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A Comprehensive Review on Superconducting Fault Current Limiters in Electrical Utility Network

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Abstract

As a result of the increasing power demand and the high penetration of distributed generations (DG), a current can suddenly increase during a contingency. This fault current gives the possibility of exceeding the ratings of the existing protective devices. Therefore, in power systems, the utilization of superconducting fault current limiters (SFCLs) can suppress the unanticipated short-circuit currents in utility distribution and transmission networks, so that the underrated switchgears can be operated safely. SFCL's eliminate or greatly reduce the financial burden on the utilities by reducing the wear on circuit breakers and protecting other expensive equipment. Superconducting fault current limiter (SFCL) based on high temperature superconductors (HTS) is an enabling technology for the extensive fault current limitation when compared to conventional circuit breakers (CBs) and other fault current limiters. Superconducting FCLs can be installed at optimum locations in the transmission network to reduce fault currents to within a tolerable range when a new power plant is installed. With these placements, we can make full use of the advantages of smart grid's communication network and different characteristics of FCL devices in different categories to offer a more flexible and reliable protection for future power grid. This paper outlines various types and basic application guidelines for using superconducting fault current limiters in electrical utility network.

Keywords: *Fault current, smart grid, superconducting fault current limiter*

1. Introduction

With current initiatives on smart grid and sustainable energy, distributed generations (DGs) are going to play vital role in the emerging electric power systems [1]. Recent studies have predicted that by year 2010, distributed generation will account for up to 25% of all new generation [2]. By the addition of Distribution Generation (DG) to distribution networks, voltage profile of the network is improved and loss reduction and energy demand decreases from the utility network. Also enhancing DG is an attractive distribution planning option will avoids causing degradation of power quality, reliability and control of the utility systems [3]. The high degree of penetration of DGs has a considerable impact on the operation, control, protection and reliability of existing power utility systems. The introduction of a DG into a distribution system brings about a change in the fault current level of the system and causes many problems in the protection system, such as false tripping of protective devices, protection blinding, an increase and decrease in short-circuit levels, undesirable network islanding and out of- synchronism reclosers [4].

Several possible solutions have been proposed to overcome the above problems, such as upgrading circuit breakers, installing microprocessor based recluses [5], employing adaptive protection [6], decreasing the generation capacity of DGs or even cut off the DGs from the main grid during fault conditions [7]. These methods are complex and expensive, and in many cases put constraint in using DG capacity and limiting the benefits from DG units.

Among the countermeasures to solve the short-circuit problem in a power distribution system considering the increase of the DG, the superconducting fault current limiter (SFCL) has been noticed as one of the promising devices [8], because it has negligible power loss and capability to limit initial fault currents effectively [9]. Nexans is the premier developer of FCL in Europe and has installed several devices. The initial work by Nexans was on resistive SFCLs, and they were the first to fabricate and install a commercial SFCL [10].

This paper describes potential application of High Temperature Superconducting Fault Current limiter presently under development by American Superconductor. Zenergy Power Inc. and Super Power Inc. etc:

- A project implemented by Zenergy Power Inc. and aiming to design, test and demonstrate a 138-kV transmission class inductive HTS FCL
- A project implemented by SuperPower Inc. and aiming to design, test and demonstrate a 138-kV resistive HTS FCL that features a matrix design
- A project implemented by American Superconductor which is developing and in-grid testing a three-phase, high-voltage, 138-kV resistive HTS FCL, called a Super Limiter™, which uses second-generation (2G) wire [11].

In 1996, the first prototype high-temperature-superconductor SFCL with a rating of 1MVA at 10.5kV was installed in Switzerland [12]. On March 7, 2001, ABB demonstrated the world's most powerful SFCL with a rated power of 6.4MVA at Baden, Switzerland [13]. No major SFCL developments have been announced by ABB since 2001 [14]. The SFCL systems based on CC tapes are the subject of two running projects ENSYTROB and ECCOFLOW. These are coordinated by NEXANS. "ENSYSTROB" aiming at the development of a SFCL for the application in the auxiliary supply of a power station rated at 12kV & 800A. The European "ECCOFLOW" project aims at developing a resistive SFCL which will serve two installation sites of two different utilities. Even though one site operates at 16 kV as a bus bar coupling in the grid of Endesa and another at 24 kV as a transformer feeder in the grid of VSE, it was possible to find a common design [15].

2. High-Temperature Superconducting (HTS) FCL:

The first superconducting fault current limiters (SFCLs) were proposed in the 1970s [16], and significant research and development has been undertaken, particularly since the discovery of so-called high-temperature superconductors (HTS) in 1986. HTS materials typically permit liquid nitrogen to be used for cooling the superconductor, rather than a more costly cryogen such as liquid hydrogen.

High-Temperature Superconducting (HTS) FCLs, as its name suggests, this category uses superconducting-based material, which has the following properties:

- Zero resistivity below a critical temperature (T_C) and a critical current density (J_C).
- As soon as J_C and/or T_C are surpassed, the resistivity of the material increases rapidly.

As explained in [17], most HTS FCL concepts exploit this sharp transition of superconductors from zero resistance at normal currents to a finite resistance at higher current densities. Therefore, fault currents are limited instantly when the critical current is exceeded. Thanks to these characteristics, a superconducting FCL comes close to the "ideal" fault current limiter behavior of a self-triggered, failsafe device.

The continuous efforts to suppress the increase of the short-circuit current have resulted in the development of various types of superconducting fault current limiters (SFCL) in many countries [18].

