A Comprehensive Review for Application of Fault Current Limiters in Power Systems

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Abstract

The integration regarding various power electronic devices has led to an increase in the complexity of power systems. Limiting the fault currents is crucial for protecting these systems, the augmentation of fault reliability, and the stability. Many Faults Current Limiters (FCLs) were used in power systems because they quickly and effectively fault current limiters. The presented work gives a thorough literature review regarding the use of various FCL types in the power systems. The non-superconducting and superconducting FCL applications have been divided into five categories: (a) application in transmission, distribution and generation networks; (b) applications in the systems of alternating current (AC)/direct current (DC); (c) applications in the integration of renewable sources of energy; (d) applications in the distributed generation (DG); (e) applications for improving stability, reliability, and fault ride through capabilities. With examples of their practical implementation in various nations, impact, modeling, and control approaches of various FCLs in the power systems have been shown. With the alteration of its structures, appropriate control design, and optimal placement recommendations have been given in order to enhance performance regarding FCLs in the power systems. In order to incorporate the continuing research advances in practical systems, industry and researchers working on power system stability concerns can benefit greatly from this study.

Keywords- superconducting; fault current limiter; non-superconducting; power system stability; optimal placement; fault ride through capability.

I. INTRODUCTION

The majority of nations have changed the way their electric systems are managed, with distinct businesses now in charge of transmission, generation, and distribution. The distribution and transmission systems have added more energy producers, such as residential and independent ones, raising levels of fault current. New agents occasionally raise fault current levels, over-stressing installed protection equipment and requiring system modifications. Although it requires money and time, replacing the overstressed equipment is the best course of action. For the operation of circuit breakers (CB), it is frequently necessary to reduce the fault current to levels that are safe. There was a hunt for trustworthy FCL devices since the 1970s. The cost of introducing a FCL device is less than completely upgrading substation's equipment without decreasing reliability and redundancy [1] .

Electromechanical circuit breakers, which typically require no less than one current cycle for opening the circuit, are the standard method of overcurrent protection in the power systems. In the case when a fault current exceeds the substation limits, such technology could interrupt the circuit following the fault but cannot prevent damage. FCL devices are indicated in the case when circuit breakers cannot interrupt a short circuit. The majority of power systems operate as a voltage source; however, certain wind farms and photovoltaic plants operate as current sources because of their power electronics-controlled output. The only approach to control fault currents in voltage source system is to enhance the fault transmission circuit by inserting a series line impedance. Given the inductive nature regarding line transmission and the majority of the loads, it would be dangerous to add capacitive impedance in series with load because it would reduce system's global impedance and raise fault current. Thus, the quickest and simplest approach for limiting current is to quickly connect an inductive or a resistive impedance in series with distribution (or transmission) line after the fault current is recognized. The symmetrical current throughout the fault is a benefit of a resistive limiter, yet there are losses because of resistance, and heat that has been generated must be dissipated. Asymmetrical current and significant electro-magnetic pollution in substation throughout fault are drawbacks of inductive limiter. Losses are nevertheless less than the resistive FCLs. Those ideas outline the operation of FCL. Let's assume for the time being that FCL is a black box connected to the system in series, as shown in single-line diagram of Fig1. This black box has variable impedance which could increase in the case when the current rises unexpectedly. The transmission (or distribution) line is shown in Fig. 1 (a) without any FCL, and the FCL is inserted in Fig. 1 (b). All these 'black boxes' will be discussed and opened together with the manuscript. The FCL's impedance should be as low as feasible for the system to operate normally. Its energy dissipation must be minimal at this point. The device is in charge of inserting series impedance into system so as to reduce the amount of the current in a case when a fault occurs, though.

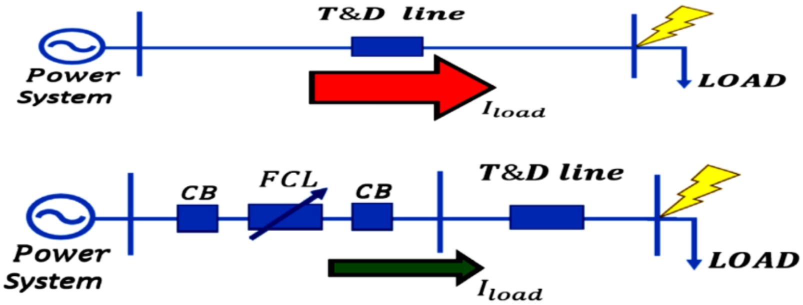

Fig1. Single-line diagram of distribution or transmission system:
(a) With no FCL (b) with including a FCL device.

Fig. 2 shows how FCL is actuated following a system fault. The electric current which might flow through the conventional system in a case of a fault is represented by the red curve in the literature as the prospective current. The green dashed curve displays how the overcurrent is constrained by FCL's impedance.

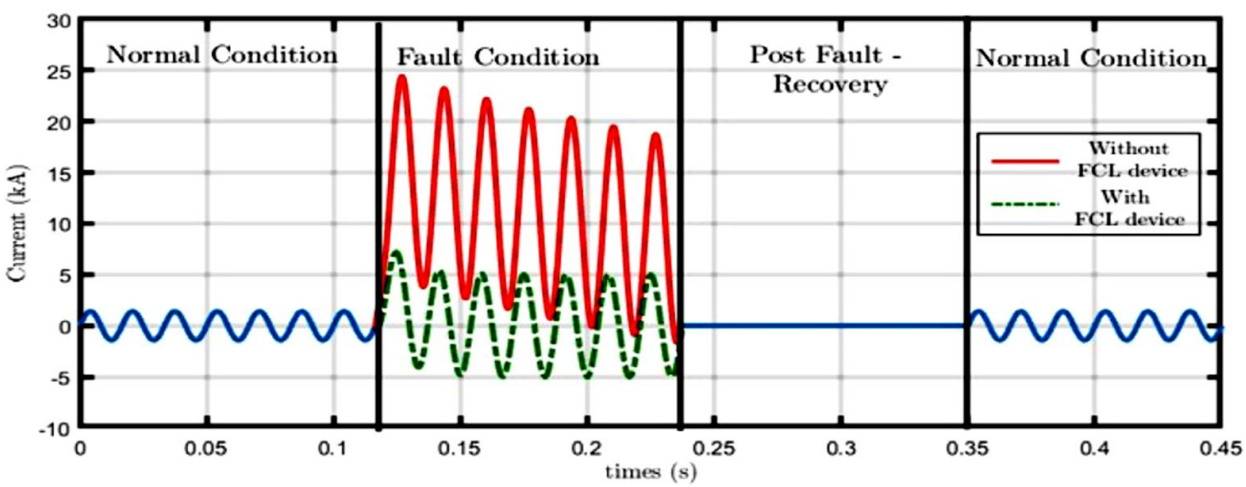

Fig2. Comparisons of the electric currents for a system with and without an FCL device.

