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Superconducting Fault Current Limiters: Enhancing Power Grid Reliability and Protection

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Abstract: ***With the increasing complexity of modern power systems, managing fault currents has become a critical aspect of power grid protection. This study explores Fault Current Limiters (FCLs), with a primary focus on Superconducting Fault Current Limiters (SFCLs). It evaluates the working principles, classification, and operational advantages of SFCLs in mitigating electrical faults. Additionally, the study discusses the practical challenges in implementing these technologies and highlights real - world applications. Findings suggest that SFCLs significantly enhance power grid reliability while addressing limitations related to cost, material complexity, and integration. This study aims to investigate the role of Superconducting Fault Current Limiters (SFCLs) in enhancing power grid reliability, reducing electrical fault risks, and improving system efficiency. The article aligns well with the scope of the International Journal of Science and Research (IJSR), as it delves into electrical engineering, fault current limiters, and power system reliability. The subject is relevant for researchers and professionals in electrical and power systems engineering.***

Keywords: Superconducting Fault Current Limiter, Power Grid Protection, Electrical Fault Mitigation, Smart Grid Technologies, Resistive and Inductive SFCL

1. Introduction

This research is significant as it explores how SFCLs can improve grid resilience, reduce electrical failures, and enhance power system stability. By analyzing real - world applications, it provides valuable insights for engineers and policymakers in power system management. There is a sudden increment in using power in this cutting - edge electrical system as energy is the main parameter in the ecosystem. [3] The complexity of the power system is directly proportional to the high magnitude of fault currents. There would be an increase in the current due to interconnectivity of the power system, and the network has become a major threat to smooth operations.

This paper seeks to augment the current understanding within the section of power system protection by extensively investigating fault current limiters, particularly Superconducting Fault Current Limiters (SFCLs). Among these methods, R - SFCL is considered to have good prospects, which can respond rapidly and automatically, leading to minimizing the value of current [11]. Through a thorough examination of the operational principles and structures of these devices, the research aims to elucidate their practicality, constraints, and capacity to improve the dependability and robustness of contemporary power grids. Several SFCLs have already been put into operation in grids. A prominent recent example is the SuperOx 220 kV/460 MVA 3 - phase device installed in Moscow, Russia, in 2019 [12].

During the Transition process, when in normal condition, the FCL must have its impedance as low as possible. In this stage, its energy dissipation has to be negligible. During faults, it introduces high impedance to limit current, preventing circuit failures, limiting the current magnitude. [1]

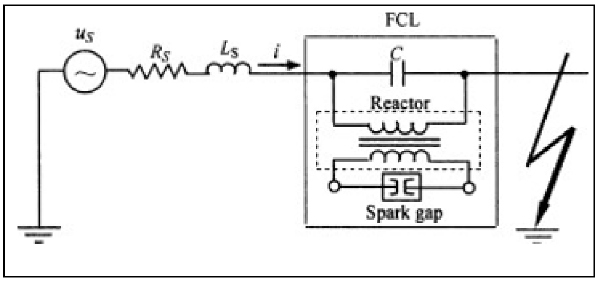


Figure 1: Inductive - SFCL

As per the above diagram, the capacitor is connected parallel to the reactor and the secondary winding of the reactor is attached with the spark gap to control inductive reactance. [3]

FCL are of 2 types: -
- Superconducting FCL
- Non- Superconducting FCL

Superconducting FCL	Non - Superconducting FCL
Resistive Type SFCL Inductive Type SFCL	Current Limiting Reactor Solid State FCL Hybrid FCL

Paper is structured as follows: Section II provides the information regarding Superconducting fault current limiters, Section III delves into brief introduction of Working principle of SFCLs, Section IV focuses on the classification of FCL, Section V discusses challenges of SFCL, Section VI. tells about case study, Finally, research concludes with a summary and possible solution in Section VII.