2.1. Resistive type SFCL

A generic configuration of a resistive-type SFCL is provided in figure 1. The figure includes HTS elements (superconducting part) in a vacuum-insulated vessel filled with coolant (usually liquid nitrogen, LN_2), a pair of current leads (to connect HTS elements at cryogenic temperature to room-temperature bushings), and a cooling system. The HTS elements are inserted in series with the line being protected. During a fault, the critical current (I_C) is surpassed and their resistance increases rapidly, leading to quenching of HTS elements before the first peak of short-circuit current is reached. In 50 or 60 Hz AC systems, HTS elements quench within 1-2 ms after initiation of a fault, depending on the ratio of prospective fault current to normal current. Dimensions of the bushings and cryostat are substantial for achieving adequate voltage standoffs, particularly at the transmission voltage levels. [19] Prototype FCL concepts have been built and tested with varying degrees of success.

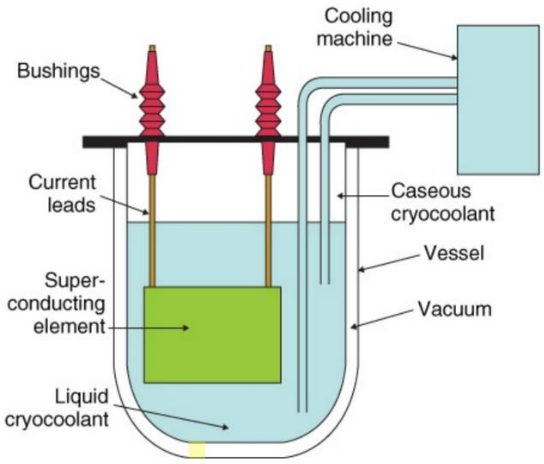

Figure 1: An arrangement of SFCL

Figure 2 shows a typical circuit for a resistive fault current limiter.

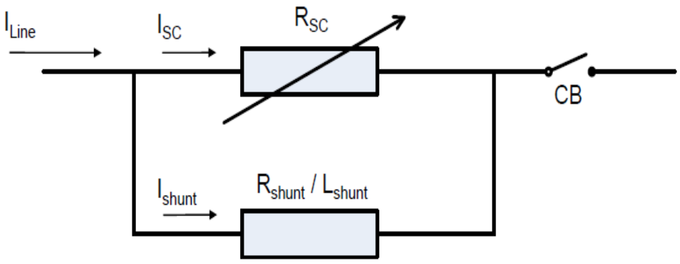

Figure 2: Resistive SFCL

Resistive SFCL works with the concept of zero resistance under normal operating conditions i.e. current is below a critical value I_C and temperature below a critical value T_C. Under fault conditions, when the current exceeds I_C, the resistance of superconductor significantly increases due to quenching and this S-N transitions then acts like a limiter switch [20]. This version of the SFCL utilizes a resistor in parallel with the superconducting material that protects the superconductor from hotspots that may develop during the quench, as well as avoiding over-voltages. Resistive SFCLs are considered fail safe and can be built to exhibit negligible impedance during normal system operation. A recovery time is however required following a quench, which can range from one second to one minute, depending on the superconducting material employed. One of the disadvantages is that there is energy loss in the current leads coming from room temperature to cryogenic temperature. According to [21], this will result in approximately 40-50 W/kA heat loss per current lead at cold temperature. This would equate to a maximum operating loss of approximately 80kW for a three phase SFCL operating in series with a 10MW generator connected at 11kV.

From the point of view of power systems, the resistive SFCL is preferable because it increases the decay speed of the fault current by reducing the time constant of the decay component of the fault currents, and can also make system less inductive [22].

2.2. Inductive type SFCL[23]

Inductive SFCLs come in many designs; the simplest design is a transformer with a closed superconducting ring as the secondary. In un-faulted operation, there is no resistance in the secondary and so the inductance of the device is low. The inductive limiter can be modeled as a transformer (Figure 3).

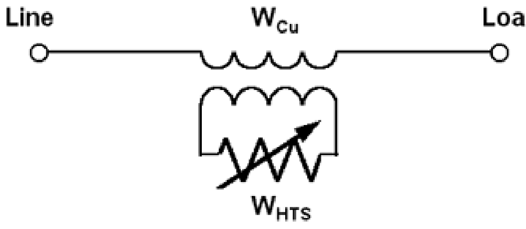

Figure 3: Inductive SFCL [24]

The impedance of this limiter in the steady state is nearly zero, since the zero impedance of the secondary (HTS) winding is reflected to the primary. In the event of a fault, the large current in the circuit induces a large current in the secondary winding causes loss of superconductivity. The resistance in the secondary is reflected into the primary circuit and limits the fault. The advantage of this design is that there is no heat ingress through current leads into the superconductor, and so the cryogenic power load may be lower. However, a large amount of iron is required and hence inductive SFCLs are much bigger and heavier than resistive SFCLs [23].

2.2.1. Inductive FCL with Shielded-Core

One of the first SFCL designs developed for grid deployment was the shielded-core design. Figure 4 shows the scheme of a shielded iron core SFCL, which is made up of a primary winding around an iron core with a superconducting cylinder in between. This SFCL is also called an inductive SFCL because its structure is similar to a transformer with a short circuit secondary winding. During normal operation, the current in the superconducting cylinder is lower than its critical current and it screens all the flux from the iron core. The impedance of the device, which consists of the resistance of the primary winding and the stray inductance, is very low. In the event of a fault, the current in the superconducting cylinder exceeds the critical current and the cylinder starts to develop a resistance. The magnetic flux penetrates into the iron core, so the inductance of the primary winding increases. The equivalent impedance of the device becomes the inductance of the primary winding and the referred cylinder resistance to the primary in parallel.