II. BASIC CONCEPT OF FCL

The use of a FCL can be defined as one of the alternative solutions being studied more frequently to strengthen the reliability regarding electrical systems. Suppressing the fault current is the main goal of installing FCL in a distribution or transmission system. In a case when functioning normally, FCL is a series element with a relatively low impedance. FCL increases its impedance when the fault takes place, preventing high current stresses that might have likely caused mechanical forces, degradation, and additional heating of electrical equipment. For combatting transmission and distribution voltages and currents, such FCLs are required. In the case when it comes to performance, FCLs are held to particular expectations. Throughout normal operation, they must have low impedance, low voltage drop, and low power loss, whereas under fault conditions, they must have a high impedance. In the faulty state of operation, such attribute must stop the large fault current. FCLs must limit the amount of current before the fault current reaches its first peak and should have a very quick recovery time. Any value regarding the magnitude of the fault current and/or phase combination should cause them to react appropriately. They ought to be able to withstand faulty conditions for a long enough period of time. They must have great reliability, thermal endurance, and longevity. They must operate entirely automatically and have a quick recovery time so that they can quickly return to normal state following a fault rem oval. Also, they must have a low cost and generation volume regarding their own to reduce power generation and transmission costs [2].

III. CLASSIFICATION OF FAULT CURRENT LIMITERS

As shown in fig. 3, the enhancement of power electronics, superconducting and magnetic resource technologies has led to the development of several types of fault current constraining devices recently.

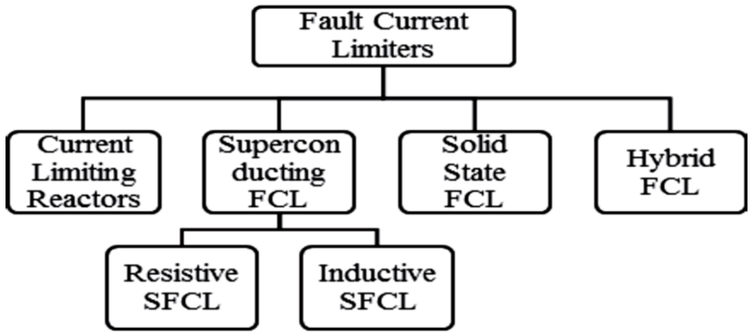

Fig. 3. Classification of FCL

1. Current Limiting Reactors:

Current limiting reactors have been studied in the start of 19th century with the goal of protecting equipment. The reactor has been inserted in series with the line for limiting current in a concept of the current limiting reactors. With regard to short circuit conditions, behavior regarding current limiting reactors with the turbo generator systems was studied [3]. For one of the high current superconductors in the power devices, current limiting is added after some changes [4]. In [5], the key components of installation and use of the current limiting reactors are provided.

2. Superconducting FCL (SFCL):

All SFCL designs utilize a superconducting to conventional conversion, and the superconducting components are directly implanted after the power circuit to be safeguarded. With regard to a current limiter, a superconducting trigger coil has been developed and tested [6]. So as to examine the impact of SFCL on the power grid, wind power generation serves as a good example of renewable energy sources. When it comes in contact with current system, it may be simpler to increase short circuit current during the error than at its most advanced stage of applications that comes before the evaluation of circuit breaker. The system network as a whole could become less consistent as a result [7] .SFCLs are viewed as a reasonable way to prevent a power network shutdown that would result in significant social and economic damages [8]. By using such current limiters, perpetual power supply and power supremacy could be supported and strengthened. The modified SFCL system could protect the critical load power as well as grid connection point of fault collapse with just a superconducting coil in addition to being able for limiting peak and continuous fault current [9].

New SFCL designs have been suggested with straightforward design to instantaneously direct superconductor current to the appropriate coil [10] .This design can hold load of superconductor to a minimum, resulting in a smaller and less expensive superconductor. In some cases, such as when lightning strikes a power line, power lines become shorted to the ground, or trees fall on power lines, it might result in the error state in the system of electric power transmission. In order to limit the high short-circuit current in the power grids, SFCL is a newly developed technology [11]. In [12] ,a technique for choosing an appropriate site and designing the minimum SFCL capacity in the loop power system was developed. The system's reliability and voltage must be improved. Without the increase of short circuit stress on network's components, an SFCL with parallel combination regarding radial feeder system has been presented [13].SFCL principles are evaluated for some certain transmission current, voltage, and fault limiting level. With electromagnetic transients' programs, theoretical suggestions are industrialized and adjustments are discussed [14] .SFCLs have been identified as top hierarchical approach using new growths and having great deal of the potential for the future cost-cutting practical advancements. For limiting the fault current in the power grid networks, the saturated core SFCL is a major and novel technology. For the calculation of current limiting effect of the SFCL, a field circuit connected simulation method has been provided in [15].

In order to withstand the different faults of the short circuit in a modern power system, a high temperature SFCL offers a potential solution[16-19]. The requirements of the performance of a power system component can now be met by superconducting materials. For performing fault current limiting action, a significant fraction of suggested FCL designs make use of the superconducting materials. With its superconducting property, SFCL represents a new power technology that can result in the automatic limitation of fault current to safe levels. SFCLs have successfully met almost all of the criteria for an effective current limiter, just a few of which were specified in the preceding article. One kind of SFCL is the transformer type SFCL [20-23].

