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Forward-Looking Planning for Distribution Grids: Deploying Superconducting Fault-Current Limiters

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Abstract

Electric distribution networks are witnessing rapid growth in distributed generation units (DGs), with renewables forming the majority of new connections. To raise the maximum DG hosting capacity, operators increasingly consider transitioning from strictly radial feeders to selectively meshed arrangements, allowing improved sharing and balancing of power flows across circuits. When we mesh the network, prospective short-circuit currents rise. That makes protection coordination harder and pushes us to specify higher-rated transformers and primary gear. Superconducting fault current limiters (SCFCLs) present a compelling pathway to mitigate these elevated fault duties without compromising normal operation.

This study examines a strategy that retrofits existing distribution topologies with meshed (looped) operation supported by SCFCLs to enable higher DG penetration. The operating concept leverages SCFCLs to permit rapid reconfiguration from meshed to radial topology when a fault occurs, thereby constraining fault current magnitudes. Because radial operation in the faulted state matches current practice, the approach preserves existing protection schemes and avoids changes to equipment ratings or layouts. In normal service, the network runs meshed to improve power-flow management; under faults, it reverts to radial behavior to contain short-circuit levels. This article tests that premise by evaluating whether SCFCL-assisted meshing (superconducting fault current limiter) can increase DG hosting capacity while remaining compatible with existing protection philosophies and equipment—minimizing or eliminating redesigns and upgrades.

Keywords: Distributed Generation (Dg); Superconducting Fault Current Limiter (Scfcl) Network Reconfiguration; Dg Hosting Capacity Enhancement

1. Introduction

At present, distribution networks are operating with increasingly tight margins as overall demand grows. In parallel driven by environmental objectives utilities are connecting larger volumes of distributed generation (DG) at the distribution level. As DG penetration rises, feeders can experience reverse or bidirectional power flow, increasing the risk of overvoltage and overcurrent conditions [1]. ChatGPT said

A standard radial power distribution system is designed so that electrical power flows outward from a single source through progressively branching feeders. As the electrical path extends farther from the source, the magnitude of the fault current generally diminishes due to the cumulative impedance of the distribution lines and equipment.[2].

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Meshing, however, has a significant drawback: prospective short-circuit currents increase, which complicates protection coordination and forces higher duty ratings for cables, switchgear, and especially transformers. These impacts make rapid, system-wide architectural changes difficult and often cost-prohibitive. This paper examines a practical alternative reconfiguring the existing grid with fault current limiters (FCLs) so operators can obtain the power-flow benefits of meshing under normal conditions while containing fault levels and preserving compatibility with established protection philosophies, thereby minimizing or avoiding redesigns and equipment upgrades.

The objective is to enable greater DG integration without necessitating a complete redesign of the protection system or widespread equipment upgrades.

