As a variant of the hybrid FCL circuit breaker principle described and demonstrated in [24] AREVA Technicatome division (French Navy), France, has developed a hybrid FCL circuit breaker targeted for shipboard applications [34]. The basic circuit is shown in Figure 3-14. The main current path consists of the main IGCT in series with an ultra-fast switch which is capable of starting contact separation 100 µs after trigger. With a target voltage of 6.6 kV for shipboard systems the aim is to minimize the number of semiconductor (IGCT) switches required in order to minimize on-state conduction losses. When a fault occurs, the IGCT switch commutates the current into the parallel resonance path consisting of the commutation thyristors, which is triggered to accept current, a resonance inductor, and an energy storage element. After this initial current commutation process the ultra-fast switch opens without arcing and provides dielectric isolation for the IGCT switch from the subsequent transient recovery voltage. According to [34], the resonance circuit generates high frequency oscillations for fast current interruption by the commutation thyristors, resulting in a breaking of the fault current within the first half cycle. The energy storage module stores the energy built-up in the line reactance during the fault. Optionally, a current limiting inductor provides the ability of this circuit to maintain a follow current flow for downstream protection coordination. A 3.8 kV / 500 A rated single phase demonstrator device was successfully tested in 2005. The project is currently on hold due to lack of funding from the French Military (Division Generale de L'Armement DGA).

As described in [35], AREVA T&D independently pursues a similar hybrid concept but targeted at utility system voltages between 24 kV and 145 kV and prospective short circuit currents of 80 kA. In the future, the design may utilize semiconductors of types other than IGCTs. The goal of this hybrid concept is the same as for the one described in [24]: to minimize losses originating in the semiconductor switches. The challenge in this project is to develop the ultra fast mechanical switch which should open within 50 µs for high voltage applications. The current design, which targets an opening time of 600 µs as an interim goal, exhibits many features similar to the metallic return transfer breaker (MRTB) used in HVDC systems.

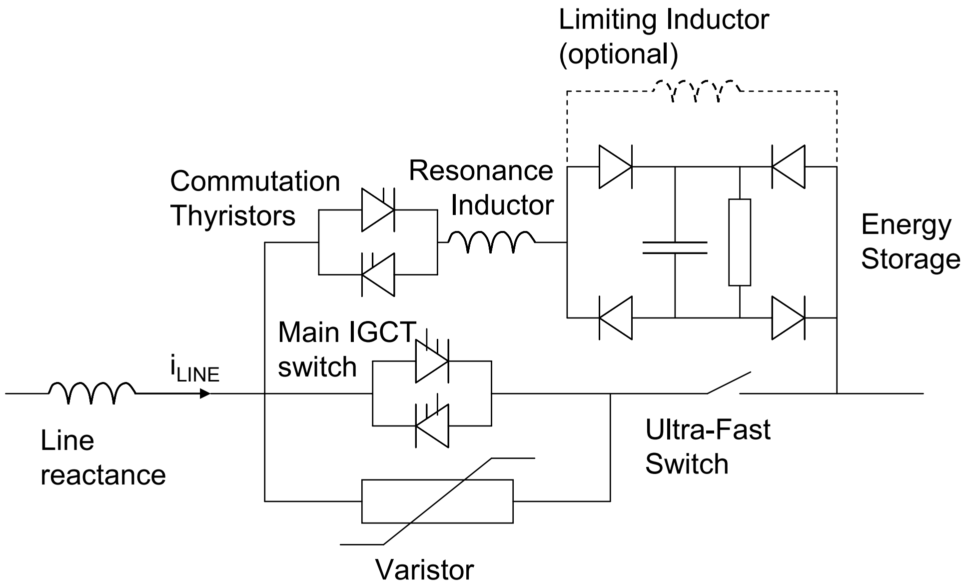


Figure 3-14
Basic equivalent circuit of the hybrid FCL circuit breaker by AREVA (adopted from [34])

