Active Distribution Networks with Fault Current Limiters

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To cope with the increasing energy demand, power systems, especially distribution networks, face many challenges. These networks have become complex and large, and their stability and reliability are not easy to be handled. The integration of renewable energy resources and at the same time limiting their accompanied high fault currents is one of the approvable suggestions. Many solutions have appeared to restrict the fault currents, but fault current limiters (FCLs) arise as an efficient and promising solution to whether to interrupt or limit the fault currents to allowable limits.

Keywords: distributed generation ; solar energy ; wind energy ; superconducting material fault current limiters

1. Introduction

Electricity has become a necessity—no longer a luxury—where life almost stops without electricity. Among power system networks (generation, transmission, and distribution), the last networks form the most critical ones as they greatly affect the whole system reliability and the quality of the service. In addition, the operation of the distribution networks can determine 90% of the reliability of the system introduced to the customers whilst both generation and transmission can determine the rest [1]. In order to meet the high demand for electrical power and accelerating loads, power system operators seek to supply more electrical power by the integration of distributed generation (DG) units [2]. These units are connected beside the loads without any need for power plant and transmission network construction. There are many types of DGs that can be classified in terms of size, the type of energy they are based on, and their capability to deliver real and reactive power.

In order to avoid the problems associated with badly allocated DGs, their location, sizing, type, and number should be optimally determined. The optimal allocation of DGs has been widely introduced in the research area, achieving several objective functions, whilst analytical methods and different optimization techniques have been employed to realize this allocation.

As shown in [3], the optimal placements and sizes of DG units were identified in a 33-node system using a circuit-based branch-oriented method in order to reduce power losses. Instead of this method, the identification of susceptible nodes has been assigned to determine the position of DGs in order to reduce actual and reactive losses [4]. The mixed nonlinear programming (MINLP) method was adopted for the classical category to determine the optimal placement of wind-based DGs in distribution systems with minimal power losses [5]. In particular, in [6], a dynamic programming method was employed to investigate the advantages of reduced power losses, improved overall reliability, and grid voltages. This approach, however, does not ensure obtaining a global optimum.

Based on metaheuristic optimization techniques, an improved grey wolf optimizer (GWO) has been implemented to determine the optimal placement and sizing of DGs for different considerations varying between economic, environmental, and technical [7], while the genetic algorithm (GA) has been adapted to select the optimal penetration, location, and sizing of DGs. This approach aims for minimizing power losses in radial distribution systems as the size ranges from 6.25 to 100% of the maximum unit size with a step of 6.25% [8]. In addition, the optimal location and size of the DGs have been selected depending on particle swarm optimization (PSO) [9]. This has been proposed to convert the radial distribution system into a loop regarding the reduction in the voltage difference between the endpoints of the longest feeder. As well, a PSO has been introduced to allocate the DGs for only minimizing the active power losses [10]. Looking at the voltage enhancement, the research in [11] harnesses a Heap-based optimizer (HO) for optimally allocated DGs. For working on reducing computational time, discrete PSO has been employed for handling the optimal allocation of the DGs of different power factors. This allocation is obtained for power loss minimization and voltage profile improvement [12]. Other than PSO, a global harmony search algorithm has been applied to obtain the optimal placement and sizing of DGs in radial distribution systems [13]. Added to that, reference [14] has a hybridized multiverse optimizer with a space transformation search method and chaotic mapping to optimally integrate the DGs into distribution networks. Considering the economical side, optimal operating capacity, and electricity prices besides the optimal payback investment time, the mixed integer nonlinear programming has been utilized to maintain the optimal DG allocation [15].

Although DG integration in distribution networks has many avails, it is not without some obstacles. These obstacles greatly appear in the malfunction in the protective devices' operation, as DGs can increase the fault currents to higher values exceeding the predefined limits. Moreover, the higher fault currents accompanied by DGs can override the thermal limits of power system components, leading to the deterioration of these components developing to the expulsion of some. Many solutions have been found to return these higher currents to their initial value, among which fault current limiters (FCLs) have arisen as an economical and reliable solution. The integration of FCLs can be considered as a vital tool to reduce the fault currents to affordable values, which can safely flow through the components and at the same time keep the required coordination between the protective devices. According to this, there is no need to upgrade the protective devices, and this gives the ability to sustain the existing ones [16]. During normal operation, FCLs form a low impedance, so they pose insignificant power losses. On the other side, FCLs introduce a high impedance, as it is required to be apparent only in the fault condition in order to reduce fault currents [17]. According to this, the enhancement of the overall distribution networks' performance, whether in a steady state or a fault condition, can be handled through both DGs and FCLs.

2. Distributed Generation (DG) Units

Distributed generation, or decentralized generation, as it is known in some areas, is an electric source of limited capacity connected to the customer side [2] According to the energy power association (EPA), it is defined as a small, modular, decentralized, grid-connected or disconnected energy system located in or near the place where the energy is used. In recent years, DGs have been widely used due to their reliability and endurance in addition to their efficiency and economy. Moreover, they are considered as an effective component that clarifies the penetration of renewable energy resources in the network [18]. DGs can be categorized in different terms according to their size and the type of energy on which they operate besides their capability to deliver real and reactive power.