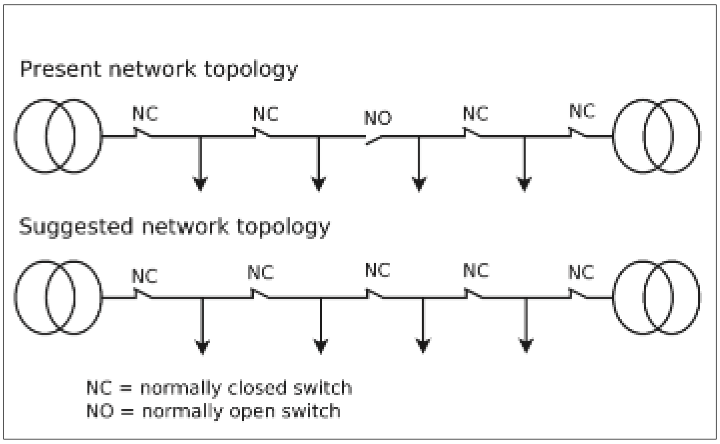

Figure 1 The topology of switching

In this work, we advocate a "small changes, big gains" approach. Rather than overhauling the network, we derive a new operational topology directly from the existing infrastructure by reconfiguring selected normally open tie switches in combination with judicious deployment of superconducting fault-current limiters (SCFCLs). This reconfiguration approach—forming looped paths within an otherwise radial network—has been examined in prior work [3]. Here, we refine and extend it for practical distribution-grid operation. The proposed topology measurably increases DG hosting capacity, allowing more distributed resources to connect without immediate large-scale reinforcement. On the other hand, we outline the innovative application of SCFCLs that underpins the scheme, explaining how their intrinsic behavior allows the grid to enjoy meshed benefits in normal service while reverting to radial-like behavior under faults. Finally, we evaluate the proposed practice through simulation, reporting results that clarify performance, coordination with existing protections, and the conditions under which the approach delivers the most benefit.

2. Material and methods

2.1. Proposed Reconfiguration of the Distribution Network Topology

In present-day practice, distribution systems are predominantly arranged in a radial configuration. In such schemes, each load is supplied by a single feeder, with continuity of any potential loop intentionally broken by a normally open switch see the first panel of Fig. 1. The entire protection philosophy is built around this operating mode. When a sustained (permanent) fault arises, protective devices isolate the affected feeder by opening at the source end, thereby removing energy to the faulted section. The faulty segment is then sectionalized, after which restoration procedures can re-energize unaffected portions: operators may close the normally open point and open selected normally closed switches to backfeed healthy sections from an alternate feeder. This standard arrangement enhances service reliability by enabling partial restoration following contingencies. For this reason, many networks are often described as loopable in design but radially operated in day-to-day conditions.To expand the hosting capacity for distributed generation (DG), this work proposes leveraging that built-in redundancy to reconfigure the network's operating topology. Specifically, by closing one of the normally open switches, two feeders can be tied through a portion of the network, thereby creating a looped (meshed) path—illustrated in the second panel of Fig. 1. Notably, this modification is straightforward to implement: it does not require constructing new lines or adding new feeders. Utilities only need to change the positions of existing switches to realize the proposed topology.

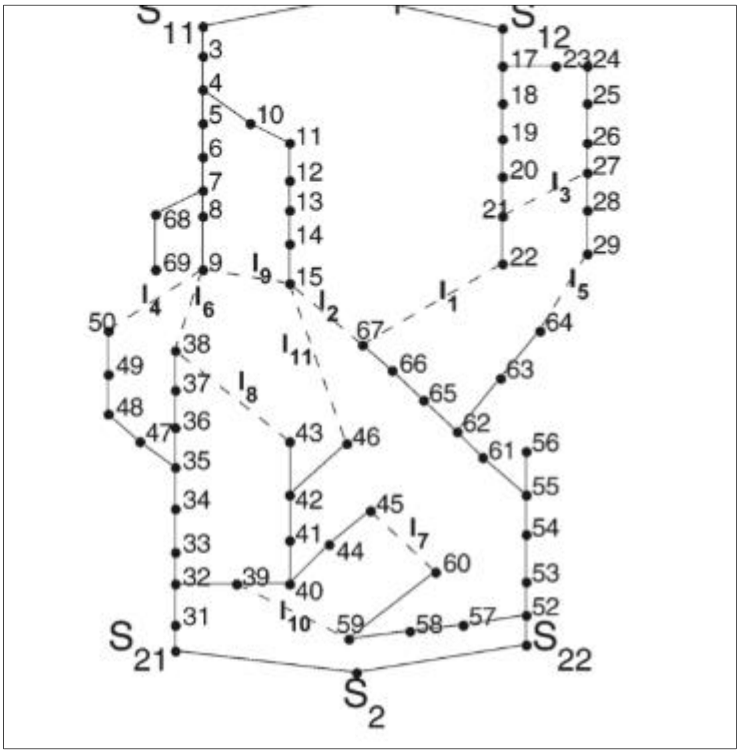

Figure 2 Seventh node of our network workflow flow

To implement the proposed looped configuration, utilities simply need to make some one time normally open and second possibility which will be normally close of the normally open points (NOPs) The principal prerequisite for creating these loops is to ensure that the interconnected feeders are supplied by electrically compatible transformers that is, units with matching winding connections, phase-angle displacement, and related vector group characteristics so that circulating currents and phase mismatches are avoided. When this condition is satisfied, the resulting topology raises the network's DG hosting capacity, enabling more distributed generators to connect without immediate reinforcement.