Resistance of mercury vanished as temperature degree dropped to less than a set of critical values, according to a Nobel Prize Dutch Scientist, Kamerlingh Onnes, who made this discovery in 1911 [24]. This phenomenon is known as mercury superconductivity. Subsequent studies also revealed that numerous additional materials or components show those same properties of superconductivity with their own critical degree of the temperature[25]. Current limiting SFCL properties are dependent upon its non-linear responses to the magnetic field (B), temperature (T), and current. [26]

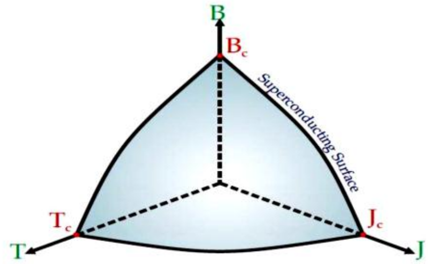

Figure 4 Showing Critical Characteristics of a Superconductor FCL

In the case when a superconducting material is exposed to conditions above critical levels for temperature, current density, and magnetic field, the superconductivity of the material is destroyed [27] . It possesses negligible resistance below such critical values, indicating that it is in its superconducting mode, and substantial resistance beyond such critical levels, indicating that it is in its current limiting state. As a result, increasing any of such 3 parameters above their critical limit will result in conducting material losing its feature of superconductivity[28, 29]. As depicted in Fig.4, SFCL utilizes its changing resistance property throughout a fault to limit fault current.

2. 1. Resistive SFCL

With regard to field tests of SFCLs, resistive SFCLs were the preferred option. Its comparatively straightforward concept, lower weight and size, and resistive nature are all factors. Recent studies examined the application of such technology as a potential preventative measure in distributed generation distribution systems and islanded electrical power distribution systems[30-32]. An R-SFCL operation depends on SC fast resistivity increase owing to superconductor quenching that has been generated by excess current throughout a fault. The current flowing through the SC during a short circuit rises significantly over its critical current (Ic), causing a rapid change from superconducting to normal states. RSFCL's thermal control of heat that has been created in SC throughout the time of fault limitation as well as heat that has been released in the quench is its main weakness. In the superconducting state, superconductors have extremely low level of thermal conductivity. They are exposed to hot areas as a result, which may cause the quench to occur before Jc is reached. In order to prevent thermal instability and hotspots, superconductors that have been made for the applications were created and inserted to the material of high thermal conductivity. The electrical schematic for this equipment is shown in Fig. 5. The improvement of analytical models under different simulation suppositions and the detailed description of the correlation with experimental test results may be found in [33] .

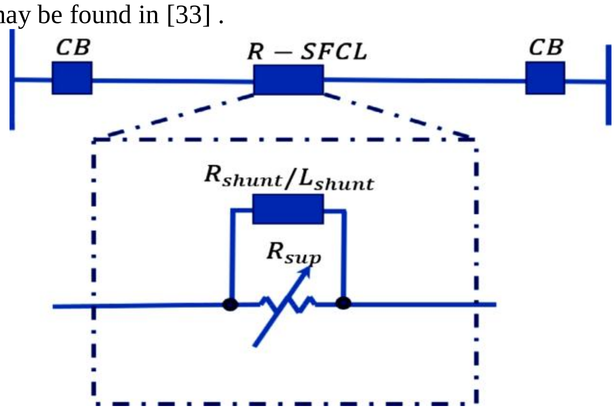

Fig.5. Electrical Circuit of an R-SFCL.

2. 2. Inductive SFCL:

FCL is typically regarded as one of first high temperature superconductor materials to be relevant in energy technology. Typical Inductive type SFCL is depicted in Figure 6. In the case where discriminating current has been surpassed, the use of constitutional presumptions regarding the superconductor converts zero-resistance case to high resistance one. For current limitation that has been obtained through progressive transition regarding superconducting tubes to the resistive state, homogeneous superconducting and thermal management qualities had been created in Inductive FCLs [34]. Active superconducting elements in inductive FCL with high short-circuit current are afflicted by existence of superheated thermal domains. Throughout incidents, excessive thermal domain expansion results in the datal mechanical destruction related to the superconducting element [35]. With numerous optimization techniques of the design of distribution network parameters of the power system, subsequent advances of the Inductive type SFCL are organized. The open core inductive SFCL design parameter was optimized using the finite element method.

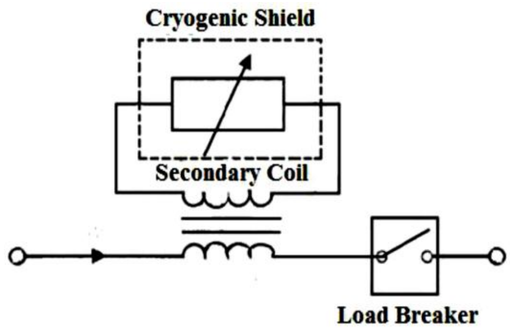

Fig. 6. Inductive SFCL

Case1: SFCL Applications in Power Grid

A. SFCL in Main Position

The FCL is utilized in this instance to protect the entire bus. The direct application of FCL to the power grid occurs when it is mounted in the primary position on a bus as shown in figure 7. The following are the key benefits of FCL:

- Without upgrading the breakers, a larger transformer could be utilized in order to handle the increased demands on a bus.
- I^2R_t damages to transformer are limited because of lower prospective fault current values.

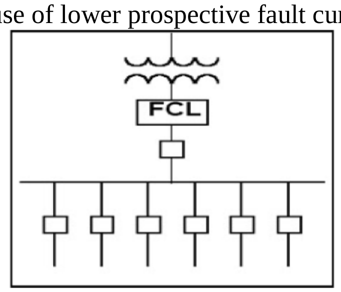

Fig7: FCL in the Main Position

B. SFCL in the Feeder Position

An individual load on a bus is protected by FCL in this position,as shown in figure 8 . Underrated equipment could be protected selectively as necessary. The individual circuit on the bus is thus protected by an SFCL. Here, the small and less expensive limiters are employed in a selective manner so as to protect wired off or overly stressed equipment, like as transformers and underground cables, that is difficult to replace.

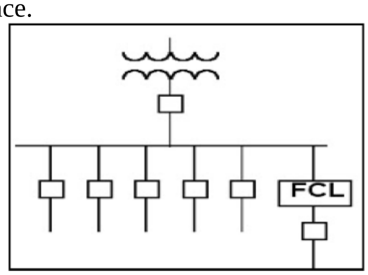

Fig. 8: an FCL in Feeder Position

C. SFCL in the bus-tie Position

Two buses that are comparable to one another are joined by a bus-tie knot. Just one transformer will supply the entire fault current to a potential bus fault. The employed limiter might require a small current rating while simultaneously having the next advantages:

- No bus will see a significant increase in the fault duty. Different buses might then be connected.
- The voltage drop across the Limiter increases dramatically when a fault occurs, keeping the level of the voltage on non-faulted bus constant [36, 37] .