Superconducting Fault Current Limiter
This is an advanced fault current limiter technology that uses

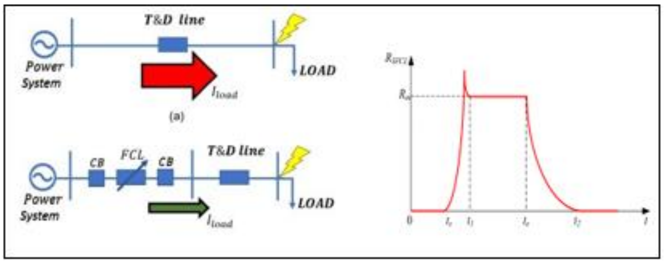
superconducting materials to limit and control excessive currents during faults.

It works on the process of transition between superconducting and resistive state or inductive state in superconductors. In normal conditions superconductors carry current with null electrical resistance. However, during fault condition it undergoes a transition state which introduces impedance and limits high magnitude of fault current.

Mainly, SFCL's are used in the power grid where limiting fault current is essential. They are used in substation and transmission networks to enhance the protection of the overall system. Generally, SFCL's manufactured from LTS superconductor materials such as NbTi consist of high magnitude of current carrying capacity. However, it contains a drawback which is cooling cost. To overcome this issue HTS FCL is developed [3]. As compared to LTS, HTS is more suitable because,

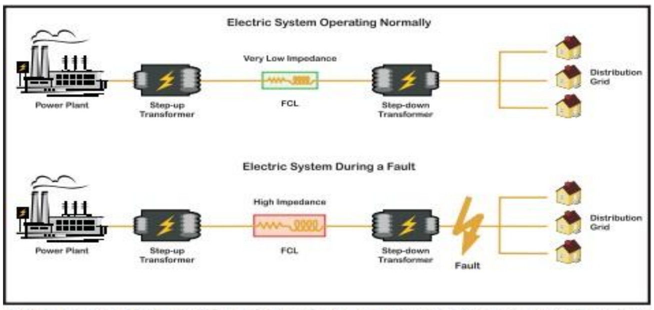
- Needs less cooling cost
- Thermal Stability

It consists of fluctuating impedance due to changes with operating conditions. SFCLs allow current to flow with minimal impedance under normal conditions but introduce high impedance during faults, effectively limiting current. Inserted impedance limits the flow of high current within the circuit [8]. Moreover, resistance decreases whenever the cycle repeats again. Generally, we are considering the cycle of 25 ms. [9]



Working Principle of Superconducting Fault Current Limiters

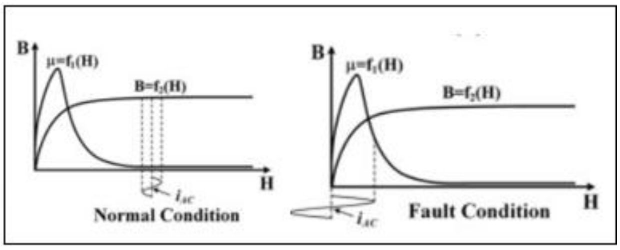
The Saturated Iron - Core Superconducting Fault Current Limiter (SISCL), a common example of an Iron - based Superconducting Fault Current Limiter (I - SFCL), is utilized in actual power grid projects to demonstrate its operational principle. Comprising three primary components - iron cores, alternating current (AC) coils, and lossless direct current (DC) superconducting coils along with a magnetization circuit as depicted in below diagram [4]. The AC coils are connected in series with the power transmission line, while the superconducting DC coils are designed to provide DC supply without any power loss.



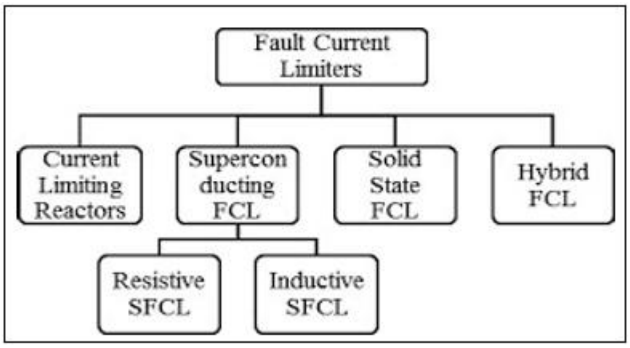
During a ground fault, an FCL safely mitigates the excess energy that would normally effect utility transmission and distribution equipment, preventing damage.