Liquid Metal FCL by ABB

This technology utilizes liquid metal which can move quickly along the resistive walls of a capillary in order to cause the condition based increase in impedance during the fault. The fundamental principle of this technology was reported in [2]. The state of the art in 2005 was that ABB researchers demonstrated successful voltage build up of almost 100 V per capillary at currents of up to 2.7 kA [4]. Meanwhile, improvements to the liquid metal switching elements resulted in successful testing of a 1 kV / 2 kA rated experimental device. Due to the time required for the liquid metal to move after fault inception which is currently around 5-8 ms this concept currently targets 16.7 Hz railroad applications in Europe. Utility power system applications at 50 Hz or 60 Hz will require a significantly shorter commutating time on the order of 1-2 ms.

4
COMPARISON OF FCL PROJECTS

Comparison of key data of novel FCL projects

Providing an objective comparison of the major projects featuring the different technologies described in chapter 3 is difficult, since they all utilize different specifications and ratings for their respective demonstration devices and prototypes. Therefore, we developed tables with a set of key data which we believe provides a reasonable basis for such an objective comparison. As stated in chapter 2 we sought input to these tables by the contact person of each project. Only minor modifications to these inputs were adopted by the authors in some cases to ensure a uniform presentation of the data in this report.

The most intensive developments can be observed currently with superconducting FCL technologies. Table 4-1 through Table 4-3 provides a comparison projects utilizing superconductivity as the dominant technology. The data entries have been provided by the contacts of listed earlier in Table 2-1.

Subsequently, Table 4-4 and Table 4-5 compare non-superconducting technologies. Those columns shown in Table 4-2 through Table 4-3 where no data was available for on-superconducting technologies, or which where not applicable, have been omitted entirely.

Many of the data entries provided in Table 4-1 through Table 4-5 require additional comments for better understanding and clarifications which are given below. Note that the rated voltage given in these tables Table 4-1 and Table 4-4 are line-neutral voltages, even for 3-phase devices. This value was chosen to allow an easier comparison of mix of tested 1-phase and 3-phase devices (i.e. 3-phase rating divided by √3). Furthermore, current ratios are calculated from peak values.

Comments (footnotes) in Table 4-1 through Table 4-3:

(a)	Insulaton rated for 2 kV
(b)	At fault clearing time
(c)	AC losses + current lead losses at nominal current, AC losses extrapolated from a single coil measurement
(d)	Complete cryostat
(e)	Including everything, as reported in [25]
(f)	90 kApeak limited to 33.8 kA (= 2.7), 40 kApeak limited to 14.32 kA
(g)	54 kApeak limited to 19 kA (= 2.8), 25 kApeak limited to 10kA, @ 5 cylcles
(h)	1.2 kV supply voltage
(i)	Samples designed and tested for fault current only

Comments (footnotes) in Table 4-4 and Table 4-5:

(a)	Possibly up to rated value with phase angle control
(b)	Time to first cycle interruption
(c)	Voltage on thyristor stack
(d)	New design is 54 inches (1.4 m) wide; data is for 15kV/1.2kA 3-phase unit
(e)	On hold due to lack of funding from DGA (Division Generale de L'Armement) - CTSN Toulon France.
(f)	Equivlent to the 2.5 kV maximum voltage of the DC capacitor used in the component test
(g)	Commutates onto a parallel inductor which determines the follow current, hence no interruption
(h)	depends on the
(i)	tested circutry only
(j)	The test circuit used 14 A, but this is not representative for real applications
(k)	Turn-off time of the thyristor in test circuit. Will be significantly olnger in utility applications (i.e. 1/4 - 1/2 cycle)
(m)	SiC thyristors are assymertic and require a blocking diode in series. The total voltage drop across this arrangement is 3x the diode voltage drop
(n)	Immediate recovery in this case means 100 ms to 150 ms (time of the liquid metal droplets to fall down into the bottom part of the capillaries). Reclosing on an uncleared short circuit is problematic (resistive material may be thermally overloaded)
(o)	Significant increase in resistivity already after approximately 10 ms. Resistivity of the limiter may still increase until approximately 40 ms after the fault inception.