To quantify this benefit, we employ a Monte Carlo–based assessment that estimates the maximum DG insertion rate achievable without violating operational limits on bus voltages and line/transformer currents [4]. In the procedure, for each candidate insertion rate, a specified number of DG units is randomly placed across the network. Power-flow checks are then performed to verify compliance with technical constraints; the probability of success is computed as the ratio of feasible outcomes to the total number of random trials. The maximum acceptable insertion rate is identified at the point where this success probability declines beyond an acceptable threshold. We use this algorithm to highlight how closing normally open points influences the evolution of the network's maximum DG penetration.

The test system is the seventh node of our network workflow flow or in hand, the distribution k shown in Fig. 2 [5]. This 11 kV test network consists of there is two things the S1 and S two, four outbound feeders S11, S12, S21, and S22 and eleven normally open switches (NOPs), which are depicted as dotted interties on the diagram. We begin by running Monte Carlo simulations on the baseline radial arrangement and then evaluate a set of reconfigured topologies obtained by closing NOPs #3, #6, and #11. As summarized in Fig. 3, driving the system toward a fully meshed configuration that is, closing all normally open switches—markedly enhances the network's DG hosting capability and expands the pool of feasible connection points, while, as expected, raising prospective short-circuit levels that must be managed by protection and limiting devices. yields a sixfold increase in the number of DG connections that can be accommodated.

This gain, however, comes with a critical drawback: under faulted conditions, prospective short-circuit currents rise sharply relative to the radial case. Moreover, the existing protection coordination—engineered for radial power flow may no longer operate correctly once parallel paths are introduced. To address these concerns within the meshed arrangement, we propose deploying a resistive superconducting fault current limiter (SCFCL) at strategic tie points or feeder interfaces, as illustrated in Fig. 4. The SCFCL exhibits very low impedance during normal operation, preserving the benefits of meshing, yet transitions to a high-impedance state during faults, effectively curbing fault current magnitudes and helping maintain compatibility with legacy protection settings.

2.2. RESISTIVE-TYPE SUPERCONDUCTING FCL (SCFCL)

As established in the preceding section, operating the distribution network in a looped (meshed) configuration can substantially increase DG hosting capacity. The drawback, however, is that during fault conditions, the prospective short-circuit current can rise to very high levels. Under such circumstances, the existing protection coordination designed for radial operation may misoperate or fail to clear correctly, and many grid components (e.g., transformers, cables, switchgear) would need to be re-specified, re-rated, and manufactured to withstand the elevated fault duties. Our central idea is to deploy a fault-current limiter that, upon a fault, rapidly and automatically alters the effective network topology, restoring radial-like behavior and containing fault current magnitudes. To realize this with minimal control complexity, we propose exploiting the inherent properties of superconducting (SC) tape in a resistive-type SCFCL. In normal operation, the SC element presents negligible impedance, preserving the efficiency and power-flow benefits of a meshed grid. When a fault drives current above the tape's critical threshold, the superconductor quenches—transitioning within milliseconds to a high-resistance state. This sudden rise in impedance limits the fault current, effectively "de-meshing" the tie path and allowing the system to behave like a radial network while protection devices act as intended. After the fault is cleared and the element cools, the SC tape recovers its superconducting state, reinstating low impedance and the advantages of meshed operation. This passive, self-acting mechanism provides the fast topological response required to support higher DG penetration without wholesale redesign of protection schemes or equipment ratings.