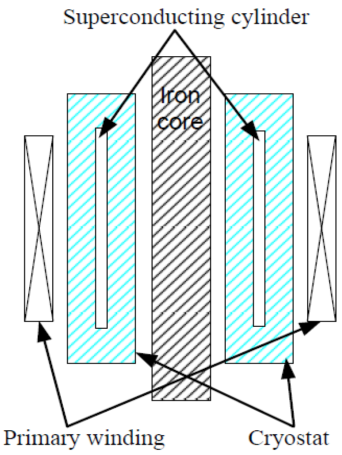

Figure 4: Shielded iron core SFCL [20]

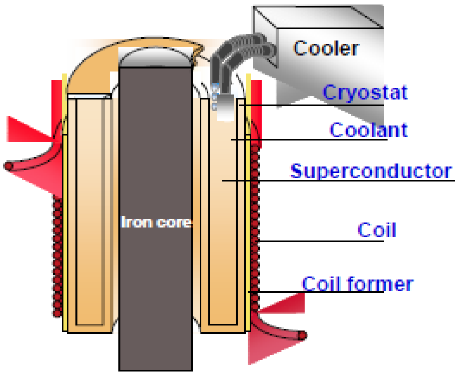

Figure 5: Shielded iron core superconducting fault current limiter. [25]

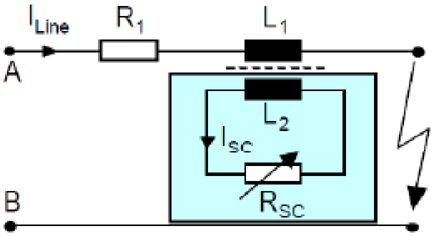

Figure 6: Shielded-Core SFCL Concept [20]

According to [17], shielded iron core FCLs have the following advantages: no current leads are needed, and since the number of turns of the secondary winding can be much smaller than the primary turns, only short superconductors are needed and the voltage drop in the cryogenic part of the device is very low. However, their main drawbacks are their relatively large volume and high weight.

2.2.2. Inductive FCL with Saturated Iron Core

Unlike resistive and shielded-core SFCLs, which rely on quenching of superconductors to achieve increased impedance, saturable core SFCLs utilize the dynamic behavior of the magnetic properties of iron to change the inductive reactance on the AC line [23].

The saturated iron - core concept utilizes two iron core per phase as shown in Figure 7. A conventional copper coil could be used to saturate the cores during normal operation. However, in order to reduce I 2 R losses in the copper coil and to make the device acceptable to the users, developers have opted to use a superconducting coil for saturating the core. The most attractive feature of this FCL is simplicity and a fail - safe mode of operation. Faults of long durations can be handled and recovery from a fault is instantaneous, enabling the device to handle multiple successive faults in rapid succession, such as auto - recloses on a protected line or circuit breakers with existing reclosing logic. Explained below is the principle of operation [26]**:**

- During normal operation, large ampere - turns created with DC in the secondary superconducting HTS coil drive the core into saturation. This lowers impedance of the copper coil in the primary AC side near to that of an air - core coil.
- During a fault, a large fault current demagnetizes the core and drives it from the saturated to unsaturated state (Linear B – H region). This increases the primary AC coil impedance. The increased impedance limits the fault current to the desired level.

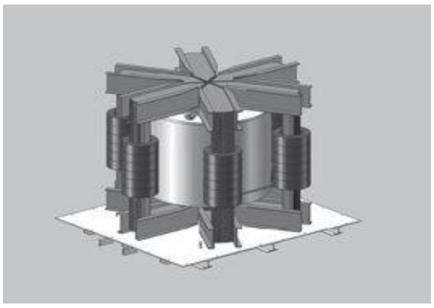

Figure 7: Inductive FCL concept with saturated iron core (Courtesy Zenergy Power)

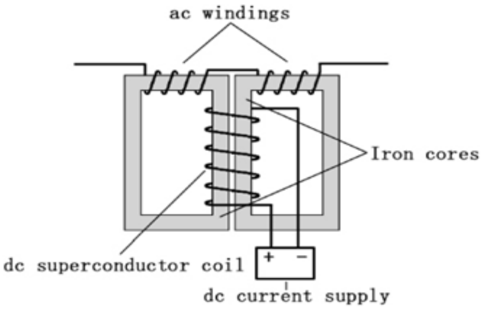

Figure 8: Saturable-Core superconducting fault-current limiter [27]

Since an AC wave has both positive and negative peaks to magnetize the iron core, it becomes necessary to employ two separate cores for each phase. Each core has a normal (copper) coil in series with the line being protected. One core works with the positive peak of the AC and the other with the negative peak. A three - phase arrangement of this concept is shown in Figure 7 , which has six primary copper coils (two for each phase) and a common secondary DC HTS coil for saturating all cores simultaneously. This device, installed in the Avanti Circuit of Southern California Edison in March 2009, became the first SFCL to operate in a US utility system. Abbott [28] has described operation of such a limiter.

A major drawback of saturable-core SFCL technology is the volume and weight associated with the heavy iron core; however, manufacturers hope to improve this issue in future prototypes. Zenergy has recently tested a prototype saturable-core SFCL based on an entirely new design concept that is four times smaller than its predecessor. GridON, an Israeli-based startup company, is in the process of developing saturable-core concept intent on reducing size and weight to more accommodating levels for commercial use [27].

2.3. DC biased iron core type SFCLs [23]

Noe and Steurer (2007) explained that these devices incorporate two iron-core coils that are driven into saturation by introducing a DC bias current under normal operating conditions. These two cores are placed in series path of the potential fault current. While these two cores are operating in saturation mode, their (and hence the SFCL) inductances are low. When a fault current flows, these coils will be driven out of saturation, resulting in an increase of the apparent coil inductance. [20], [25], [27].

This concept has the advantage of requiring relatively less superconductor material and a smaller cryogenic system to cool the device. The requirement for the iron cores does however make the device bulky when compared to other SFCL devices [20].