Table 4-1
Comparison of superconducting FCL (SCFCL) technologies (part 1)

Proj. No	Project Lead	Country	Partners	Comments	Tested rated voltage level L-N [kVrms]	Tested rated current level [Arms]	Emax [V/cm]	Tested phases	Year tested	HTS configuration
BSCCO 2212										
1	ACCEL	Germany	RWE, Nexans SC, FZK	Long term tests at FZK until mid of 2007	6.9	600	0.57	3	2005	bifilar coil
2	Nexans SC	Germany	KEPRI	updated CURL-10 design	14.4	800	0.85	1	2007	monfilar coil
3	Nexans SC	Germany	FZK, RWE, University Hannover	New project targeting 110 kV	0.12	1850	3.00	1	2006	coils
MgB2										
4	CESI RICERCA	Italy	none	first prototype	0.525 (a)	270	0.19	1	2005	anti-inductive coil
BSCCO 2223										
5	CESI RICERCA	Italy	none	largest prototype by CESIRICERCA	3.17	220	0.16	3	2005	tape, anti-inductive coil
6	CESI RICERCA	Italy	none	Protoype being field tested at CESI Ricerca (DG test facility)	0.52	280	0.05	3	2006	tape, anti-inductive coil
YBCO										
7	Siemens & AMSC	Germany & USA	none		7.5	300	0.5	1	2007	cotaed conductor bifilar coil
8	SuperPower	US		2G module test	1.2 (h)	N/A (i)	to 2.5	1	2006	YBCO tape w/ Cu shunt coil
YBCO, with bypass switch										
9	KEPRI	Korea	LSIS	Field test expected 2007	13.2	630	6.0	3	2006	YBCO film, stripes

Table 4-2
Comparison of superconducting FCL (SCFCL) technologies (part 2, Table 4-1 continued)

Proj. No	Device characteristic (shunt)	HTS thermally coupled to shunt	Operating Temperature	Current Limitation - first peak (Ipk/INpk)	Current Limitation - follow (Ipk/INpk)	Fault clearing time [ms]	Prospective current ratio (IP/IN, symm.)	Transient Over Voltage [pu]	Recovery time [s]
BSCCO 2212									
1	resistive	yes	66.0	8.8	3.6	60	12	1.13	~30
2	resistive	yes	77.0	6.6	2.7	80	31.3	1.23	~60
3	resistive/ inductive	no	77.0	15.10	4.60	60	33.33	not yet determined	few s
MgB2									
4	resistive	no	27.0	8.2	3.8	100	22.6	none	< 5 s
BSCCO 2223									
5	resistive	no	65	8.10	2.60	100	27.7	none	< 2 s
6	resistive	no	65-70	7.20	3.80	100	18.2	none	< 1 s
YBCO									
7	resistive (only the steel on the wire)	yes	77.0	7.5	2.3 (b)	50.0	up to 90	< 1.2	2.5
8	inductive/ resistive	no	77.0	2.7 (f)	2.7 (g)	83	N/A	None	< 5 sec (no load)
YBCO, with bypass switch									
9	resistive	Yes	77 K	27.5	19.0	No limit	41.3	1.1	~ 0.5 s

Table 4-3
Comparison of superconducting FCL (SCFCL) technologies (part 3, Table 4-2 continued)

Proj. No	Impedance after 1 cycle [Ohm]	Losses [W/kVA] at room temp	Over current allowance	Weight	Size	Cooling medium	Cooling machine	Total appartus Volume V [m^3]	Rated Power P [MVA]	V/P [m^3/MVA]
BSCCO 2212										
1	~ 3	~ 2.2		5 tons	W: 1.6 m L: 3.5 m H: 3 m	LN2	Stirling LPC2	5.3	12.5	0.42
2	6.7					LN2	Open bath			
3	0.01				two 20cm tubes	LN2			0.22	
MgB2										
4	0.41	0.54	>120%		0.01	LNe	closed-circuit LNe system	0.35	0.14	2.47
BSCCO 2223										
5	3.10	0.34	>120%		0.012	LN2	closed-circuit LN2 system	0.88	1.21	0.73
6	0.35	1.128	>120%	0.0185		LN2	closed-circuit LN2 system	0.206	0.253	0.81
YBCO										
7	7.2	~0.03 (c)	110%	500 kg (d)	1 m^3 (d)	LN_2	LN2 dewar + GM coldhead	1.0	2.25	0.44
5						LN2	LN2 open bath			
YBCO, with bypass switch										
6	2	~ 0	110%		W: 1.0 m L: 2.5 m H: 2.0 m	sub-cooled LN2	LN2 dewar + cryocooler	5 (e)	25.0	0.14