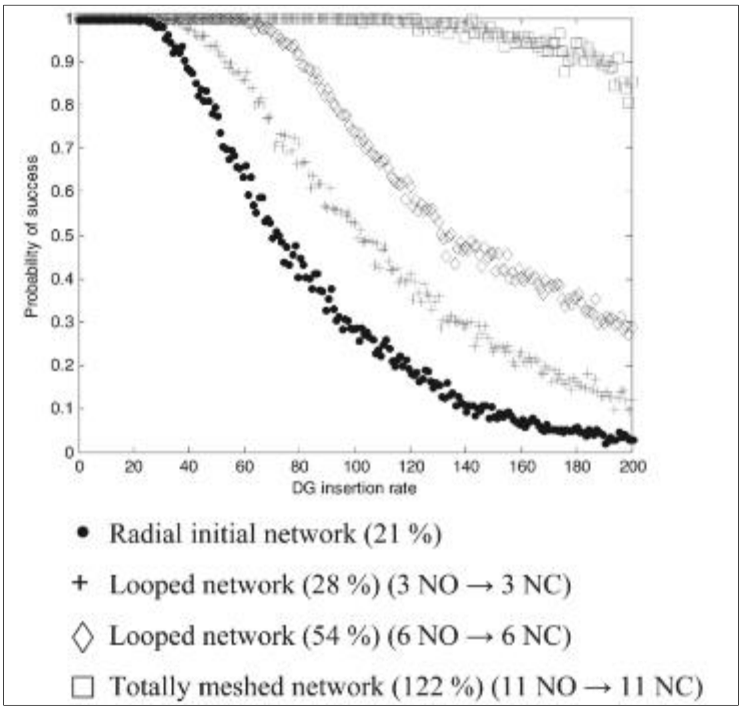

Figure 3 Fully meshed configuration graph

We propose installing SCFCL units in Superconducting fault-current limiters are connected in parallel across the normally open points (see Fig. 4). During normal service, they stay in the superconducting state, presenting negligible impedance to keep the loop energized., each SCFCL remains in its superconducting state, presenting negligible impedance; consequently, the tie path conducts and the network operates as a looped (meshed) system. When a fault arises, the current through the SC element surges beyond its critical threshold, prompting a quench. The device's resistance then rises rapidly to a high value, so the effective network configuration reverts to an almost radial topology. In this state, the fault current at the loop point is substantially reduced, making interruption by nearby protective devices more manageable. In addition, measuring the voltage across the SCFCL provides a simple supervisory signal to command the opening of the two switches located on either side of the limiter. A key question governs the scheme: after quench, is the SCFCL's impedance high enough to (i) prevent the healthy side protection from "seeing" the fault and (ii) trigger tripping of the switches flanking

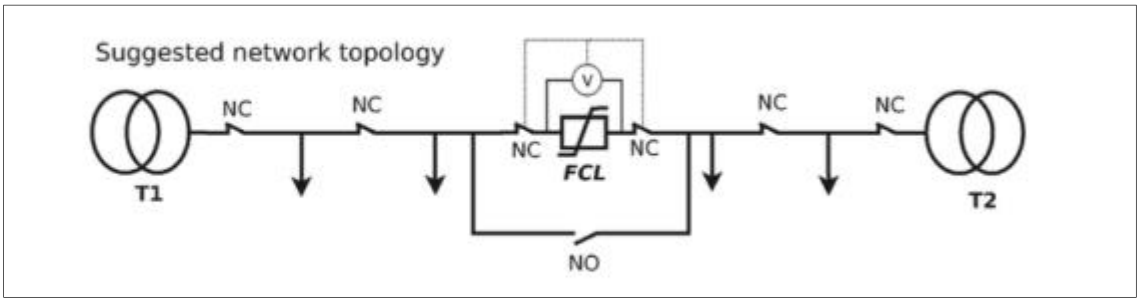

Figure 4 Resistive superconducting fault current limiter

(SCFCL? We assess this using time-domain simulations in ATPDraw (Alternative Transient Program) [6] to verify the SCFCL response and confirm correct protection operation.