2.4. Magnetic assisted resistive type

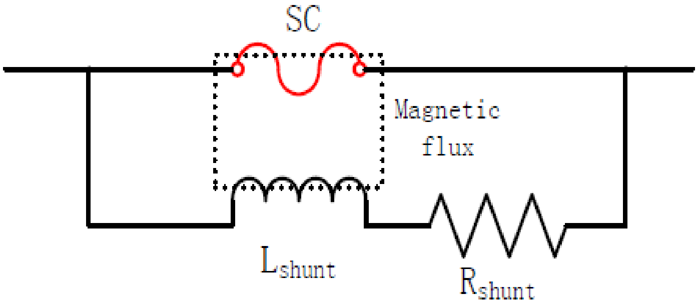

Figure 9: Schematic of magnetic assisted resistive type SCFCL

As implied by its name, the magnetic assisted resistive SCFCL works similar in principle to the resistive SCFCL described above. A copper coil is connected in parallel with the superconductor elements. Also, this shunt coil is physically wrapped around elements. During normal operation, the superconductor carries all the normal operation current and presents little impedance to the power network. Under fault, the resistance of the shunt coil has the same function as the shunt resistor in the resistive type SCFCL, bypassing the fault current and preventing hot-spots caused by inhomogeneous quenching of the superconductor. Other than this, a voltage drop caused by the initial quench is seen by the shunt copper coil, and builds up a magnetic field inside the coil. This magnetic field effectively accelerates the quenching process of the superconductor, since the superconductors' critical temperature reduces substantially when exposed to external magnetic fields (as shown in Figure 9) [20], [29].

2.5. The Active SFCL [30]

Active-type SFCL take full advantage of high-density superconductors unimpeded carrying capacity, combined with modern power electronics and control technology with fast response and flexible control features to achieve active current limiting, breaking the previous limitations of superconducting current limiter sex.

Figure 10 for the Institute of electrical current compensation proposed superconducting current limiter.

In the event of failure, the system rapidly increased the main current I_1, I_2 have increased accordingly, the outside I_P (I_P remains the same) part of the compensation will be transferred to the current limiting resistor R, equal to R immediately put into the fault current limiter. With modern power electronics and control technology continues to evolve, devices continue to lower prices and loss of control increasing accuracy and speed of response, and the real high-temperature superconducting materials, especially the second generation high temperature superconducting tapes continues to develop, there Source superconducting current limiter will have a good prospect.

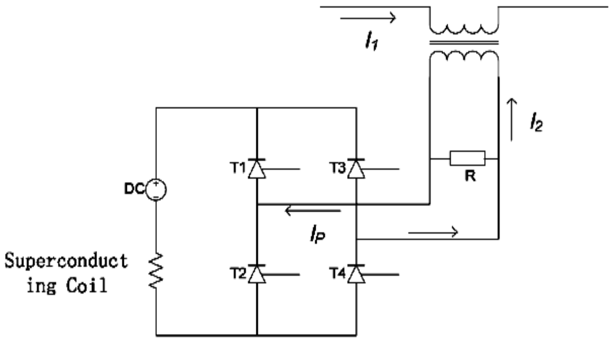

Figure 10: The structure of the active SFCL

2.6. The Bridge SFCL [30]

The concept of bridge-type SFCL by the LANL and the U.S. power company Westinghouse in 1983 made. The limiter works is not based on superconducting materials from the superconducting state to normal state transition, but to use a superconducting material in the DC state of unimpeded carrier characteristics. This SFCL employs solid state technology to control the flow of current through a superconducting inductance. Figure 11 for the bridge type SFCL single-phase circuit. It consists of diode bridge D1-D4, the superconducting coil L and the composition bias supply V_b, V_b for the superconducting coil to provide bias current I_L.

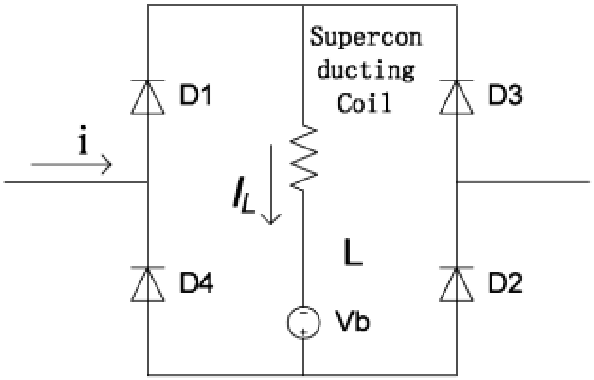

Figure11: The structure of Bridge SFCL

In a failed state, when i amplitude increased to I0 when i was a half weeks in the diodes D3 and D4 is not conducting, while the negative half weeks in the Dl and D2 is not conducting, superconducting coils in series on the line is automatically , fault current was limited by a large inductance L. However, during normal operation, the superconducting coil current amplitude by more than the DC circuit, so by the introduction of low loss current leads large. It also needs the power diode bridge and the bias power, the system is more complex [31].

The inductor does not have to be made of superconducting material, but superconducting material can be used to minimise the losses. In addition, during normal conditions, the inductor only carries DC current, which makes a superconductor an ideal choice. Thyristors can be used to replace the diodes, so it is possible for them to turn off the current at the next current zero-crossing after a fault occurs.

Advantages:

- No AC losses in the superconducting coil because it is operating with DC current.
- Fast recovery after the fault clears because the coil remains in the superconducting state during the fault.
- The trigger current level can be adjusted by the DC current source.

- Does not require a room temperature/cryogenic interface in the power line.

Disadvantages [32]:

- AC losses in the semiconductors are relatively high.
- No fail safe mechanism. If one of the semiconductors fails and creates a short circuit, the SFCL cannot limit the fault current.