Table 4-4
Comparison of non-superconducting FCL technologies (part 1)

Proj. No	Project Lead	Country	Partners	Comments	Tested rated voltage level L-N [kVrms]	Tested rated current level [Arms]	Tested phases	Year tested	Active devices	FCL device characteristic
Solid State, Si devices, circuit breaker type										
10	Powell	USA	EPRI, DOE	Target is 138kV	8.0	1200	3	2006	Thyristor	interrupt in 1/4 cycle, dominant resistive voltage
11	AREVA Technicatome	France	DGA-CAPSIM	on hold (e)	3.8	500	1	2005	Diodes, IGCT, fast mechanical switch	0.6 millisecond with electronic fault sensing time
Solid State, Si devices, shunt reactor type										
12	Silicon Power (SPCO)	USA	none	69kV, 3000A device being designed, test expected 2008	1.77 (f)	800	1	2007	Si SGTO	Resonant turn-off
Solid State, SiC devices, circuit breaker type										
13	APEI, Inc.	USA	NCREPT (UofA)	6 months into initial development phase (completed Phase I)	0.12	8	1	2007	SiC Thyristor	Resonant turn-off with MOV limiting device overvoltage
Liquid metal type										
14	ABB	Switzerland	none	technology still in early stage of development	1	2000	1	2006	liquid metal filled capillaries	Increase in resistivity as liquid metal moves on resistive rails

Table 4-5
Comparison of non-superconducting FCL technologies (part 2, Table 4-4 continued)

Proj. No	Current Limitation - first peak (Ipk/INpk)	Current Limitation - follow (Ipk/INpk)	Fault clearing time [ms]	Transient Over Voltage [kV]	Immediate recovery	Losses [W/kVA]	Size	Auxilaries	V [m^3]	P [MVA]	V/P [m^3/MVA]
Solid State, Si devices, circuit breaker type											
10	19	< 1 (a)	< 4.2 (b)	15 (c)	yes (after circuit modification)	1.7	W: 1.4 m L: 2.4 m H: 3 m (d)	air cooling (integrated)	10.1	28.7	0.35
11	2.83	None (interrupted current)	< 0.6	12.5	Yes	not larger than 0.5 W/kVA	Prototype:1 x 1 x 3 meters	Electronic	3	1.9053	1.57
Solid State, Si devices, shunt reactor type											
12	3.75	N/A (g)	N/A (g)	3 (h)	yes	~ 1.3	W: 0.4 m L: 1.2 m H: 0.2 m	N/A	0.096	3	0.03
Solid State, SiC devices, circuit breaker type											
13	N/A (j)	N/A (j)	20us (k)	limited by MOV	yes	~15 (m)	W: 15 cm L: 15 cm H: 5 cm	Liquid cooling (external)	0.0013	0.001	1.35
Liquid metal type											
14	7.9		< 10ms (o)		yes (n)	0.02	W: 0.3m, L: 0.3m, H: 0.15m (i)		0.0135	2	0.0068

Discussion

Figure 4-1 summarizes the current trend in novel type FCLs by indicating the voltage and current ratings of successfully tested devices. The number next to the project leader's name signifies the year of the test. It becomes clear from Figure 4-1 that the majority of the devices appear in the medium voltage range (below 20 kV line-neutral or 35 kV line-line) with maximum current ratings below 2000 A. Current developments with significant tests scheduled between 2008 and 2010 target the lowest transmission system voltages.