https: //www.energy. gov/oe/articles/fault - current - limiters - fcl - fact - sheet

Under normal operating conditions, the DC power supply energizes the superconducting DC coils, creating a biased magnetic field that deeply saturates the iron cores. The AC magnetic field produced by the normal AC current in the AC coils is inadequate to desaturate these cores, leading to minimal flux variation within them [5]. If a fault occurs, a fast switch cuts off the DC circuit, preventing overvoltage. This allows the fault current in the AC coils to desaturate the iron cores, greatly increasing their magnetic permeability. As a result, the AC coils quickly raise the circuit's inductive impedance.

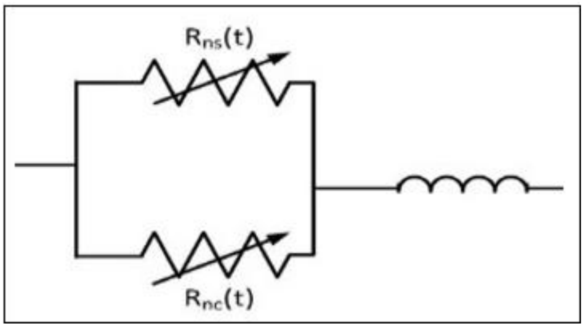


Classification of FCL



Superconductors can be LTS and HTS. Due to their high cooling costs, Low Temperature Superconducting (LTS) materials are not widely commercialized for Fault Current Limiters (FCLs). Instead, High Temperature Superconducting (HTS) materials are more commonly used in Resistive Superconducting Fault Current Limiters (RSFCLs), which are connected in series with the electrical circuit. HTS – based RSFCLs are advantageous because they can self - detect faults, automatically recover, and respond quickly. [6]

Resistive Type SFCL - Resistive type SFCL can improve the transient stability of the power system by suppressing the level of fault currents in a quick and efficient manner. This setup is characterized by 'n' number of units, each comprising both stabilizing and superconducting resistors, aligned in a parallel configuration. The purpose of these resistors is to provide stability and superconducting properties necessary for the SFCL's operation. Alongside these parallel resistors, there's an inductive component, also divided into 'n' units, that is connected in series with the resistive branch. This series connection of the coil inductance with the parallel resistive components forms the fundamental structure of the resistive SFCL, contributing to its ability to limit fault currents effectively in power systems. Up to now, the highest voltage level of R - SFCL in an AC system is 220 kV with more than 40 Ω resistance in fault [11].



In the normal steady state condition, the values of stabilizing (Rns) and superconducting (Rnc) resistances are zero. However, during fault conditions, these resistances become non zero time - varying parameters to maintain superconducting states. (Method, 2019) (Zampa et al., 2022)

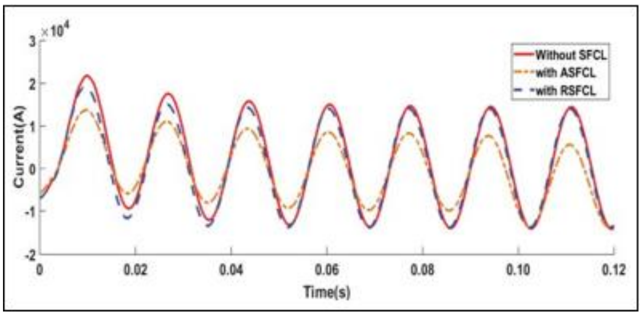
The main disadvantage of the resistive type SFCL is it releases heat in the quench as well as it needs long length to make a high voltage system.

Simulation

$$R_{sfcl} = \begin{cases} 0 & t < t_0, \\ R_M[1 - e^{(\frac{-t+t_{0(quench)}}{T_{sc}})^{1/2}}] & t_0 \le t < t_1 \\ \alpha(t - t_1) + \beta_1 & t_1 \le t < t_2 \\ \alpha(t - t_2) & t > t_2, \end{cases}$$

RM - maximum resistance of SFCL in quenching state
T sc - time constant of SFCL during transition to normal state from superconducting state.
t0 - quenching start time.
t1 - first recovery time. t2 - second recovery time

As per the above mentioned equations, it calculates the resistance of start to end recovery time in a quenching state. The modeling has been done by considering four fundamental parameters of a RSFCL [6] .

