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Review on Superconducting Fault Current Limiter

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***Abstract*- In this paper, different current limiting techniques are explained which are used to suppress the excess magnitude of fault current during fault. A various types of fault Current limiters (FCL) are used to suppress fault current and hence saving in the investment of high capacity circuit breakers. It uses variety of new techniques for limiting excess fault current. The focus is on superconducting technologies i.e. Superconducting Fault Current Limiters (SFCL). The various types of superconducting fault current limiters are explained with their advantages, disadvantages and applications. This paper reviews, various concepts related to superconducting fault current limiters and present research and developments in SFCL. At present, SFCLs are not commercially available in electrical power market but, present research and some successful field trials shows that it will be available for commercial applications soon.**

***Keywords*- Fault current Limiter, Transition, Superconducting Fault current Limiter.**

I. INTRODUCTION

Now adays there is dramatic growth in power system and interconnected networks. This growth is expected to continue in future. When there is occurrence of an accidental events like lightning or downed power lines, a large amount of power flows through the grid which results in a failure of the electric system. These faults can generate surge currents more than one hundred times the normal operating current, hence damage the expensive grid-connected equipments. Therefore protection of the system is an important consideration to avoid harm to the system parameters and system equipments from large amount of current during fault [1] [3]. A Fault Current Limiter (FCL) is a device which limits the short circuit current during fault in a power transmission network. Fault current limiters (FCL) provides an effective way to suppress fault current and result in considerable saving in the investment of high capacity circuit breakers. A various types of fault current limiters uses variety of new techniques for limiting excess fault current [4]. However focus is on superconducting technologies i.e. Superconducting Fault current Limiters (SFCL). Whereas non-superconducting technologies contain devices like simple inductors or variable resistors are also known as Fault Current Controllers. Due to the rapid growth in the power generation systems there is a growth in fault current level, which may cross the rated capacity of available circuit breaker. Replacement of this existing switchgears due to increased fault level will not be the feasible option by considering cost parameter. By considering all these parameters it is necessary to use some reliable means to minimize fault current level and hence allow the circuit breaker to operate at lower fault Currents. Superconducting Fault current Limiters provides an effective way to suppress fault current [3], [6]. current limiting behavior of these superconductors depends on their non-linear characteristics with Temperature, current and magnetic field variations. If there is Increase in any one of these three parameters can cause transition of superconducting state to normal state. As per the development of superconducting materials SFCLs are of three types [3],

- Low Temperature SFCL
- High Temperature SFCL
- Superconducting Film Type SFCL

Recently there is a significant progress in Research and Development of SFCL [3]. This paper reviews different SFCL concepts, classification and their performance comparison. Also, it highlights the technological R & D status of SFCL.

II. CONVENTIONAL METHODS TO LIMIT FAULT CURRENT

Growth in power system and interconnected network causes increase in level of fault current. This increased fault current results in adverse effect on power system equipments. Such as,

- Increase in dynamic influence of current
- Increase in thermal influence
- Capability of circuit breaker to interrupt current may exceed [3].

Therefore it is necessary to minimize this level of fault current. Power system operators can use different techniques to minimize fault current level.

III. TECHNOLOGIES

A. Non-Superconducting:- Fault Current Limiters that do not depend on Superconducting materials to perform the current limiting action. It contains current limiting fuses, solid-state devices & many other[3].

B. Superconducting:- Fault current Limiters that depend on Superconducting material to perform the current limiting action. More specifically, the current limiting behavior depends on the non-linear characteristics of superconductors with temperature, current and magnetic field variations. If we increase any one of these parameters can cause transition from superconducting to normal state[3]

IV. CLASSIFICATION AND COMPARISION

4.1 Classification

4.1.1 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, LN2), 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 (IC) 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 [5].

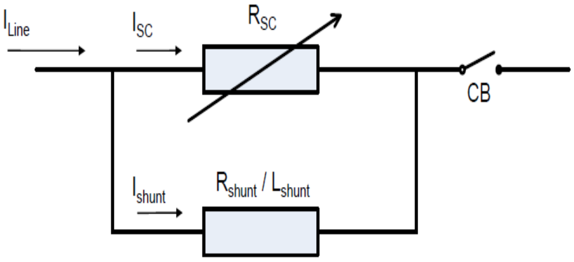

Figure 1: Resistive SFCL

Prototype FCL concepts have been built and tested with varying degrees of success. Resistive SFCL works with the concept of zero resistance under normal operating conditions i.e. current is below a critical value IC and temperature below a critical value TC. Under fault conditions, when the current exceeds IC, the resistance of superconductor significantly increases due to quenching and this S-N transitions then acts like a limiter switch [6]. 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 [7], 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 [8]. Advantages: Smaller and lighter than inductive SFCL. Disadvantages: Energy Loss

4.1.2 Inductive type SFCL [9]

Inductive SFCLs come in many designs; the simplest design is a transformer with a closed superconducting ring as the secondary. In unfaulted 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 2).

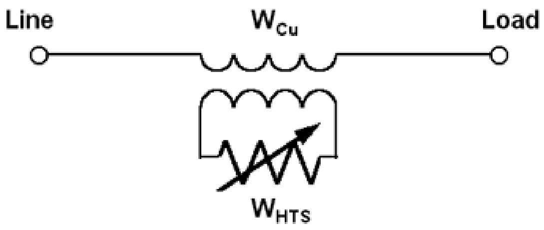

Figure 2: Inductive type SFCL

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 cause's 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 [9].