In current French distribution practice, feeder protections at both outgoing and incoming terminals address non-resistive faults (a separate scheme handles resistive faults). These relays are intentionally time-delayed and do not begin to act earlier than 80 ms after fault inception to avoid tripping on self-extinguishing disturbances. If the fault persists beyond 80 ms, the relevant protection trips.

To maintain coordination with this philosophy, operators must remove the SCFCL path before the feeder protection reaches its operating time i.e., open the meshed tie to unloop the network and isolate the SCFCL within ≤80 ms. The objective is to retain existing protection settings and equipment ratings while still realizing the operational benefits of meshing under healthy conditions. For practicality, we assume no active communications between the SCFCL, adjacent switches, and protection relays; the behavior relies on the SCFCL's intrinsic, passive response and local device characteristics.

The scheme relies solely on the SCFCL's intrinsic quench response and a local voltage-detection measurement across its terminals. Consistent with our assumption of no direct communications between the feeder protection and the SCFCL, the device infers the system state solely from a local voltage measurement across the limiter (see Fig. 4). Whenever this measured voltage departs from zero indicating that the SC element has quenched and developed resistance, or that there is a sustained voltage difference due to a network fault the control logic commands an immediate disconnection of the SCFCL path. Under normal coordination, this action unloops the network within approximately 80 ms from the instant the fault begins, thus restoring an effectively radial configuration before the feeder protection's operating time.

After the protection sequence completes roughly 15 s for the full cycle the tie is permitted to be re-energized and the SCFCL reconnected. Upon reconnection, a zero-voltage reading across the SCFCL confirms healthy conditions and a recovered superconducting state, so the device remains in service and the grid resumes looped operation as before the disturbance. If, instead, a non-zero voltage is observed, the SCFCL is promptly opened again, the network remains unlooped, and a field visit is required to restore looped operation via the SCFCL. Residual voltage across the SCFCL can arise from two causes: (i) incomplete recovery of the superconducting element (typically ≈1 s), or (ii) a fault that remains active and uncleared. To reflect the protection timing and verify that the device opens the meshed tie before the relays operate, we run all time-domain simulations over 100-ms windows.

The SCFCL's design thermal recovery, impedance profile, and tripping logic thresholds assumes these coordination intervals (≈80 ms to unloop, ≈1 s to recover, ≈15 s for the protection cycle) to ensure selective, non-intrusive interaction with the existing protection system.

2.3. SCFCL Architecture and Parameterization

The superconducting fault-current limiter analyzed here is built from second-generation (2G) YBaCuO coated-conductor tape. The laboratory-characterized specimens are 3 mm wide and exhibit a room-temperature (300 K) resistivity of 1.88 Ω/m. These measured parameters are used directly for the device sizing and subsequent simulations, and a critical current IcI_cIc of 45 A at 77 K.

With reference to the network in Fig. 2, normal (healthy) operation involves supply from feeders, so the steady current through the proposed path is about 4.8 Amp. Since the tape's critical current is well above 5 A, there is a comfortable margin in the superconducting state; in principle, with low condcating IcI_cIc at 75 kilo could also satisfy this operating point.

A more demanding scenario occurs during contingencies in which one transformer or feeder is unavailable. For instance, if transformer T1 (see Fig. 4) is out of service, the entire network can be backfed via transformer T2. Under that degraded yet steady condition, the SCFCL branch would carry on the order of 70 A. To accommodate this, the device is initially sized and configured as 2 2,8 mm–big tap with high width in parallel, providing a combined current we don't want to exceed is about 80 A (40 A × 2). With this sizing, a fault located downstream of the SCFCL will, if the instantaneous current surpasses 90 A, drive the element into quench, raising its impedance sharply and curtailing the prospective short-circuit current seen by the adjacent network. In degraded or continuity-prioritized operation, the device can be bypassed via the parallel switch, in which case no fault-current limitation is applied on the downstream side. (i.e., beyond the tie point), The limiter's transition to a resistive state can reduce the prospective fault current, assisting nearby protection in clearing the event.

