

Coordinated overcurrent protection in distribution grids incorporating an active superconducting fault current limiter

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Global Journal of Engineering and Technology Advances, 2025, 24(02), 175-180

Publication history: Received on 06 July 2025; revised on 12 August 2025; accepted on 15 August 2025

Article DOI: <https://doi.org/10.30574/gjeta.2025.24.2.0244>

Abstract

The active saturated iron-core superconducting fault current limiter (SISFCL) is a promising technology for mitigating excessive fault currents in modern power distribution systems. This device is particularly valuable for integration into evolving smart grids, as it effectively suppresses fault currents during short-circuit events throughout the network. This paper offers a concise explanation of the SISFCL's working principles and its impedance behavior under fault conditions. The impact of integrating such a limiter on conventional inverse and fixed time-delay overcurrent protection schemes is examined. To ensure dependable protection performance in systems using SISFCLs, a method for coordinating protection settings is introduced. A model based on an actual 35 kV power distribution system with an integrated SISFCL was developed and evaluated using EMTDC/PSCAD software. The simulation outcomes confirm the soundness of the analytical framework. Index Terms—Active SFCL, saturated core, power distribution network, overcurrent relay, coordination, inverse-time protection.

Keywords: Active SISFCL; Saturated Iron-Core; Power Distribution Network; Overcurrent Relay Coordination; Inverse-Time Protection

1 Introduction

The fast increase in energy demand, and the increasing integration of distributed energy resources in the power networks of modern grids is pushing the development of power distribution systems into increasingly intelligent and integrated grid structures [1]. The high level of fault current is one of the main problems that emerge and this presents a challenge to the safety and stability of these networks. Traditional methods of restricting fault current normally introduce impedance in both normal and fault operating conditions, which can impact adversely on the quality of voltage and efficiency of a system [2]. In place of this, superconducting fault current limiters (SFCLs) have been proposed as useful tools in limiting the excessive magnitude of fault current [3]. One of the earliest such devices was the saturated iron-core SFCL (SISFCL) which was invented in the early 1980s [4]. SISFCLs do not require superconductor quenching unlike resistive SFCLs making them easy to cryogenically cool and lowering their operating cost. Through high temperature superconducting (HTS) systems, SISFCLs may be reduced in size and become cost effective [5]. Subsequent developments saw the construction of the active SISFCL by addition of control logic to the DC magnetization circuit [6], [7]. A complete operational active SISFCL unit has now been installed and tested in live distribution grid [8]-[10]. Also hybrid systems in which superconductors are coupled to conventional limiting reactors have been put into utilities practice: their impact on protective relays has been demonstrated to work successfully [11], [12].

Despite these efforts, thorough coordination of protective relays—especially under conditions with active SISFCL integration—remains underexplored. In this study, we evaluate how inverse-time overcurrent protection schemes

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operate in the presence of an active SISFCL, and propose suitable coordination strategies to maintain reliable system operation.

2 Material and methods

2.1 Current-Limiting Behavior of the SISFCL

The saturated iron-core superconducting fault current limiter (SISFCL) incorporates two magnetic cores as its primary magnetic components, alternating current (AC) windings, and a superconducting direct current (DC) coil connected to a magnetization control circuit. The structural schematic is illustrated in *Figure 1*.

By regulating the DC bias current in the superconducting coil, the impedance of the AC windings exhibits a nonlinear behavior. To overcome several design challenges, including heavy structure, magnetic coupling issues between the AC and DC paths, and insufficient limiting capability, recent SISFCL designs feature optimized iron-core geometry and high-speed electronic switches. These improvements collectively define the “active SISFCL.”