2.6. The Three-Phase Circuit Reactance SFCL [30]

The Three-Phase Circuit Reactance SFCL consists of 3 same superconducting windings which is in a single core. The structure model is given in Fig 12. When 2-phase or 3-phase short-circuit fault occurs, the impedance of the device increases. When the short-circuit current reach to the critical value, the superconducting windings will quench, the short-circuit current will be limited by a large normal resistance.

The outstanding advantage of the Three-Phase Circuit Reactance SFCL is that it will not quench when a single-phase ground fault occurs. 90% of the power system fault is the single-phase ground fault so that the Three-Phase Circuit Reactance SFCL cannot limit major short-circuit current in the condition of non-quenching.

In addition, it is necessary to improve the normal resistance of high-temperature superconducting wire (with materials) to make it widely be used because the cost of cooling high-temperature superconducting material is much lower than the low-temperature superconducting material.

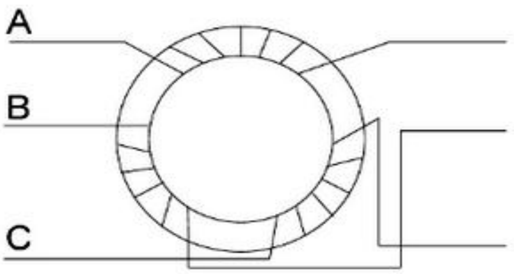

Figure 12: The structure of the Three-Phase circuit reactance SFCL

2.7. Flux-lock type SFCL

A flux-lock type SFCL consists of a flux-lock reactor with a superconducting coil L3 and a magnetic field coil. A schematic circuit of a flux-lock type SFCL is shown in Figure 13. During normal operation, the superconducting element is in the superconducting state, so the voltage across it is zero. The magnetic flux linkage through the iron core is constant in a DC mode and therefore the voltages across these three coils are zero, and the impedance of the SFCL is negligible. Once a fault occurs, the superconducting element loses its superconductivity and develops a resistance, which reduces the fault current. The magnetic flux then varies in the iron core and the induced voltage across the coils changes. The current flows in the magnetic field coil and the external magnetic field is applied to the superconducting element, which causes the resistance of the superconducting element to increase faster and relatively evenly along its length. [32]

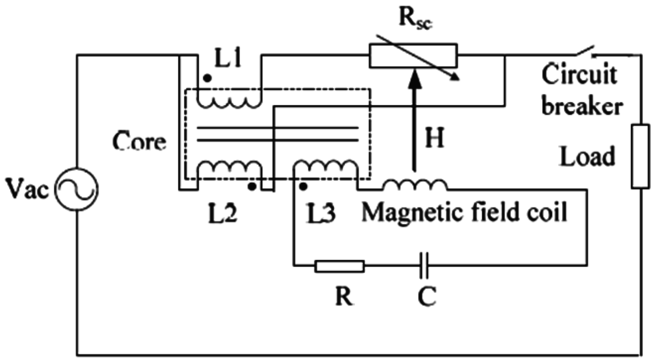

Figure 13: Flux-lock type SFCL

Advantages:

- During a fault condition, the magnetic field coil applies the magnetic field to the superconducting element to make it quench equally, which prevents hot spot problems in the superconducting element.
- The superconducting element is isolated from the power line.

Disadvantages:

- The device is very bulky and heavy due to the iron core.
- AC losses in the three windings.

- Long recovery time. Due to the heat dissipated and temperature rise of the superconductor, it may take several seconds to several minutes to recover.

A flux-lock type SFCL with two triggering current levels produces more effective current-limiting using a second superconducting element in case the initial transient component of the fault current is large [33].

2.8. Fault current controller SFCL [20]

A fault current controller SFCL consists of two anti-series connected thyristors, with each thyristor connected with a superconducting coil inductor in parallel, as shown in Figure 14.

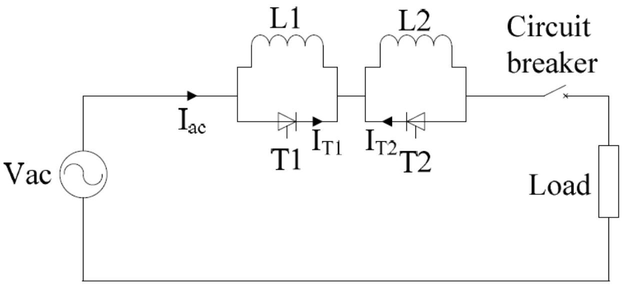

Figure 14: Fault current controller SFCL

The thyristors are triggered at their respective peak load current and then constant DC currents circulate through the parallel thyristors and inductors. The triggering signals are removed after the thyristors are turned on. During normal operation, the AC current is lower than the constant DC current, so that the thyristors are conducting and short-circuit the inductors. When a fault occurs, the AC current rises above the constant DC current. When the current is in the positive half-cycle, the current through thyristor *T2* will go across zero and then *T2* will turn off. Inductor *L2* is inserted into the circuit to reduce the fault current. Thyristor *T1* will subsequently turn off at the negative half cycle and insert inductor *L1* into the circuit [32].This FCC type has similar characteristics to the diode bridge type SFCL but requires less power electronics [23].

Advantage:

- Fast recovery after the fault clears because the coil remains in the superconducting state during the fault.

Disadvantages:

- AC losses in the semiconductors and superconducting coil.
- No fail safe mechanism. If one of the semiconductors fails and creates a short circuit, the SFCL cannot limit the fault current.

2.9. Matrix-Type Superconducting Fault Current Limiter

The matrix-type superconducting fault current limiter (MSFCL) consists of the trigger and current-limiting parts. The trigger part with reactors connected in parallel improves the quenching characteristics by applying the external magnetic field into the superconducting units. The current-limiting part with superconducting units connected in parallel and shunt reactors connected in series limit the fault current when the fault occurs [34].