For certain maintenance or extreme contingency cases, it may be advantageous to bypass the limiter altogether. A parallel switch provides this function: when closed, it short-circuits the SCFCL path, ensuring robust continuity but, by design, disabling fault-current limitation for faults located beyond the limiter. This bypass option is intended for degraded-mode operation where continuity is prioritized over limiting performance.

Tape length is a key sizing parameter. We set the active length to 250 m to distribute quench energy and limit hot-spot temperature. Under severe fault conditions, this length helps keep the superconductor below 300 K, protecting the conductor and supporting post-fault recovery.SCFCL Model

2.4. SCFCL Model

We model the superconductor using the formulation in [7]. The model provides the instantaneous resistance of the superconducting element and, by extension, the SCFCL over arbitrary current and temperature excursions. It is grounded in the coated-conductor power-law E–J relationship, capturing pre-quench conduction, quench onset, and the resistive regime that delivers fault-current limitation.

3. Results and discussion

All simulations use the test system introduced as shown in Fig. 2 of [5]. Within the French distribution context, feeder protection is installed near substations with two locations per feeder (excluding transformer-specific protection): one device on the incoming side and one on the outgoing side.

Our objective is to apply the SCFCL so that a fault on one side does not propagate its effects into the healthy section. Concretely, if a fault occurs anywhere between transformer T1 and the SCFCL location, the protection associated with T2 must not trip, and the converse must also hold.

To remain compatible with existing practice, we adopt the current timing philosophy: feeder protections employ an intentional delay and do not act before 80 ms after fault inception. If the fault persists beyond 80 ms, the relevant relay issues a trip. Accordingly, the SCFCL path must be removed and the meshed tie opened (i.e., the network unlooped and the SCFCL isolated) within ≤ 80 ms.To bound the behavior of the protection scheme, we analyze two limiting scenarios:

- Case 1: a bolted three-phase fault (indicating a high prospective short-circuit level) at a location adjacent to the SCFCL, specifically nodes N9 or N38 per Fig. 2.
- Case 2: a resistive single-phase fault (thus yielding a low prospective short-circuit level)—applied at the busbar on the feeder side (nodes S11 or S21 in Fig. 2)

For Case 1, correct operation requires the SCFCL impedance to rise very rapidly—to several tens of ohms within a few milliseconds—otherwise the "healthy" feeder's protection could see excessive current and trip undesirably. For Case 2, the prospective fault current can be only marginally above rated load (a few amperes), so the SCFCL may not quench or may do so only slowly. In such low-current circumstances, the SCFCL must not detect the event as abnormal; the network should remain looped, and protection should behave as designed. Accordingly, with protection thresholds in mind, we place faults at two representative locations: in the vicinity of the SCFCL and at the feeder end terminals.

Our analysis focuses on non-resistive (zero-impedance) faults, whereas resistive faults are handled by a separate scheme tied to the neutral-impedance protection. Accordingly, Case 2 considers a solid single-phase fault.

In the modeled topology, the SCFCL is installed at node N9/N38, creating a tie between feeders S11 and S21 through the network and the limiter, while the opposite side of the system—feeders S12 and S22—is kept radial. This arrangement focuses the analysis on S11 and S21. Unless otherwise stated, the SCFCL is rated with a 90 A critical current, realized by paralleling two 45 A coated-conductor tapes.

3.1. The Case 1

To investigate Case 1, we impose a bolted three-phase short circuit at node N9 and analyze the ensuing system response. The resulting waveforms are presented in Fig. 5. Because distribution-level protection decisions are based exclusively on currents, only currents are plotted. Voltage depressions during the event are on the order of 5% of nominal, a change that can also arise from transient loading; consequently, voltage traces are much less indicative of fault behavior than current traces in this context.