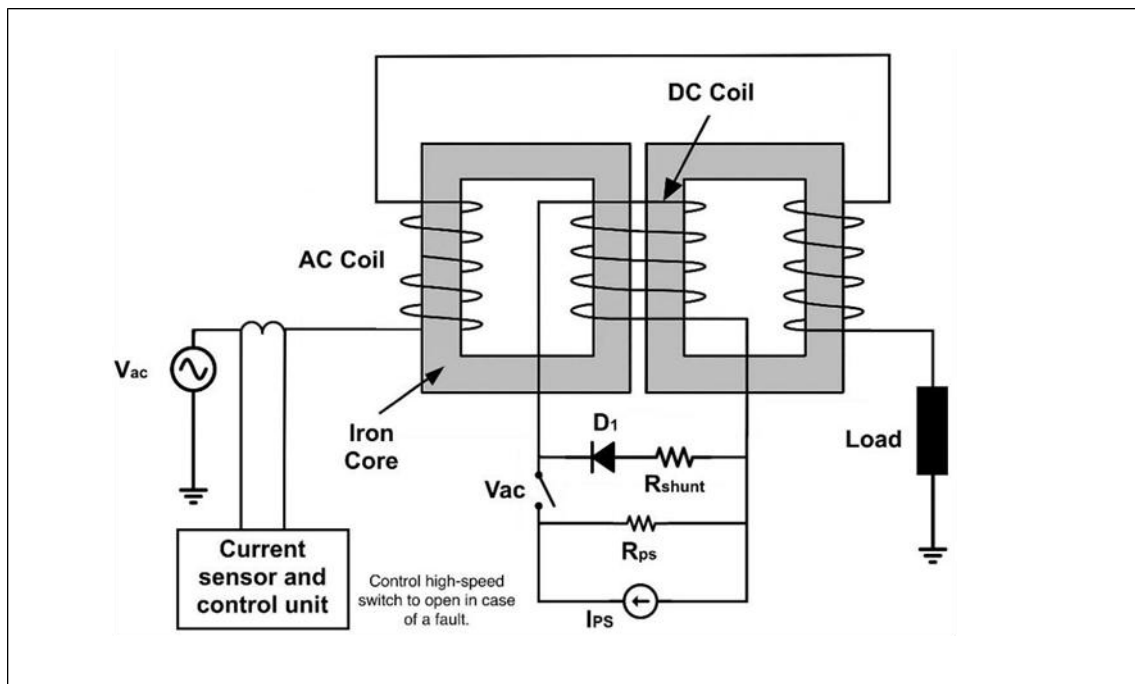


Figure 1 Schematic electrical circuit of an SISFCL

Under normal operation, under the influence of the applied direct current, both magnetic cores are forced into deep magnetic saturation, which forces the magnetic fields close to their respective DC bias points. Subsequently, the inductances are greatly decreased, which makes the SISFCL almost invisible to the power system, as depicted in Figure 2(a).

During a short-circuit event, deactivation of the high-speed switch in the direct current circuit occurs, eliminating the bias magnetic field and causing a sharp increase in the inductances, as illustrated in Figure 2(b). Accordingly, the SISFCL imposes a high impedance into the circuit, which inversely depends on the fault current magnitude, as presented in Figure 2(c).

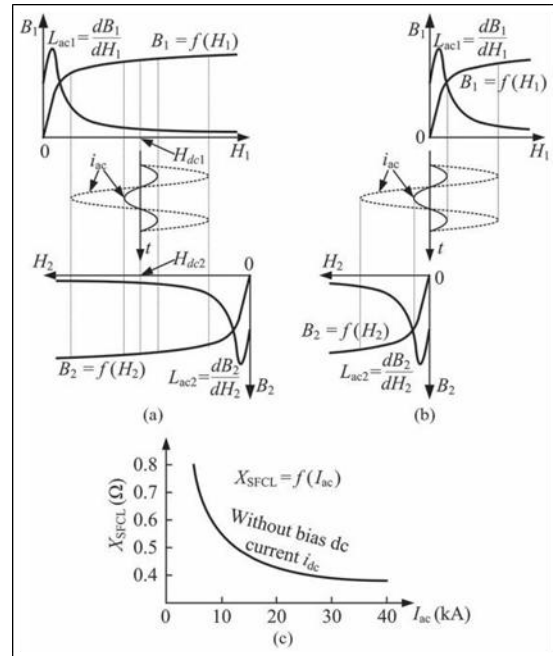


Figure 2 Illustrative comparison of SISFCL performance (a) passive configuration, (b) active configuration, and (c) impedance profile of a 35 kV SISFCL during current limitation

2.2 Coordinating Overcurrent Protection with SISFCL Integration

Figure 3 outlines a typical radial power distribution layout. Fault current amplitudes tend to decrease with increasing distance from the power source. In such settings, inverse-time overcurrent relays are preferred, and their timing behavior follows a characteristic curve.