4.1.3 Inductive FCL with Shielded-Core

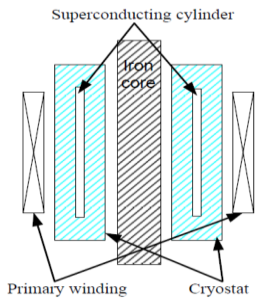

Figure 3: Shielded iron core SFCL [6]

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

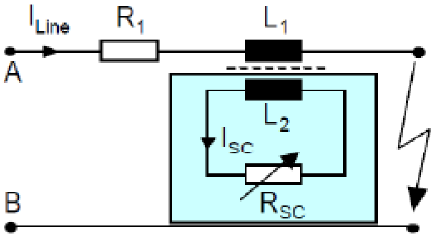

Figure 4: Shielded-Core SFCL Concept [6]

According to [10], 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.

4.1.4 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 [9]. The saturated iron - core concept utilizes two iron cores per phase as shown in Figure 5. 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 [11]. 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).

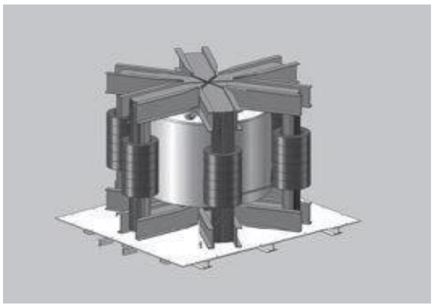

Figure 5: Inductive FCL concept with saturated iron core (Courtesy Energy Power)

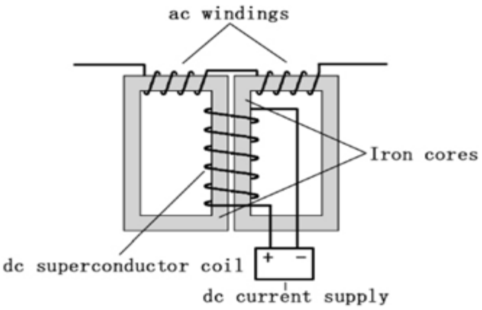

Figure 6: Saturable-Core superconducting fault current limiter [12]

This increases the primary AC coil impedance. The increased impedance limits the fault current to the desired level. 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 5 , 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 [13] 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. Grid ON, 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 [12]. Advantages: No heat ingress. Disadvantage: Large amount of iron is required, bigger in size hence heavier.

4.1.5 DC biased iron core type SFCL

In this type of construction contains two iron-core coils, which goes into saturation when DC-biased current is introduced under normal condition. These two cores are placed in series path of fault. When these two cores are operating in saturation mode there inductances are low. When there is occurrence of fault these coils come out of saturation and the coil inductance increases rapidly [18]. Advantages: Requires less superconductor material, small cryognic cooling system required. Disadvantages: Bulky due to use of iron core.

4.1.6 Resistive Magnetic type SFCL

This type of SFCL works on a principle of parallel inductance. While making setup for this type of SFCL, normal conducting coil is placed outside a superconducting tube [18].

4.1.7 The Bridge SFCL [15]

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 7 for the bridge type SFCL single-phase circuit. It consists of diode bridge D1-D4, the superconducting coil L and the composition bias supply Vb, Vb for the superconducting coil to provide bias current IL. 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.

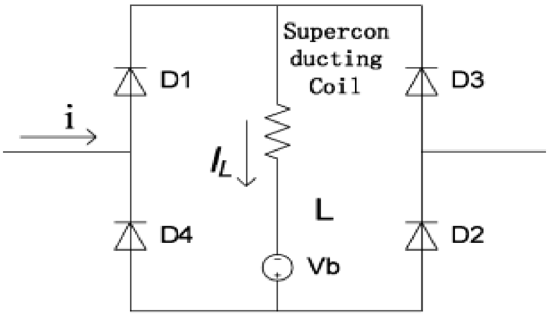

Figure 7: The structure of Bridge SFCL

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 [16]. The inductor does not have to be made of superconducting material, but superconducting material can be used to minimize 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 [17]: 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.

4.1.8 Magnetic fault current limiter (MFCL)

It uses laminated iron-core with demagnetized magnet in air gap. At normal condition reactance is low. During fault, due to the high magnitude of fault current, magnet gets magnetized and reactance of MFCL increases [19].

4.1.9 Fault current controller type SFCL [19]

Some power electronic components have ability to interrupt the current. By using this property and ability to adjust trigger level, fault current can be controlled completely. Therefore these SFCLs offer adjustable trigger current and complete fault current interruption, hence named fault current controller.

4.1.10 Interphase power controllers (IPC)

It contains two parallel phase shifting transformer and series combination of reactors and capacitors are connected in each parallel branch [18]. Disadvantages: High capital investment required.

4.2 FCL Comparison criteria given as:

1. Normal Operation
2. Operation During the fault limiting action
3. Recovery period.

4.3 Criteria of SFCL Performance comparison

1. Quench Recovery: Quench recovery is depends upon, Superconducting material, heat emission condition, refrigeration capability.
2. Working Current: It is the value of critical line current which causes SFCL to transit from zero impedance to high impedance state.
3. Equivalent Fundamental Frequency impedance: It is the ratio of fundamental frequency component through it. Denoted by Zeq.
4. Response time: This is one of the important parameter to be considered while checking its

performance. Shorter response time is better. Response time is equal to quench time

5. Losses: The electrical losses due to AC currents.
6. Steady-State Impedance: The impedance under normal operating conditions.
7. Triggering: It is the method of initiation of fault response. Active FCLs uses sensors and control schemes to trigger whereas Passive FCLs respond to faults through changes in material properties associated with increased current or magnetic field
8. Recovery: It is the time required for FCL to come to its original state after limiting action.
9. Size/Weight: It should be compact.
10. Distortion: Related with the uneven shape of the AC current waveform [3].

V 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.

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