Each feeder is equipped with Each feeder is equipped with one protections—one at the incoming side and another at the outgoing side—hence both corresponding currents are shown in Fig. 5. The top plots present the incoming-feeder currents (S1 and S2), . The protection thresholds are overlaid as dotted black lines.The simulated response confirms the intended behavior of the SCFCL. With the fault applied at N9, only S1 (incoming) and S11 (outgoing) should exhibit currents that exceed their protection thresholds, and this is exactly what is observed. By contrast, the incoming feeder S2 remains below its trip threshold throughout the event, indicating that the fault is effectively contained on the T1 side of the SCFCL. The outgoing feeder S21 shows a brief transient excursion above its limit lasting only a few milliseconds—insufficient to elicit a protective operation—so no adverse consequence (i.e., no unwanted trip) occurs on that side. Overall, these results validate that, for a severe nearby fault, the SCFCL's rapid impedance rise shields the healthy feeder while allowing the affected feeder's protection to see and clear the fault as designed.

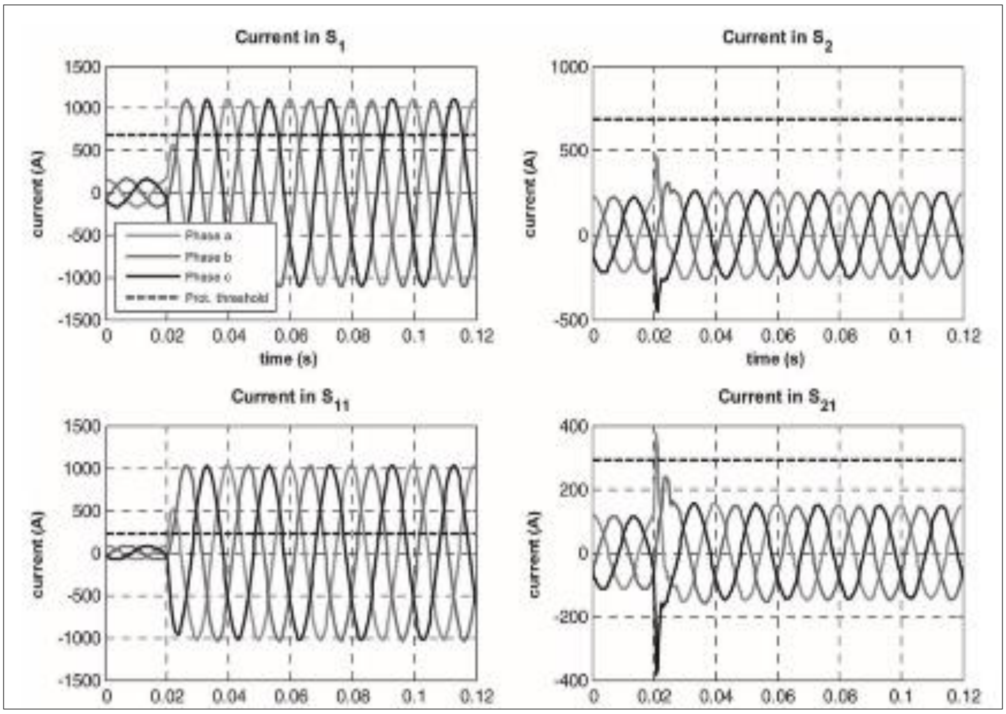

Figure 5 The resulting waveforms

With respect to protection timing, a trip is issued only if the measured current exceeds the pickup threshold for at least ~80 ms. In our simulation, the SCFCL quenches correctly, developing a kilovolt-level voltage across its terminals. Because the breaker control is supervised by this SCFCL voltage, it receives a clear trip signal and operates as intended. As a result, the tie is opened, the loop is broken, and the network reverts to an effectively radial configuration—all without initiating feeder protection trips on the healthy side. This confirms that Case 1 behaves as desired and validates the approach.