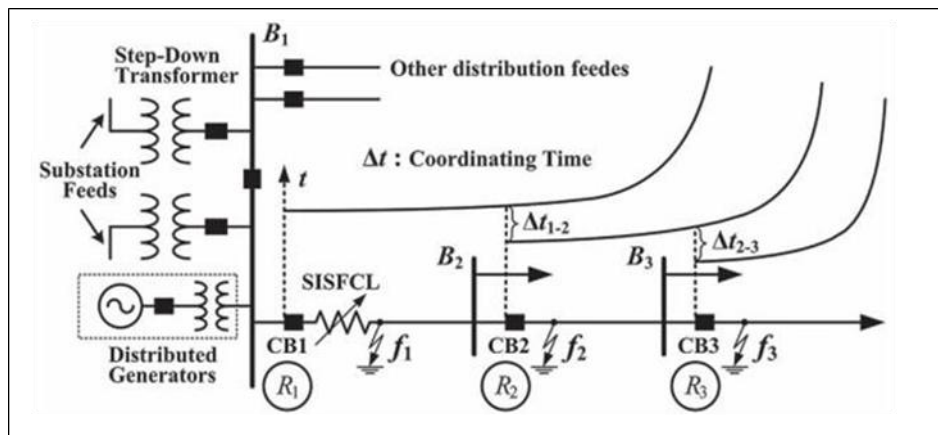


Figure 3 Power disturbance typical configuration

Coordination is structured as follows: for a fault at point F3, relay R3 responds first, causing circuit breaker CB3 to open. Upstream relay R2, guarding CB2, incorporates a coordination delay (commonly 0.3 to 0.5 seconds) to allow downstream tripping. Similarly, R1 delays its action behind R2 by another coordination interval.

Figure 4 compares fault current profiles with and without SISFCL deployment. If the limiter is placed near the beginning of the feeder, the farther the fault, the more impedance is introduced by the SISFCL. The extremes of SISFCL impedance are denoted as minimum and maximum impedance values. The corresponding fault current profile is shown as a dashed line in Figure 4.

From this, we can conclude

- The relay pickup current is not altered by the SISFCL in standard operation, since the device presents minimal impedance.
- When the SISFCL engages, it lowers fault currents and thus extends the relay tripping times, but still maintains time coordination among relays.
- Coordination between the upstream substation relay and feeder protection (R1) must be reviewed against the altered fault current curve.
- In practice, the altered curve may be hard to derive. As a workaround, engineers may adopt constant limiting values to retune relays, ensuring system-wide coordination.

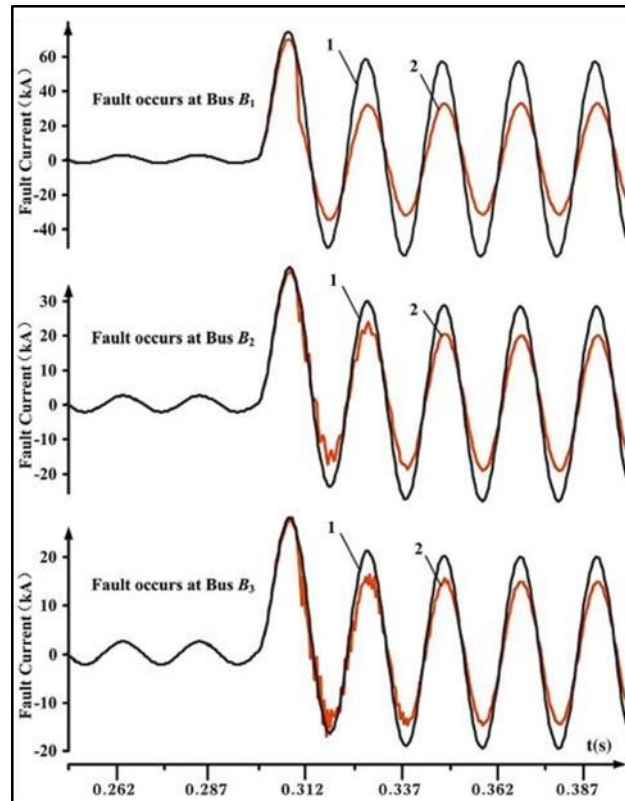


Figure 4 Three-phase fault current profiles at different bus locations B1, B2, and B3

2.3 Instantaneous and Definite-Time Overcurrent Settings

Inverse-time schemes introduce longer delays for lower currents—hence, closer faults result in quicker operation. When a feeder is long and fault current drops with distance, instantaneous protection becomes effective, provided its pickup threshold is set above the highest fault level at the feeder end. With the SISFCL in place, fault magnitudes are curtailed, reducing the effective zone of instantaneous protection and maintaining selectivity.