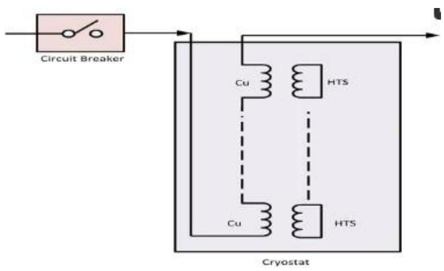


The graphical representation shows the fluctuation of the current with SFCL as well as without SFCL.

Without using any limiter, it contains a high amount of current. However, on the other side, RFCL contains low values because it controls the high fault current [8] .

S. No.	Parameters	Values
1	Transition/ Response Time	2 msecs
2	Minimum Impedance	0.01
3	Maximum Impedance	20A
4	Triggering Current	1000A

Inductive Type SFCL - It follows the concept of transformer with resistive FCL because it consists of 2 windings, primary winding is made up of Cu whereas secondary winding is made up of HTS. It connects with the circuit breaker which works on the mechanism of switching to prevent the circuit from failure. For the cryogenic cooling, it uses liquid nitrogen.



In the given circuit, circuit breakers follow the mechanism of switching, whenever current increases it results in trippin which makes the connected network into short - circuit, Due to that it prevents the flow of high amount of fault currents. Both the transformers are covered with cryostat. In the secondary it uses HTS material [5] [6].

During the operational transition process, the steady state mode of the power system, nearly zero impedance is shown by inductive SFCL as the zero impedance of the secondary superconducting winding is reflected to the primary. However, during faults, it introduces the impedance in secondary winding which reflects in primary to limit high magnitude of currents.

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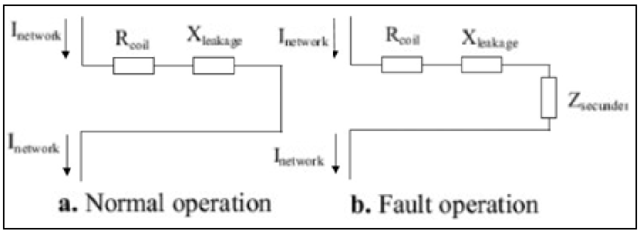
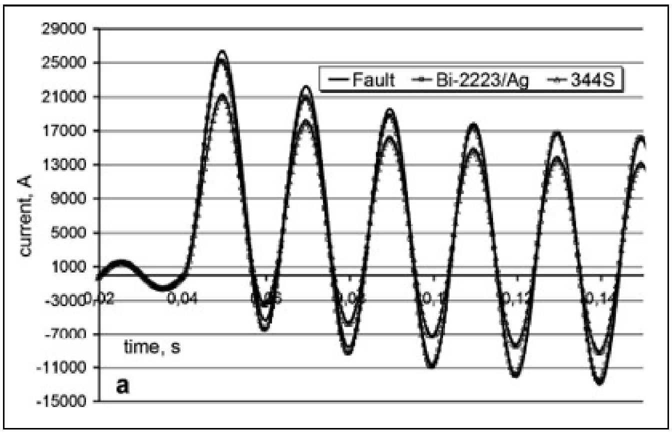


Simulation-



Critical current of the HTS tap is 60A at a temperature of 77K [8]. Above equations, calculates the value of resistance as well cross sectional area of it. The work parameters of inductive type SFCL have the resistivity of HTS tape during the resistive state. The greater resistance of secondary superconducting winding is the larger limitation of current rush and alternating current component's amplitudes.2nd generation HTS tapes.

Lastly, Resistive Superconducting Fault Current Limiters (RSFCLs) have a simpler and more efficient design compared to Inductive Superconducting Fault Current Limiters (ISFCLs), offering faster response times during faults. They exhibit lower energy losses in normal operation and are easier to integrate into existing power systems.