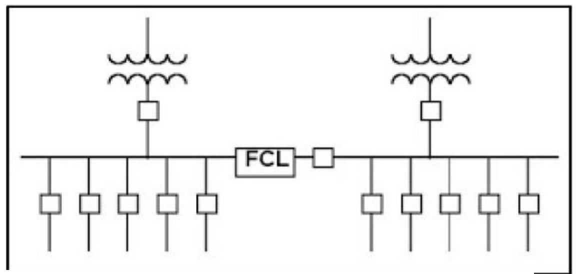

Fig. 9: An FCL in the bus-tie Position

Case2: Application of SFCLs in improving power system reliability and stability

The fault levels in the power systems rise as a result of the increased electrical power demand, seriously damaging power system equipment. Connecting the power systems so they may exchange power with one another is one of the key approaches to enhance the stability and reliability of a power system [38] . Yet, in the case when a fault develops in system, fault current is added to fault point from all inter-connected parts, limiting the inter-connection to specific level so that fault current might be kept within breaking capacity of circuit breakers. To improve reliability and stability of interconnected power systems, FCLs can be used [39] . Application of SFCLs was described [40] for limiting fault current and enhancing active distribution network stability through lowering influence upon the circuit breaker. In [41, 42], various SFCL types were used in a medium voltage active distribution networks in order to examine how they affected the circuit breaker's transient recovery voltage. This study demonstrates how SFCLs can increase system stability by lowering the amount and rate regarding the rise of transient recovery voltage on circuit breakers. Several FCLs have been used to improve the stability of micro grids, multimachine systems, wind systems smart grids, high voltage direct current (HVDC), and PV systems. Several branches of power system were used to evaluate the SFCLs. Unfortunately, non-superconducting FCL has only been used in a few power system branches.

3. Solid State FCL (SSFCL)

The FCL is a crucial feature of SSFCL. Fault limiting functionality is achieved by SSFCL by combining capacitors, inductors, and a Thyristor or IGBT. A variable impedance device called a FCL is put in series with a circuit to limit the current during fault conditions[43] . SSFL must have extremely low impedance when running normally and a high impedance when experiencing a fault [44] . Figure 10 depicts the SSFCL's fundamental configuration, which consists of two parallel-connected solid-state switches. The first branch, referred to as Thyristor Branch 1, consists of switches made of thermistors, while the second branch, referred to as Thyristor Branch 2, consists of a thyristor and a reactor for current limiting. For the two branches, switches are connected in an inverse parallel way. The system is shielded from voltage surges throughout switching by a surge arrester [45]. SSFCL current limiting behavior depend on quick acting ON/OFF status change regarding semiconductor switches for inserting current limiting reactor. In order to decrease or limit transient fault currents from growing overly big, a SSFCL could be activated extremely quickly[46, 47]. The development of high-power semiconductor technologies, like Emitter Turn-off Thyristors (ETO), emerging SiC devices, new thyristors, and high power IGBTs, enables the implementation of a SSFCL that is commercially practical .

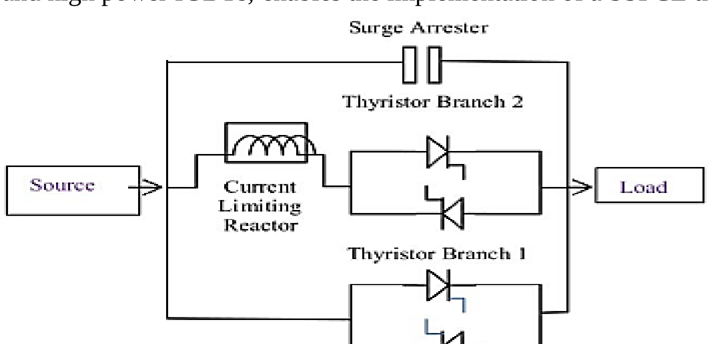

Fig. 10 The basic configuration of the SSFCL

Case1: Applications of SSFCL in Power Grid

A. Reduction of voltage on the distribution system

Through limiting the short circuit current, the voltage sag is undoubtedly decreased. The FCL's task is to limit potential fault current levels to a reasonable level without significantly affecting the distribution system. [48]shows the modeling of SSFCL regarding a single line diagram of an existent distribution line with the use of the sim-power System in MATLAB/SIMULINK. The first scenario was a simulation without SSFCL, whereas the second case was a model that included SSFCL. Also, SSFCL serves as a circuit breaker element in a power system by limiting the fault current to a safe level. SSFCL is regarded as a solution for the rise in power system short circuit current levels. It is the most cost-effective alternative to other traditional solutions to solve this problem. Data gathered from the distribution line was evaluated to better understand the impact of voltage sag brought on by fault current. The results of the simulations demonstrated that SSFCL efficiently reduces the current throughout fault occurrence.

B. Improvement of Smart Grid Performance

The effect of SSFCL on the smart grid is discussed in[49, 50] . Both a fault current limiter and a circuit breaker, SSFCL was utilized in this instance. The fault current has been limited by SSFCL, which also enhances the functionality of the smart grid. With regard to the power system, a simulation model of SSFCL as well as its control system is created and validated. When inserting SSFCL throughout a three-phase fault, the smart grid system simulation model is employed to evaluate its effectiveness. For different fault types, a comparison regarding the current smart grid system without and with SSFCL was conducted. FCL's use in electric power networks goes beyond just regulating current magnitudes in short circuits. They might be working on other projects including improving power system reliability, power quality, enhancing the transfer capacity of transformers, and limiting transformer inrush currents. To lessen the negative effects of the DGs on transient stability, power quality and power protection, various FCL configurations are recommended.[7, 51-60]. Through regulating the voltage drop throughout a fault, SSFCL-L has been utilized as inductor to limit short circuit current levels and is more successful at enhancing the quality of the system power. The transient stability regarding SSFCL-R, at the same time, is improved by utilizing the generator's acceleration energy throughout a fault [61].

4. Hybrid SFCL

Hybrid SFCLs generally include superconducting material, switching component (it could be a solid-state device or fast switch), and shunt component for limiting fault current and dissipating power. Combination of superconducting material as well as solid-state switch device (i.e. thyristors, in the present study) in same equipment can maintain benefits of every technology and avoid issues that are found in the two. Suggested Hybrid SFCL, which has been depicted in figure11, is made up of the anti-parallel thyristors that are connected in series with 2Gtape (i.e. variable resistance - Rtape). This branch has been connected in a parallel manner to air-core reactor (L) that enhances restriction and assures superconductor element's safe operations.