Definite time-delay relays are also unlike inverse-time relays because they rely only on the magnitude of the fault. This can lead to them triggering outside of their designed range especially when there is an SISFCL nearby. Consequently, these environments have to be reconsidered in order to keep the right functioning.

3 Results and discussion

The SISFCL had been successful in reducing the level of faults of all locations. Nevertheless, to achieve definite time-delay protection the wider impedance can have the effect of extending the protected region of the relay and longer trip delays are needed to coordinate it appropriately. The factors of time adjustment (scaling) of each relay were estimated. The operation time of faults at F3 and F2 confirms that the operation time between R2R3 and R1R2 differs by more than 0.3 seconds with the SISFCL installed, hence the maintenance of coordination. Vast simulation conditions were carried out. The findings indicate that inverse-time protection is stable and more appropriate than time-delay settings of certainty in systems that make use of active SISFCLs.

Table 1 Operational Time Delays of Overcurrent Relays in Non Proposed SISFCL scenarios

Inverse Time-delay Types	Δ_{t1-2} (Without SISFCL)	Δ_{t2-3} (Without SISFCL)	Δ_{t1-2} (With SISFCL)	Δ_{t2-3} (With SISFCL)
Normal Inverse Time	0.3 s	0.3 s	0.358 s	0.355 s
Very Inverse Time	0.3 s	0.3 s	0.455 s	0.428 s
Extreme Inverse Time	0.3 s	0.3 s	0.632 s	0.552 s

Table 2 Operational Time Delays of over current Relays in situations with the proposed SISFCL

Inverse Time-delay Types	Fault Point	t1	t2	t3
Normal Inverse Time-delay	f1	0.488 s	-	-
	f2	0.638 s	0.338 s	-
	f3	0.755 s	0.400 s	0.100 s
Very Inverse Time-delay	f1	0.271 s	-	-
	f2	0.569 s	0.269 s	-
	f3	0.846 s	0.400 s	0.100 s
Extreme Inverse Time-delay	f1	0.124 s	-	-
	f2	0.497 s	0.197 s	-
	f3	1.010 s	0.400 s	0.100 s

Table 3 Inverse Time-Delay overcurrent Relay Coordination Times on the Feeder

Inverse Time-delay Types	Fault Point	t1	t2	t3
Normal Inverse Time-delay	f1	0.604 s	-	-
	f2	0.762 s	0.404 s	-
	f3	0.893 s	0.473 s	0.118 s
Very Inverse Time-delay	f1	0.494 s	-	-
	f2	0.864 s	0.408 s	-
	f3	1.208 s	0.571 s	0.143 s
Extreme Inverse Time-delay	f1	0.384 s	-	-
	f2	1.046 s	0.414 s	-
	f3	1.860 s	0.737 s	0.184 s

4 Conclusion

Active Superconducting Fault Current Limiter (SISFCL) is a dynamic and effective fault current management solution to modern day distribution grids. Its impedance response reducing with fault current makes it seamlessly integrate with the system without affecting the normal functioning of the system. Though it alters fault levels, our investigation confirms that inverse-time overcurrent relay coordination remains intact. Only the relay linking the substation and feeder may require recalibration. For definite time-delay relays, careful analysis of actual fault currents is essential to preserve sensitivity and selectivity when SISFCLs are deployed. Compliance with ethical standards.

Compliance with ethical standards

Acknowledgments

The authors would like to thank all individuals who contributed to the completion of this research.

Disclosure of conflict of interest

The authors declare that they have no conflicts of interest regarding the publication of this research work.

Statement of informed consent

Informed consent was obtained from all individual participants included in the study.

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