Figure 15 shows a simplified equivalent circuit representation of the MFCL in a transmission system. Here the MFCL is represented by an HTS element shown as variable resistance in parallel with a reactor. Under normal operating conditions, the peak of the AC current level of the power transmission network is always below the critical current level of the superconductor, therefore there is essentially not voltage drop across the device and there are no I^2R losses. The device is "invisible" to the grid. When the fault occurs, the fault current level exceeds the critical current level of the superconductor, creating a quench condition. The superconductor is forced to transition to the high resistive state and most of the fault current is shunted into the parallel inductor to introduce the current limiting impedance Z_0 into the grid to limit the fault current [35].

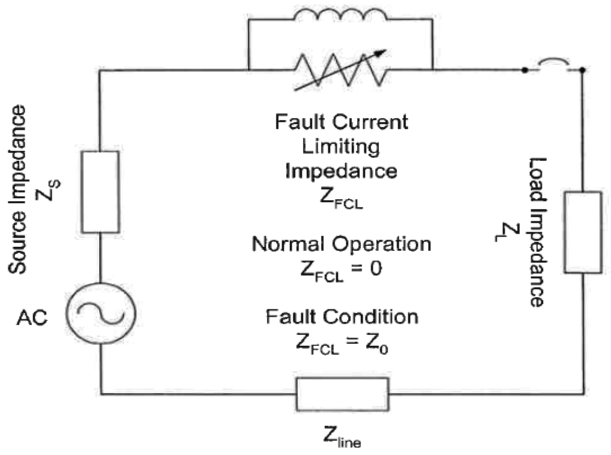

Figure 15: Electrical Equivalent of MFCL in a Power System

3. Fault-Current Limiter Applications [36]

Fault-current limiters can be applied in a number of distribution or transmission areas. Three main applications areas are shown in Figs. 16, 17, and 18.

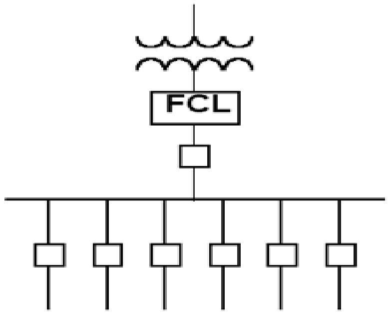

Figure 16: Fault-current limiter in the main position

The fault-current limiter FCL protects the entire bus.

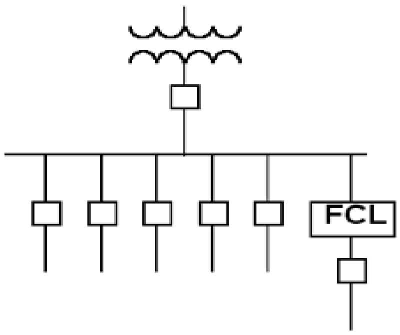

Figure 17: Fault-current limiter in the feeder position

The fault-current limiter FCL protects an individual circuit on the bus. Underrated equipment can be selectively protected as needed in this manner.

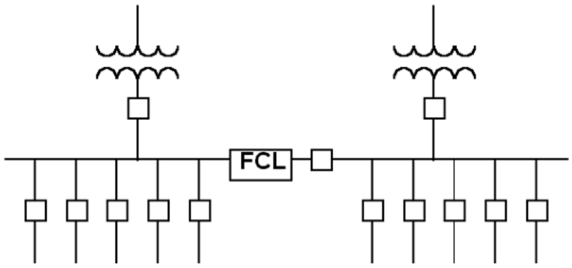

Figure 18: Fault-Current limiter in the bus-tie position

The two uses are tied, yet a faulted bus receives the full fault current of only one transformer.

The most direct application of a fault-current limiter is in the main position on a bus (Fig. 16). Benefits of an FCL in this application include the following:

- a larger transformer can be used to meet increased demand on a bus without breaker upgrades
- a large, low impedance transformer can be used to maintain voltage regulation at the new power level
- I^2t damage to the transformer is limited
- reduced fault-current flows in the high-voltage circuit that feeds the transformer, which minimizes the voltage dip on the upstream high-voltage bus during a fault on the medium-voltage bus

An FCL can also be used to protect individual loads on the bus (Fig. 17). The selective application of small and less expensive limiters can be used to protect old or overstressed equipment that is difficult to replace, such as underground cables or transformers in vaults.

An FCL can be used in the bus-tie position (Fig. 18). Such a limiter would require only a small load current rating but would deliver the following benefits:

- separate buses can be tied together without a large increase in the fault duty on either bus
- during a fault, a large voltage drop across the limiter maintains voltage level on the unfaulted bus
- the paralleled transformers result in low system impedance and good voltage regulation; tap-changing transformers can be avoided
- Excess capacity of each bus is available to both buses, thus making better use of the transformer rating.

Table 1: SFCLs' installation options and related advantages [21]

Installation options	Related Advantages of SFCL Installation
Fault current limiters in the incoming feeders	▪ The short-circuit current of the feeding sources (transformers and generator) will be reduced ▪ By parallel connection of transformers (two systems), one will get an even distribution of the feeding transformers ▪ Reduction of the network impedance ▪ Reduction of the required short-circuit capability of the system
Fault current limiter in the coupling	▪ No disconnection of the feeding transformers after tripping of the FCL. By parallel connection of transformers (two systems), one will get an even distribution of the feeding transformers ▪ Reduction of the network impedance ▪ Reduction of the required short-circuit capability of the system
Fault current limiters in the outgoing feeder	▪ Reduction of the network impedance ▪ Reduction of the required short-circuit capability of the subsystems ▪ By parallel connection of the transformer (two systems), one will get an even distribution of the feeding transformers ▪ In each outgoing feeder, an FCL is installed. By doing this, only the short-circuit current flowing to the faulty outgoing feeder will be reduced. The main bus must be designed to carry the total short-circuit current

The results of an inquiry carried out by the Working Group regarding the preferred locations for installing fault current limiters are shown in Figure 19. From this survey follows that the majority of fault current limiters will be installed in bus ties (52 %) and incoming feeders (33 %) [25].