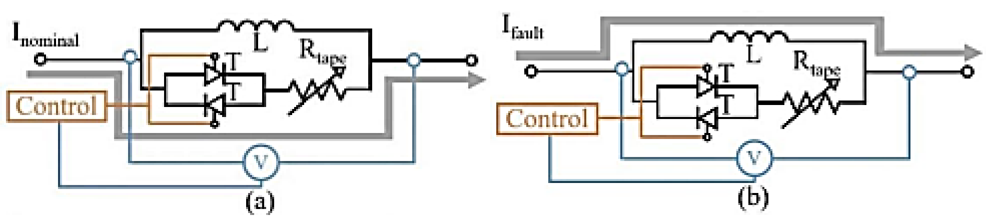

Fig. 11. Simplified hybrid SFCL circuit in
(a) a normal operation (b) throughout fault conditions

According to Fig. 11, the suggested Hybrid SFCL operates as follows: as seen in figure 11(a), system current passes through thyristors and superconducting element (R_{tape}) in steady state. The current increases and superconducting transition begin when the fault occurs. Because of the inherent properties of such materials, a voltage drop arises in the material current throughout such process as the current increases. The thyristors are instructed to open using the voltage drop as a control parameter. As shown in figure 11 (b), the current then travels to shunt reactor that serves to limit fault current. At the Hybrid SFCL terminals, the voltage is measured, and its value is put to comparison with the limit values. The thyristors get the open command signal in the case when the threshold is crossed. Because of the features of this switch, it will just open in the case where current reaches 0-value. Fault current will totally pass through super-conducting element throughout this time that will be in charge of limiting itself. Fault current won’t be limited throughout the 1st half-cycle without superconducting element, and the system could have certain electromechanical stress problems [62] .

IV. OPTIMUM PARAMETERS AND PLACEMENTS OF THE FAULT CURRENT LIMITERS

There are various potential advantages to placing FCLs at the optimal location in power network. They include increasing the interconnection regarding renewable energy, boosting fault ride through capability, decreasing fault voltage and fault current, and enhancing system security and reliability. Many optimal placement approaches were published in literature [24, 63-72] . The FCL placement in power systems is done while keeping a number of goals in mind, including fault and system improvement, fault current reduction, FCL cost reduction, and optimizations of over current relays' operating time. Several of works primarily concentrated on optimum placement with a specific objective function, such as stability enhancement[12, 73] or fault current reduction[72] . When there is a trade-off between different objectives, advancing one could result in the decline of the others. The aforementioned issue has been reported to be resolved using multi objective optimization approaches [66, 74] . Unfortunately, the majority of optimal placement algorithms do not consider uncertainties in the power systems, particularly unpredictable changes in status of wind, DG, and PV systems in the case of identifying ideal site for SFCL. For improved performance, new algorithms of placement could be created while taking into account various network uncertainties. Table 1 summarizes optimal placement parameter selection methods for various SFCLs.[63]

Table 1. Optimization approaches for superconducting FCL placement.

Objective Functions	Used /Algorithm	Types of FCL	Considered Networks	These strategies	Ref.
Minimizing main-backup Over-current relay, (OCR)-pairs coordination maintenance index and total required FCL costs.	Multi objective Particle Swarm Optimization (MOPSO)	SFCL of Impedance	IEEE 33bus radial system & IEEE 30bus Meshed system	- Locatiom and size may be obtained with no pre-assumption - Applications for the meshed as well as radial networks.	[65]
Maximization of the reliability, minimization of both I_F & FCL costs	Multi objective using Pareto algorithms	Impedance SFCL	IEEE 39 bus & IEEE 57bus systems	Penalty factor has been introduced in the problem of the optimization for the purpose of keeping I_F within maximal allowable ranges.	[74]
Minimizing SFCL number, I_F and optimum relay operating time	Scenario optimizations	Hybrid resistive SFCL	17-bus power system including the DGs	-optimum SFCL placement keeps I_F within the breaking capacity of the protective devices. - No changes in relays of coordination are needed throughout installation of the DGs in a system.	[64]
Minimizing Angular deviations between synchronous machine rotors	Transient stability index approach	Resistive SFCL	IEEE Bench marked 4-machine 2-area test system	The optimum location of the method of SFCL has the ability to limit I_F for 3 Φ-fault at any point in this network.	[72]
Minimizing total installation costs, which include fixed installation costs and incremental impedance costs	Iterative mixed integer non-linear programming	Impedance SFCL	IEEE 9-bus, IEEE 30-bus and real North American 395-bus transmission system	-FCL installation costs are minimized throughout the reduction of I_F . - this approach is restricted by pre-determined location and random search methods. - Location sensitivity indexed isn't required for suggested approach - Method is straight-forward and may be implemented for any mesh networks.	[66]
Minimizing FCL unit and parameters	Genetic algorithms	Impedance SFCL	6-bus testing system and IEEE 30-bus system	- utilizing minimal FCL unit amount and settings, I_F is kept under CB interrupt rating. - The proposed method approach includes a factor of	[69]

				sensitivity for the search space reduction.	
Minimizing power loss	Sensitivity index approach	Resistive SFCL	IEEE Bench marked 4-machine 2-area test systems	- Efficient enhancement of system damping. - In the case where even fault develops distant from optimal SFCL placement, shot circuit current decreases drastically. - The flaw of this method is that it disregards the problem of the protection coordination.	[70]

SUMMARY

Table-2 provides guidance for choosing the ideal application regarding a FCL based on a number of factors. The following data shows that hybrid FCL is preferred for a medium voltage and highest current rating. For external triggering applications, SSFCL has been considered as the most preferable and has a benefit of working with no special cooling. Hybrid FCL and SSFCL are desirable since they require less time to reset. Resistive type FCL are preferred for the applications of short and small voltage. Generally, Hybrid FCL and SSFCL function well, and both are at various stages of development and research.