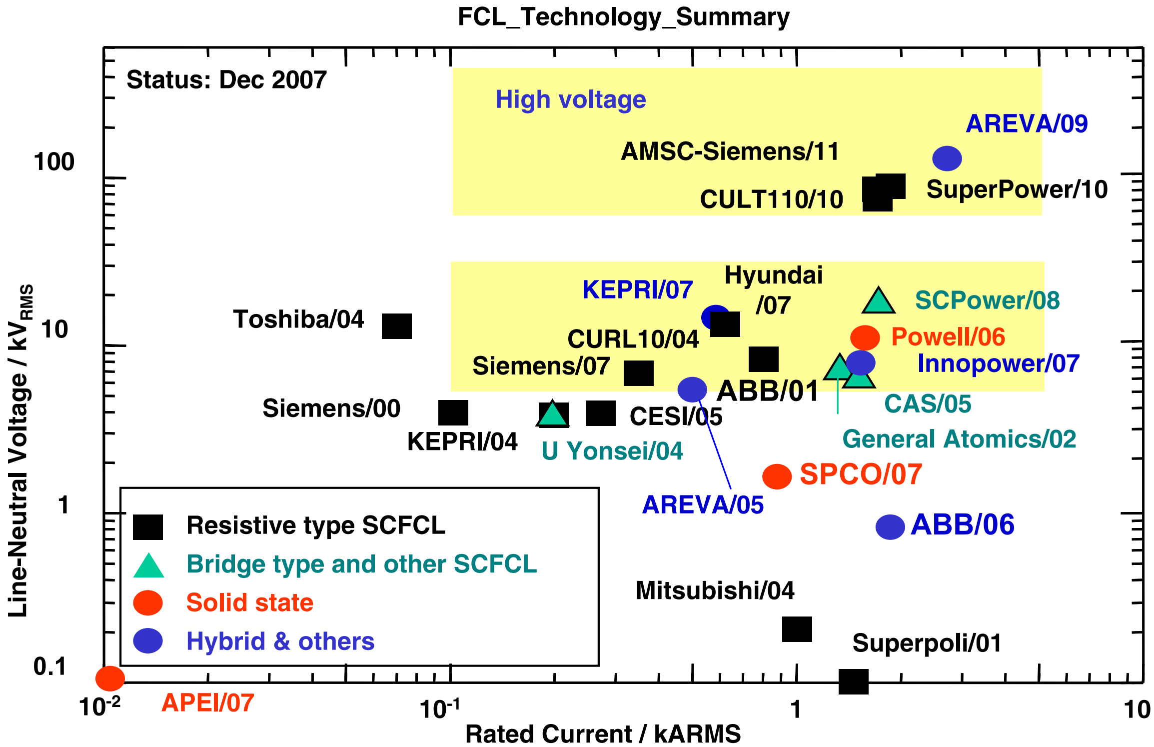


Figure 4-1
Trend in Novel FCL Technology

From the data compiled in Figure 4-1 through Table 4-5 the following additional observations can be made:

Losses

While losses in any power transmission and distribution apparatus should be as small as possible to minimize economical penalties, losses in current limiters do not appear to be a limiting factor for practical applications from the power system operation point of view. The data shows that the efficiencies of all types of current limiters are 99% and above.

However, reducing the AC losses in superconducting FCLs is still important because the size of the system for continuous cooling is primarily determined by those AC losses and costs of these cooling systems are not negligible. Reducing the losses in semiconductor based systems will also be advantageous in order to reduce size, weight, and cost of the devices.

Size and Weight

Many of the projects have demonstrated the technologies through experimental devices which are not size and weight optimized. Therefore, useful estimations form available data of sizes and weights of actual devices to be deployed in the field are impossible at this time.

Recovery

Fast recovery or recovery under load is still a challenge for many SCFCL approaches when considering economical aspects. The long-length approach is more advantageous regarding recovery since the superconductor does not reach the resistive state. Semiconductor based FCLs can be more economically designed for fast recovery (i.e. within one cycle) and even for recovery under load.