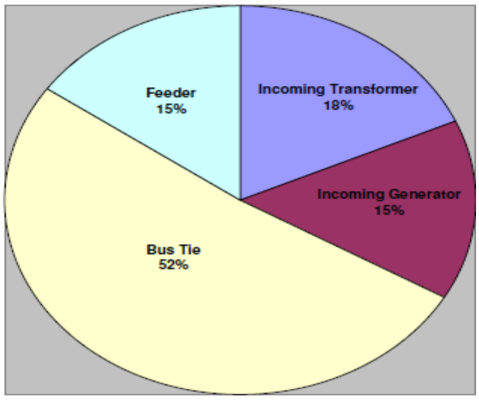

Figure 19: Preferred locations for installing fault current limiters

The optimal location of the SFCL in electric power grid is determined so as to improve transient stability and low-frequency oscillation damping performance of the system, when a severe damage is introduced (three-phase fault). The advantage of the proposed method in Ref. [37] is that the selected location of the SFCL takes into account the fact that the fault can occur anywhere in the studied grid.

4. Conclusion:

Utilities always look for ways to get more out of their existing equipment. The HTS FCLs present an option to rein in the fault current levels to within the capability of existing equipment. To help address these problems, with R & D funding from the US Department of Energy, equipment manufacturers, electric utilities, and researchers from private industry, universities, and national laboratories are teaming up to spur innovation and development of new technologies, tools, and techniques. Because of these efforts, the future electric grid will likely incorporate technologies very different from those that have been traditionally employed. The S FCL is one of these technologies, and the first units are already being deployed commercially. Manufacturers and users are already working on developing standards for FCLs under IEEE.

With the use of 2G HTS, SFCLs have to compete with the conventional breakers in cost, size, long operation feasibility and cryogenic reliability. The most compact SFCL at distribution voltage levels are viable in the near future. Some projects have already started recently to develop SFCL prototypes for transmission voltage levels. To commercialize SFCLs, it is essential to further improve their properties (e.g. superconductor AC loss) and reliable, compact and low-cost cryocoolers.

There are many possible locations in power systems where FCLs installation offers technical and economical benefits. The bus-tie position appears to be the most economical option among other alternatives.

REFERANCES:

1. T. Ackermann, G. Anderson, L. Söder, “Distributed generation: a definition,” Electric Power Systems Research, 57, 195–204 (2001).
2. Y. G. Hegazy, M. M. A. Salama, and A. Y. Chikhani, “Adequacy Assessment of Distributed Generation Systems using Monte Carlo Simulation,” IEEE Trans. Power Syst., vol. 18, no. 1, pp. 48–52, Feb. 2003.
3. Dugan R.C., McDermott T.E. and G.J. Ball,"Planning for Distributed Generation", IEEE Industrial Application Magazine, Vol. 7, pp. 80-88, 2001.
4. Hadi Zayandehroodi, Azah Mohamed, Hussain Shareef, and Marjan Mohammadjafari, "A Comprehensive review of protection coordination methods in power distribution systems in the presence of DG" *Electrical Review*.8, 142-148, 2011. Available at: http://works.bepress.com/hadi_zayandehroodi/11
5. S. M. Brahma and A. A. Girgis, “Microprocessor Based Reclosing to Coordinate Fuse and Recloser in a System with High Penetration of Distributed Generation,” in Proceedings of IEEE Power Engineering and Society, Winter Meeting, Vol. 1, pp. 453-458, 2002.
6. S. M. Brahma and A. A. Girgis, “Development of Adaptive Protection Scheme for Distribution Systems with high Penetration of Distributed Generation,” IEEE trans-action Power Delivery, Vol. 19, No. 1, pp. 56-63, 2004. DOI:10.1109/TPWRD.2003.820204
7. S. Chaitusaney and A. Yokoyama, “Impact of Protection Coordination on Sizes of Several Distributed Generation Sources,” 7th International Power Engineering Conference, Vol. 2, pp. 669-674, 2005.
8. Sung-Hun Lim, Jin-Seok Kim, Myong-Hyon Kim, Jae-Chul Kim, “Improvement of Protection Coordination of Protective Devices

through Application of a SFCL in a Power Distribution System with a Dispersed Generation", IEEE Transactions on Applied Superconductivity (Impact Factor: 1.32); 22(3):5601004-5601004, 06/2012. DOI: 10.1109/TASC.2011.2181930