Table 2
Comparison of Various Fault Current Limiters

Parameters	Resistive SFCL	Solid-State FCL	Inductive SFCL	Hybrid FCL
Maximum rating	138 kV 0.9A	69 kV 3 kA	11 kV 2 kA	12 kV 2 kA
Activation Time	T≤ ¼cycle	< 10μs	Immediately	100 ms
Triggering	Internal	External	Internal	External
Need cooling	Yes	No	Yes	Yes
Reset Time	Tens ms - 2 s	Controllable	≤5 ms	Controllable
Status	Design & tested	Development stage	R&D stage	Research stage
Weight and Size	Small	Medium	Heavy and Large	Small but additional component could increase the size

V. CONCLUSION

This study aims to provide a thorough and in-depth analysis of FCLs in power systems. The use of the FCLs in various power system branches, including transmission, generation, and distribution networks, AC/DC systems, distributed network systems, and integration of renewable energy sources, is documented and examined. The main discussion is broken down into many sections, including the use of the FCLs in various branches regarding power systems, discussing and categorizing structure of various FCLs, the advantages and disadvantages of various FCLs, grid operation and testing FCLs, parameter design and fault augmentation, and real and real ride through capability systems using various FCLs. The literature study reveals that FCL placement is crucial for limiting fault current and enhancing power system stability. Yet, there are still many obstacles to overcome when using FCLs in a power system, including the minimization of interference with nearby communication lines, reducing loss during normal operations, developing optimal parameters, coordinating the control design of the FCL as well as other protective devices, field testing, feasibility analysis, and real grid line operation. This study highlights a number of gaps that present difficulties for FCL application and control in the power systems that have been considered as fascinating subjects for the power system researches.

REFERENCES

[1] B. Raju, K. Parton, and T. Bartram, "A current limiting device using superconducting dc bias applications and prospects," *IEEE Transactions on Power Apparatus and Systems,* no. 9, pp. 3173-3177, 1982.

[2] S. S. Kalsi and A. Malozemoff, "HTS fault current limiter concept," in *IEEE Power Engineering Society General Meeting, 2004.*, 2004: IEEE, pp. 1426-1430.
[3] P. Juhnke, "Effect of current limiting reactors on turbo-generator systems under conditions of short circuit," *Proceedings of the American Institute of Electrical Engineers,* vol. 36, no. 2, pp. 281-290, 1917.
[4] Y. A. Bashkirov, L. Fleishman, T. Y. Patsayeva, A. Sobolev, and A. Vdovin, "Current-limiting reactor based on high-T/sub c/superconductors," *IEEE transactions on magnetics,* vol. 27, no. 2, pp. 1089-1092, 1991.
[5] F. Kierstead and H. Stephens, "Current-limiting reactors their design, installation and operation," *Transactions of the American Institute of Electrical Engineers,* vol. 43, pp. 902-913, 1924.
[6] D. Ito *et al.*, "6.6 kV/1.5 kA-class superconducting fault current limiter development," *IEEE Transactions on Magnetics,* vol. 28, no. 1, pp. 438-441, 1992.
[7] W.-J. Park, B. C. Sung, and J.-W. Park, "The effect of SFCL on electric power grid with wind-turbine generation system," *IEEE Transactions on Applied Superconductivity,* vol. 20, no. 3, pp. 1177-1181, 2010.
[8] B. Lee *et al.*, "Design and experiments of novel hybrid type superconducting fault current limiters," *IEEE transactions on applied superconductivity,* vol. 18, no. 2, pp. 624-627, 2008.
[9] C. Zhao *et al.*, "Development and test of a superconducting fault current limiter-magnetic energy storage (SFCL-MES) system," *IEEE transactions on applied superconductivity,* vol. 17, no. 2, pp. 2014-2017, 2007.
[10] T. Hori, A. Otani, K. Kaiho, I. Yamaguchi, M. Morita, and S. Yanabu, "Study of superconducting fault current limiter using vacuum interrupter driven by electromagnetic repulsion force for commutating switch," *IEEE transactions on applied superconductivity,* vol. 16, no. 4, pp. 1999-2004, 2006.
[11] L. Kovalsky, X. Yuan, K. Tekletsadik, A. Keri, J. Bock, and F. Breuer, "Applications of superconducting fault current limiters in electric power transmission systems," *IEEE Transactions on Applied Superconductivity,* vol. 15, no. 2, pp. 2130-2133, 2005.
[12] K. Hongesombut, Y. Mitani, and K. Tsuji, "Optimal location assignment and design of superconducting fault current limiters applied to loop power systems," *IEEE Transactions on Applied Superconductivity,* vol. 13, no. 2, pp. 1828-1831, 2003.
[13] L. Ye and A. Campbell, "Behavior investigations of superconducting fault current limiters in power systems," *IEEE Transactions on applied Superconductivity,* vol. 16, no. 2, pp. 662-665, 2006.
[14] L. Salasoo, A. F. Imece, R. W. Delmerico, and R. D. Wyatt, "Comparison of superconducting fault limiter concepts in electric utility applications," *IEEE Transactions on Applied Superconductivity,* vol. 5, no. 2, pp. 1079-1082, 1995.
[15] Y. Jia, J. Yuan, Z. Shi, H. Zhu, Y. Geng, and J. Zou, "Simulation method for current-limiting effect of saturated-core superconducting fault current limiter," *IEEE Transactions on Applied Superconductivity,* vol. 26, no. 4, pp. 1-4, 2016.
[16] L. Jiang, J. X. Jin, and X. Y. Chen, "Fully controlled hybrid bridge type superconducting fault current limiter," *IEEE Transactions on Applied Superconductivity,* vol. 24, no. 5, pp. 1-5, 2014.
[17] E. Leung *et al.*, "High temperature superconducting fault current limiter for utility applications," *Advances in Cryogenic Engineering Materials*, pp. 961-968, 1997.
[18] J. Jin *et al.*, "Electrical application of high T/sub c/superconducting saturable magnetic core fault current limiter," *IEEE Transactions on Applied Superconductivity,* vol. 7, no. 2, pp. 1009-1012, 1997.
[19] Y. Xin *et al.*, "Performance of the 35 kV/90 MVA SFCL in live-grid fault current limiting tests," *IEEE transactions on applied superconductivity,* vol. 21, no. 3, pp. 1294-1297, 2011.
[20] T. Janowski, S. Kozak, B. Kondratowicz-Kucewicz, G. Wojtasiewicz, and J. Kozak, "Analysis of transformer type superconducting fault current limiters," *IEEE transactions on applied superconductivity,* vol. 17, no. 2, pp. 1788-1790, 2007.
[21] K. Fushiki, T. Nitta, J. Baba, and K. Suzuki, "Design and basic test of SFCL of transformer type by use of Ag sheathed BSCCO wire," *IEEE transactions on applied superconductivity,* vol. 17, no. 2, pp. 1815-1818, 2007.
[22] H. Yamaguchi and T. Kataoka, "Effect of magnetic saturation on the current limiting characteristics of transformer type superconducting fault current limiter," *IEEE transactions on applied superconductivity,* vol. 16, no. 2, pp. 691-694, 2006.
[23] H. Yamaguchi, K. Yoshikawa, M. Nakamura, T. Kataoka, and K. Kaiho, "Current limiting characteristics of transformer type superconducting fault current limiter," *IEEE transactions on applied superconductivity,* vol. 15, no. 2, pp. 2106-2109, 2005.
[24] X. Zhang, H. Ruiz, J. Geng, and T. Coombs, "Optimal location and minimum number of superconducting fault current limiters for the protection of power grids," *International Journal of Electrical Power & Energy Systems,* vol. 87, pp. 136-143, 2017.
[25] H. Yaghoubi, "The most important maglev applications," *Journal of Engineering,* vol. 2013, 2013.
[26] E. Muljadi, V. Gevorgian, and F. DeLaRosa, "Wind power plant enhancement with a fault current limiter," in *2011 IEEE Power and Energy Society General Meeting*, 2011: IEEE, pp. 1-7.
[27] M. S. Alam, M. A. Y. Abido, and I. El-Amin, "Fault current limiters in power systems: A comprehensive review," *Energies,* vol. 11, no. 5, p. 1025, 2018.
[28] T. Nishihara, T. Hoshino, and M. Tomita, "Analysis of FCL effect caused by superconducting DC cables for railway systems," in *IOP Conference Series: Materials Science and Engineering*, 2017, vol. 171, no. 1: IOP Publishing, p. 012122.
[29] A. Aswathi and K. Krishna, "Microgrid protection using superconducting fault current limiter," *International Research Journal of Engineering and Technology,* vol. 3, pp. 1320-1325, 2016.