3.2. The Case 2

Each feeder includes two protection devices one on the incoming side and one on the outgoing side—so Fig. 5 reports both corresponding currents. The upper plots display the incoming-feeder currents (S1 and S2); the lower plots show the outgoing-feeder currents. currents (S11 and S21). Protection pickup levels are indicated by dotted black lines. across its terminals approximately 100 ms after quench, providing a robust control signal. From a coordination standpoint, this quench and the resulting voltage rise are sufficiently fast to avoid feeder protection trips (which require ~80 ms over-threshold) and to command the switch to open, thereby restoring radial operation during the fault. In short, the 25 A design satisfies the protection objectives for Case 2.

4. Conclusion

We developed a simulation protocol to assess the feasibility of the proposed SCFCL deployment with voltage-supervised tie opening. Results indicate that an SCFCL with a critical current of approximately 25 A is well suited to non-impedance (non-resistive) faults: it quenches promptly, establishes a clear voltage across the device, and enables timely unlooping without disturbing existing feeder protections. In degraded-mode operation (e.g., single-feeder backfeed) where continuity may take precedence, the parallel bypass switch should be used, with the understanding that fault-current limitation is then disabled on the downstream side of the limiter .A full treatment of impedance (resistive) faults is outside this article's scope, but the implications are clear: because resistive faults drive lower current through the SCFCL, achieving sufficient voltage for breaker supervision generally favors a lower I_c design.. Follow-on studies indicate that, with appropriate sizing, resistive faults up to about 70 Ω can be detected by the proposed This work introduces a novel operational role for the SCFCL and demonstrates its feasibility through targeted time-domain simulations. The validated behavior opens new avenues for forward distribution-system planning, particularly for scaling the integration of distributed generation (DG) without wholesale changes to legacy protection. As utilities adopt greater degrees of meshing to balance flows and raise DG hosting capacity, a coordinated deployment of fault-current limiters becomes a practical enabler allowing meshed operation in the healthy state while restoring radial-like behavior under faults.

Looking ahead, planners can frame the approach within a cost–benefit and staging strategy: optimize the number, ratings, and locations of SCFCL devices to maximize DG penetration per unit of investment, assess CAPEX/OPEX trade-offs, and sequence installations to align with incremental DG uptake. In short, the proposed use of SCFCLs provides a scalable pathway to accommodate significantly more DG while keeping protection philosophies largely intact, with comparative evaluations guiding how far to mesh and how many limiters to install for the best return on grid flexibility and reliability.e, reinforcing the practicality of the approach across a broader range of fault impedances.

Compliance with ethical standards

Acknowledgments

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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.

References

[1] N. Hadjsaid, J.-F. Canard, and F. Dumas, "Dispersed generation impact on distribution networks," IEEE Comput. Appl. Power, vol. 12, no. 2, pp. 22– 28, Apr. 1999.

[2] Ali Taher Saber, and Aland Faraidoon Ismael," Coordinated overcurrent protection in distribution grids incorporating an active" Global Journal of Engineering and Technology Advances,2025, 24(02), 175-180.

[3] S. Repo, A. Nikander, H. Laaksonen, P. Jrventausta, and P. W. Daly, "A method to increase the integration capacity of distributed generation on weak distribution networks," presented at the 17th Int. Conf. Electricity Distribution CIRED, Barcelona, Spain, May, 2003.

[4] M.-C. Alvarez-Herault, R. Caire, B. Raison, N. Hadjsaid, W. Bienia, and J. Descloux, "Investigation of new distribution grid architecture for accom- modating higher dg penetration rate," presented at the CIRED Workshop, Lyon, France, Jun. 2010.

[5] D. Das, "A fuzzy multiobjective approach for network reconfiguration of distribution systems," IEEE Trans. Power Del., vol. 21, no. 1, pp. 202–209, Jan. 2006.

[6] L. Prikler and H. K. Hoidalen, Users' Manual. Trondheim, Norway: ATPDraw, 1998.

[7] P. Tixador, T. Nguyen Nhat, H. Okada Vieira, and R. Ponceau, "Impact of conductor inhomogeneity on FCL transient performance," IEEE Trans. Appl. Supercond., vol. 21, no. 3, pp. 1194–1197, Jun. 2011.