9. Jae-Sang Hwang; Khan, U.A.; Woo-Ju Shin; Jae-Kyu Seong; Jong-Geon Lee; Yong-Han Kim; Bang-Wook Lee, "Validity Analysis on the Positioning of Superconducting Fault Current Limiter in Neighboring AC and DC Microgrid," Applied Superconductivity, IEEE Transactions on , vol.23, no.3, pp.5600204,5600204, June 2013 doi: 10.1109/TASC.2012.2228735
10. R Dommerque et al, "First Commercial Medium Voltage Superconducting Fault-Current Limiters: Production, Test And Installation", Superconductor Science and Technology, Volume 23, Number 3, 2010. doi:10.1088/0953-2048/23/3/034020
11. Gianluigi Migliavacca, "Advanced Technologies for Future Transmission Grids", Springer Science & Business Media, Electric Power Transmission, pp. 362, 04-Dec-2012
12. ABB, "The World's First Superconducting Device for Commercail Use by an Electrical Utility", November 21, 1996, http://www.abb.com
13. ABB, The World's Most Powerful Superconducting Fault Current Limiter, March 7, 2001, http://www.abb.com
14. S. Eckroad, "Survey of Fault Current Limiter (FCL) Technologies – Update". Technical Report, EPRI, 2008. (Cited on pages viii, 4, 26, 39, 41, 42, 58)
15. Joachim Bock, Achim Hobl, Simon Krämer, Markus Bludau, Judith Schramm, Christian Jänke, Mark Rikel, Steffen Elschner, "Nexans' Superconducting Fault Current Limiters for Medium Voltage Applications – Status and Prospects**"**, CIRED 21st International Conference on Electricity Distribution Frankfurt, Paper 0352, 6-9 June 2011.
16. K.E. Gray and D.E. Fowler, "A Superconducting Fault-Current Limiter", Journal of Applied Physics, 49(4):2546{2550, April 1978. doi:10.1063/1.325061.
17. BERR, Department for Business Enterprise and Regulatory Reform: Application of Fault Current Limiters contract no.: DG/DTI/00077/06/REP, 2007.
18. Sung-Hun Lim, "Fault Current Waveform Analysis of a Flux-Lock Type SFCL According to LC Resonance Condition of Third Winding", Journal of Electrical Engineering & Technology, Vol. 3, No. 2, pp. 213~217, 2008
19. Swarn Singh Kalsi, "Fault Current Limiters", in Applied Superconductivity: Handbook on Devices and Applications, Paul Siedel(Ed), Wiley VCH, pp. 632, 2005.
20. Mathias Noe and Michael Steurer, "High-Temperature Superconductor Fault Current Limiters: Concepts, Applications, and Development Status" Supercond. Sci. Technol. Vol. 20, R15, 2007
21. AREVA T&D Research & Technology Center; Buker HTS GmbH: "Inductive and Resistive HTS Fault Current Limiters: Prototyping, Testing, Comparing", 13 May 2009. [Online]. Available: https://www.tu-braunschweig.de/Medien-DB/iot/6-inductive-and-resistive-hts-fault-current-limiter-prototyping-testing-comparing-a-usoskin-f-mumford.pdf [Accessed: April 25, 2015].
22. P. G. Slade, et al, "The Utility Requirements for A Distribution Fault Current Limiters", IEEE Transactions on Power Delivery, Vol. 7, No. 2, 507-515, April 1992. DOI: 10.1109/61.127043
23. V.V. Rao and Soumen Kar, "Superconducting Fault Current Limiters - A Review", Indian Journal of Cryogenics, Vol. 36, No. 1-4, pp.14-25, 2011.
24. Tutorial of American Superconductor Corporation (Brockenborough 1996), "FAULT-CURRENT LIMITERS (FCL)", WTEC Hyper-Librarian, Chapter 4, September 1997.
25. CIGRE WG A3.10, "Fault Current Limiters in Electrical Medium and High Voltage

Systems", CIGRE Technical Broacher 239, December 2003.

26. Swarn S. Kalsi. (8 April 2011). Applications of High Temperature Superconductors to Electric Power Equipment, A JOHN WILEY & SONS, Inc., Hoboken, New Jersey.
27. S. Eckroad, "Survey of Fault Current Limiter (FCL) Technologies," Electric Power Research Institute (EPRI), 1017793, 2009.
28. S. B. Abbott , D. A. Robinson , S. Perera , F. A. Darmann , C. J. Hawley , and T. P. Beales , " Simulation of HTS Saturable Core - Type FCLs for MV Distribution Systems , " IEEE Trans. Power Delivery 21 (2): 1013 , 2006
29. S. Elschner, F. Breuer, H. Walter, and J. Bock, "Magnetic Field Assisted Quench Propagation as a New Concept for Resistive Current Limiting Devices," in 7th European Conference on Applied Superconductivity, Vienna, Austria, 2006.
30. Linmang Wang, Pengzan Jiang, Dada Wan. (2012) Summary of Superconducting Fault Current Limiter Technology in Sabo Sambath ana EguiZhu. Frontiers in computer education, (eds.). Published: Berlin; New York: Springer, cop., Pp.819, 2012.
31. Zhang. Z., "The Research of Bridge Type High Temperature Superconductivity Current Limiter," Chinese Academy of Science Postdoctoral Work Report, 2006.
32. Xiaoze Pei, "Superconducting Fault Current Limiter with Integrated Vacuum Interrupter," PhD Thesis, University of Manchester, United Kingdom, 2012.
33. S. H. Lim, "Analysis on Current Limiting Characteristics of a Flux-lock Type SFCL with Two Triggering Current Levels," Physica C: Superconductivity, vol. 471, pp. 1354-1357, 2011.
34. Dependence of External Magnetic Field in the Matrix-Type SFCL with the Separated or the Integrated Reactors - ResearchGate. Available:http://www.researchgate.net/publication/264036066_Dependence_of_External_Magnetic_Field_in_the_Matrix-Type_SFCL_with_the_Separated_or_the_Integrated_Reactors [accessed Mar 25, 2015].
35. Kovalsky, L.; Xing Yuan; Tekletsadik, K.; Keri, A.; Bock, J.; Breuer, F., "Applications of superconducting fault current limiters in electric power transmission systems," Applied Superconductivity, IEEE Transactions on , vol.15, no.2, pp.2130,2133, June 2005. doi: 10.1109/TASC.2005.849471
36. WTEC Hyper-Librarian, (September 1997). FAULT-CURRENT LIMITERS (FCL), http://www.wtec.org/loyola/scpa/04_03.htm#foot1, [accessed Mar 3, 2015].
37. Didier, G.; Leveque, J.; Rezzoug, A., "A Novel Approach to Determine the Optimal Location of SFCL in Electric Power Grid to Improve Power System stability," Power Systems, IEEE Transactions on, vol.28, no.2, pp.978, 984, May 2013 doi: 10.1109/TPWRS.2012.2224386