[30] D. Guillen, C. Salas, F. Trillaud, L. M. Castro, A. T. Queiroz, and G. G. Sotelo, "Impact of resistive superconducting fault current limiter and distributed generation on fault location in distribution networks," *Electric Power Systems Research,* vol. 186, p. 106419, 2020.

[31] G. R. Mafra, R. M. Vidaurre, F. Z. Fortes, M. Z. Fortes, and G. G. Sotelo, "Application of a resistive superconducting fault current limiter in a distribution grid," *Electric Power Components and Systems,* vol. 44, no. 18, pp. 2084-2098, 2016.

[32] G. Mafra, G. Sotelo, M. Fortes, and W. De Sousa, "Application of resistive superconducting fault current limiters in offshore oil production platforms," *Electric Power Systems Research,* vol. 144, pp. 107-114, 2017.

[33] G. G. Sotelo *et al.*, "A review of superconducting fault current limiters compared with other proven technologies," *Superconductivity,* p. 100018, 2022.

[34] J. Cave *et al.*, "Testing and modelling of inductive superconducting fault current limiters," *IEEE transactions on applied superconductivity,* vol. 7, no. 2, pp. 832-835, 1997.

[35] V. Meerovich, V. Sokolovsky, J. Bock, S. Gauss, S. Goren, and G. Jung, "Performance of an inductive fault current limiter employing BSCCO superconducting cylinders," *IEEE transactions on applied superconductivity,* vol. 9, no. 4, pp. 4666-4676, 1999.

[36] K. Smedley and A. Abravomitz, "Development of fault current controller technology," 2011.

[37] V. Sokolovsky, V. Meerovich, and I. Vajda, "Transient stability of a power system with superconducting fault current limiters," *arXiv preprint cond-mat/0701308,* 2007.

[38] H. Singh and P. Jindal, "Enhancement of multi-machine stability using Fault Current Limiter and Thyristor Controlled Braking Resistor," *International Journal of Modern Computer Science,* vol. 4, pp. 28-31, 2016.

[39] A. Fereidouni, M. A. Masoum, T. Hosseinimehr, and M. Moghbel, "Performance of LR-type solid-state fault current limiter in improving power quality and transient stability of power network with wind turbine generators," *International Journal of Electrical Power & Energy Systems,* vol. 74, pp. 172-186, 2016.

[40] S. Robak, K. Gryszpanowicz, M. Piekarz, and M. Polewaczyk, "Transient stability enhancement by series braking resistor control using local measurements," *International Journal of Electrical Power & Energy Systems,* vol. 112, pp. 272-281, 2019.

[41] M. Firouzi, S. Aslani, G. Gharehpetian, and A. Jalilvand, "Effect of superconducting fault current limiters on successful interruption of circuit breakers," in *International Conference on Renewable Energies and Power Quality (ICREPQ'12), Santiago de Compostela, Spain*, 2012.

[42] C. Neumann, "Superconducting fault current limiter (SFCL) in the medium and high voltage grid," in *2006 IEEE Power Engineering Society General Meeting*, 2006: IEEE, p. 6 pp.

[43] L. E. Conrad and M. H. Bollen, "Voltage sag coordination for reliable plant operation," *IEEE Transactions on Industry Applications,* vol. 33, no. 6, pp. 1459-1464, 1997.

[44] W. Saeed, "Reducing the Impacts of Distributed Generation in Transmission & Distribution Networks Protection Using Fault Current Limiters," *Engineering and Technology Journal,* vol. 31, no. 12 Part (A) Engineering, 2013.

[45] J. Sharma, V. Chauhan, and H. Kamath, "Modelling and Analysis of Solid State Fault Current Limiter," *International Journal of Electrical, Electronics and Data Communication,* vol. 2, no. 6, pp. 9-13, 2014.

[46] Y. Zhang and R. A. Dougal, "State of the art of fault current limiters and their applications in smart grid," in *2012 IEEE Power and Energy Society General Meeting*, 2012: IEEE, pp. 1-6.

[47] C. W. Group, "Fault Current Limiters in Electrical medium and high voltage systems," ed: GIGRE publishing, 2003.

[48] R. GLORIA, "ASSESSMENT OF THE IMPACT OF EFFLUENTS FROM BONITE BOTTLERS AND CHINA PAPER INDUSTRIESON THE WATER QUALITY IN KARANGA RIVER, TANZANIA," Kenyatta University, 2014.

[49] A. Safaei, M. Zolfaghari, M. Gilvanejad, and G. B. Gharehpetian, "A survey on fault current limiters: Development and technical aspects," *International Journal of Electrical Power & Energy Systems,* vol. 118, p. 105729, 2020.