- It requires maintenance which includes monitoring of the elements for optimal performance.
- It depends on superconducting materials that exhibit at minimal temperature. Maintaining it while monitoring the stability would be a major task.
- It needs to handle large amounts of energy associated with fault currents without damaging electrical equipment. Integrating energy capacity with a power system is a complex task.
- It faces the challenge of transition process from resistive to non - resistive states due to the fact that it adversely affects the overall performance of the electrical system.
- Following the rules and regulations are essential for ensuring the safe and stable operation.
- Some of FCL may pose environmental impact, because that material contains certain implications related to the environment and cooling system requires an energy intensive process.

Case Study [KEPCO]

The research prioritizes identifying SFCL technology that meets specific criteria, aiming to enhance a 154 kV voltage transmission line. Moreover, launched in 2011, the project utilizes resistive SFCLs equipped with second - generation YBCO superconducting tapes. These tapes are chosen for their advanced high - temperature superconducting capabilities. These SFCLs are designed to operate at a temperature of 71 Kelvin (around - 202.15°C) and under a pressure of 5 bar, conditions necessary for maintaining the superconducting state. [10] The grid setup is bifurcated into two segments. The first includes High - Temperature Superconducting materials and a circuit breaker, arranged in series, crucial for the SFCL's operation. The second segment integrates a Current Limiting Reactor in parallel with the HTS, offering additional fault current management. The project deals with a transmission line spanning 8.1 kilometers, demonstrating the SFCL's efficiency over a significant distance, vital for broader grid application. [10]

2. Challenges of Fault Current Limiters

- The initial cost of implementation of FCL technologies, specifically advanced techniques, would be high. This factor may cause certain limitations to it.
- A few advancements such as SFCL's consist of complex material as well as operation. Furthermore, integrating it with the power system would be a big challenge.
- Need to respond quickly to limit the fault current. Achieving fast response without losing stability is a technical challenge.

This comprehensive study illustrates the practical application of SFCL technology in a real - world setting, highlighting the potential of SFCLs to enhance the reliability and efficiency of power transmission systems. The specific use of resistive - type SFCLs and 2G YBCO tapes in a well - structured electrical network underscores the technological advancements in the field of superconducting materials and their applicability in modern power grids.

Case Study II [REBCO]

This study focused on integrating stabilizers into a high - performance Superconducting Fault Current Limiter (SFCL) utilizing Rare Earth Barium Copper Oxide (REBCO) conductors [13]. Stabilizers were carefully chosen based on thermal conductivity and cryogenic compatibility. The evaluation involved simulations and practical experiments, demonstrating the superior performance of the REBCO - based SFCL with stabilizers in terms of enhanced stability and reliability during fault events. Comparative analyses against traditional SFCL designs highlighted the advantages of incorporating stabilizers. Additionally, a cost - benefit analysis underscored the economic feasibility of this approach. In conclusion, the study emphasized the valuable role of stabilizers in ensuring the robustness and effectiveness of REBCO - based SFCLs in demanding high -

performance scenarios.

3. Conclusion

To conclude, Superconducting Fault Current Limiters (SFCLs) outperform traditional Fault Current Limiters (FCLs) in quickly stopping electrical faults, preventing damage to equipment. SFCLs operate continuously, are compact, and can be tailored to specific grid needs, making them cost - effective. They require less maintenance, are energy - efficient, and contribute to a greener environment by reducing equipment damage. Despite initial challenges, SFCLs show great promise for improving the reliability and safety of power systems. Furthermore, Resistive Superconducting Fault Current Limiters (RSFCLs) are generally favored over Inductive Superconducting Fault Current Limiters (ISFCLs) due to their simpler, more efficient design, and their faster response to faults. This makes them more effective in protecting power systems, ensuring grid stability, and enhancing overall system reliability. Their straightforward operational mechanism and ability to quickly limit fault currents while maintaining minimal energy losses in normal operations position RSFCLs as a superior choice in modern electrical power systems.

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