FCL Characteristic in the Network

The term “resistive type” SCFCL

It shall be noted that the term “resistive type” SCFCL refers to the principle of utilizing the transition from superconducting into the resistive regime to force the current into a normal conducting shunt element in parallel to the otherwise superconducting elements. The term “resistive type” does not necessarily describe the FCL behavior in the system. In fact many “resistive type” SCFCL projects utilize mixed resistive-inductive shunt elements which may cause some SCFCLs to appear with a large inductive impedance component during fault current limiting phase.

Interaction between an FCL and the system protection

Since FCLs change the fault current level in a power network in many cases the system protection may have to be re-examined in order to ensure proper functionality. System protection is an indispensable part of each power system. Protection systems are based on different protection principles and sub items. Protection coordination studies are performed routinely to confirm the accomplishment of selectivity and sensitivity also under adverse influence from other network devices. Without this confirmation, or without a properly tested and fully operational protection system, a power system will never be energized. Thus to support the performance of fault current limiters (FCL) as an applicable substation equipment and technology, possible interactions between fault current limiters and protection systems have to be investigated and understood. The only international organization which has investigated this topic comprehensively so far is the CIGRE WG A3-16 [36]. The full report of the WG A3-16, which established a basic framework to investigate the interactions between FCLs and the protection system, will be published in 2008. The presented methodology, which is briefly summarized in [36], helps to clearly identify the specific conditions for which such interactions occur.

Waveform distortions of the follow current

All resistive type superconducting FCLs (SCFCLs) insert a resistive-inductive element into the short circuit current path after trigger. Therefore, they cannot switch off the current if they do not feature a circuit breaker in series with the SCFCL. In turn, they do not cause distortion of the follow current. Solid-state FCLs (SSFCLs), which utilize a parallel reactance as the means to allow through current flow, behave equally with regard to the follow current distortion. However, SCFCLs which utilize phase angle control to adjust the magnitude of the follow current flow may cause significant current distortions depending on the allowable through current value. The same is true for the saturated iron core FCL and other types which utilize non-linear or switched elements to actively adjust the follow current magnitude. The advantage of SSFCLs with phase angle control is that they can perform the function of a circuit breaker to interrupt the current. In addition, they can be used to “soft” switch-in and reduce the inrush currents experienced normally with mechanical circuit breakers when energizing induction motor loads, transformers, or synchronizing sub-grids with system voltages which are out-of-phase.

While system wide effects of such follow current distortions have yet to be investigated more rigorously, one study reported in [37] shows how conventional over current relays may be adversely influenced by such current distortions. It was shown that, in the worst case, the distortions can lead to a miss-coordination of relays.

5
OBSERVATIONS AND CONCLUSIONS

This update of the previous FCL technology survey [2] clearly indicates significant advances in conditional impedance increase type FCLs which is reflected in increases interest for these devices in the utility realm. Significant progress in technology development resulted in the first commercially available high-temperature superconductor based resistive FCL for medium voltage levels. These developments may indicate a paradigm shift in the utility industry. Limitation of fault currents through condition based impedance increase of inherently resettable devices, which is common practice in low voltage systems, may become the state of the art in medium and high voltage systems within a decade or so. This development may be similarly important for fault current management as the introduction of over voltage protection through metal oxide surge arrestors (MOVs) was for insulation coordination. Achieving this goal will still require significant research, not only into how to build these novel FCL devices, but also into how they operate in the system under various conditions. Particular emphasis should be given in proper modeling for simulating the inherent transients associated with faults limited by these novel technologies. Effects of large penetration of FCLs in T&D networks should also be studied. Furthermore, early research into how the end user (i.e. the utilities) should specify FCL devices to meet their needs in their system applications will be one key to a long term success of this new fault management technology. Finally, it is important to continue a thorough watch of future developments of the various FCL technologies and compare their performances. At the publication of this report, none of the technologies investigated herein appear to take a clear lead over others.

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