[50] A. Kavousi-Fard, B. Wang, O. Avatefipour, M. Dabbaghjamanesh, R. Sahba, and A. Sahba, "Superconducting fault current limiter allocation in reconfigurable smart grids," *arXiv preprint arXiv:1905.02324,* 2019.

[51] Y. Shirai, K. Furushiba, Y. Shouno, M. Shiotsu, and T. Nitta, "Improvement of power system stability by use of superconducting fault current limiter with ZnO device and resistor in parallel," *IEEE Transactions on Applied Superconductivity,* vol. 18, no. 2, pp. 680-683, 2008.

[52] T. Sato *et al.*, "Study on the effect of fault current limiter in power system with dispersed generators," *IEEE transactions on applied superconductivity,* vol. 17, no. 2, pp. 2331-2334, 2007.

[53] S. M. Brahma and A. A. Girgis, "Development of adaptive protection scheme for distribution systems with high penetration of distributed generation," *IEEE Transactions on power delivery,* vol. 19, no. 1, pp. 56-63, 2004.

[54] L. Ye, L. Lin, and K.-P. Juengst, "Application studies of superconducting fault current limiters in electric power systems," *IEEE Transactions on Applied Superconductivity,* vol. 12, no. 1, pp. 900-903, 2002.

[55] 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 *2002 IEEE power engineering society winter meeting. conference proceedings (Cat. No. 02CH37309),* 2002, vol. 1: IEEE, pp. 453-458.

[56] W. El-Khattam and T. S. Sidhu, "Restoration of directional overcurrent relay coordination in distributed generation systems utilizing fault current limiter," *IEEE Transactions on power delivery,* vol. 23, no. 2, pp. 576-585, 2008.

[57] M. Tsuda, Y. Mitani, K. Tsuji, and K. Kakihana, "Application of resistor based superconducting fault current limiter to enhancement of power system transient stability," *IEEE transactions on applied superconductivity*, vol. 11, no. 1, pp. 2122-2125, 2001.

[58] M. M. R. Ahmed, G. Putrus, and L. Ran, "Power quality improvement using a solid-state fault current limiter," in *IEEE/PES transmission and distribution conference and exhibition*, 2002, vol. 2: IEEE, pp. 1059-1064.

[59] C. Chang and P. Loh, "Integration of fault current limiters on power systems for voltage quality improvement," *Electric power systems research*, vol. 57, no. 2, pp. 83-92, 2001.

[60] M. M. R. Ahmed, G. A. Putrus, L. Ran, and L. Xiao, "Harmonic analysis and improvement of a new solid-state fault current limiter," *IEEE Transactions on Industry Applications*, vol. 40, no. 4, pp. 1012-1019, 2004.

[61] A. R. Fereidouni, B. Vahidi, and T. H. Mehr, "The impact of solid state fault current limiter on power network with wind-turbine power generation," *IEEE Transactions on Smart Grid*, vol. 4, no. 2, pp. 1188-1196, 2012.

[62] H. K. Miyamoto, A. T. Queiroz, D. H. Dias, B. W. França, F. Sass, and G. G. Sotelo, "Novel Design of a Hybrid Superconducting Fault Current Limiter with Controlled Solid-State Device," *Journal of Microwaves, Optoelectronics and Electromagnetic Applications*, vol. 20, pp. 334-347, 2021.

[63] H.-C. Jo and S.-K. Joo, "Superconducting fault current limiter placement for power system protection using the minimax regret criterion," *IEEE Transactions on Applied Superconductivity*, vol. 25, no. 3, pp. 1-5, 2015.

[64] H.-C. Jo, S.-K. Joo, and K. Lee, "Optimal placement of superconducting fault current limiters (SFCLs) for protection of an electric power system with distributed generations (DGs)," *IEEE Transactions on Applied Superconductivity*, vol. 23, no. 3, pp. 5600304-5600304, 2012.

[65] A. Elmitwally, E. Gouda, and S. Eladawy, "Optimal allocation of fault current limiters for sustaining overcurrent relays coordination in a power system with distributed generation," *Alexandria Engineering Journal*, vol. 54, no. 4, pp. 1077-1089, 2015.

[66] P. Yu, B. Venkatesh, A. Yazdani, and B. N. Singh, "Optimal location and sizing of fault current limiters in mesh networks using iterative mixed integer nonlinear programming," *IEEE Transactions on Power Systems*, vol. 31, no. 6, pp. 4776-4783, 2016.

[67] S. Zare, A. H. Khazali, S. M. Hashemi, F. Katebi, and R. Khaliti, "Fault current limiter optimal placement by harmony search algorithm," in *22nd International Conference and Exhibition on Electricity Distribution (CIRED 2013)*, 2013: IET, pp. 1-4.

[68] S.-Y. Kim, W.-W. Kim, and J.-O. Kim, "Determining the location of superconducting fault current limiter considering distribution reliability," *IET generation, transmission & distribution*, vol. 6, no. 3, pp. 240-246, 2012.

[69] J.-H. Teng and C.-N. Lu, "Optimum fault current limiter placement with search space reduction technique," *IET generation, transmission & distribution*, vol. 4, no. 4, pp. 485-494, 2010.

[70] B. C. Sung, D. K. Park, J.-W. Park, and T. K. Ko, "Study on optimal location of a resistive SFCL applied to an electric power grid," *IEEE Transactions on applied superconductivity*, vol. 19, no. 3, pp. 2048-2052, 2009.

[71] P. Chantachiratham and K. Hongesombut, "PSO based approach for optimum fault current limiter placement in power system," in *2012 9th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology*, 2012: IEEE, pp. 1-4.

[72] G. Didier, J. Leveque, and A. Rezzoug, "A novel approach to determine the optimal location of SFCL in electric power grid to improve power system stability," *IEEE Transactions on Power Systems*, vol. 28, no. 2, pp. 978-984, 2012.

[73] M. El Moursi and R. Hegazy, "Novel technique for reducing the high fault currents and enhancing the security of ADWEA power system," *IEEE Transactions on Power Systems*, vol. 28, no. 1, pp. 140-148, 2012.

[74] A. Mahmoudian, M. Niasati, and M. A. Khanesar, "Multi objective optimal allocation of fault current limiters in power system," *International Journal of Electrical Power & Energy Systems*, vol. 85, pp. 1-11, 2017.

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