In accordance with their size, DGs have the ability to supply different loads with different sizes; therefore, their capabilities range from tens of VAs to hundreds of MVAs. In general, there are four categories based on DG size; micro DGs (1 W to 5 kW), small DGs (5 kW to 5 MW), medium (5 MW to 50 MW), and large ones (50 MW to 300 MW) [19]. In accordance with the type of energy, there are different kinds based on which DGs can operate. These types can be divided into renewable and nonrenewable energy resources. As renewable energy resources are available forever and are friendly to the environment, most modern DGs are based on renewable energy resources like solar, wind, water, geothermal, biomass, and fuel cell. Recently, more than 90 countries have utilized at least 1 GW generated from renewable energy, whilst 30 countries have consumed 30 GW [20]. In general, the total capacity generated from renewable energy resources has reached 1454 GW in 2016, increasing to 2378 in 2018 (55% PV, 28% wind, and 11% hydropower), which represents 33% of the total world capacity. Moreover, it is expected to grow more and more in the future.

Since the 1970s, the Egyptian government has started testing and evaluating renewable energy applications [21]. In 2016, Egypt could generate 3687 MW from renewables with a percentage of 9.49% of the total energy produced. Down to 2018, it has installed amounts of 3.7 GW of renewable energy resources, including 2.8 GW of hydro and around 0.9 GW of solar and wind power [21]. Moreover, as specified in the integrated sustainable energy strategy (ISES), by 2030 Egypt, aims to produce 20% of its total capacity through renewable energy resources, reaching 42% by 2050.

2.1. Solar Energy

Generally, the amount of sunlight hitting the earth in one hour equals the total annual primary energy used by the world [22]. Through photovoltaic cells (PVs) and concentrating solar power (CSP), electricity can be generated from the sun whether via its light or its heat, respectively. Egypt is considered one of the most suitable regions for generating solar energy besides thermal heating. The total energy generated by PV was 6 MW in 2013, whilst 30 MW of off-grid was implemented at the end of 2016 [21].

For the PVs, the basic unit is the PV cell, which was discovered by Edmond Becquerel. It became available after the development of the processing of semiconductor silicon in the 1960s [22]. Furthermore, solar PV has become more applicable where there has been a significant growth rate of power during the last years [20]. When a photon penetrates the silicon PV, it gives the sufficient electron energy to become a free one, leaving the hole.

Each cell can provide 2.4 A with an output voltage from 0.5 to 0.6 V according to its size. The basic unit in the PV system is the PV cell, whereas the combination of cells (series and parallel) forms modules; combining these modules results in PV panels, whilst some panels can create the PV array.

2.2. Wind Energy

This type of energy is not new but it has been used for decades. The IEA has regarded wind as the most competitive type of renewable energy among the rest of the renewable energy resources [23]. Wind power provided a capacity of 591 GW in 2018 with the additional power of around 50 GW added to the year 2017 [20]. According to Egypt's wind Atlas (wind Atlas for Egypt measurement and modeling 1991–2005), Egypt is overgrown with wind energy, especially in the area of the Gulf of Suez [21]. Moreover, this place is one of the best locations for wind power generation in the world. This is because it has a high stable wind speed of 8 to 10 m/s at the height of 100 m. The first wind farm was constructed in Hurghada in 1993 with a capacity of 5.2 MW. Passing to 2015, the capacity increased to 750 MW through constructing new power plants like Zaafarana (545 MW) and the Gulf of El-Zayt (200 MW) [21].

2.3. Water Energy

As 71% of our planet's surface is full of water, this type of energy can be widely used through different mechanisms. These mechanisms vary between hydropower, marine, and hydrokinetic, but all of them are effective to generate power from water. Hydropower is the most common one, through which water is harnessed to generate power, using which, China produced a considerable amount of energy of more than 300 GW in 2018 [20]. This type of energy depends on the existence of a sufficient height of water (more than 40 m), which should be adequate to create potential energy. Unlike most renewable energy resources, hydropower is not intermittent, so it is suitable for a base load.

Marine and hydrokinetic energy is a new form of energy that enables generating power from water without the need of constructing dams. This energy starts to be applicable as the energy extracted reached 2 MW in 2018 [23]. There are two mechanisms through which energy can be obtained from the ocean: thermal energy from the sun and mechanical energy from the motion of both waves and tides [23]. Thermal energy from the sun is defined as ocean thermal energy conversion (OTEC) where the power is generated from the temperature difference between the surface and the deep ocean. On the other side, energy is extracted whether from the surface wave or from the fluctuations below the surface. This figure illustrates an oscillating water column system, which counts on the motion of water whether incoming or outgoing. The incoming waves compel the top air column to turn the turbine whilst the outgoing waves pull the air column down to turn the turbine.

2.4. Geothermal Energy

It is the only renewable energy resource created by the earth itself [24]. This type of energy source can be used for both heating and generating electricity; the first large municipal district heating service started in Iceland in 1930 [22]. It has become one of the leading countries in geothermal energy as it produced around 750 MW in 2018. This is a non-pollutant source of energy which helps in reducing CO_2 by 96% when relying on it instead of coal [25]. This type of energy fits with the base load as enhanced geothermal systems are expected to provide the power of 100 GW of cost-competitive electricity in the USA by 2050 [25]. There are different geothermal energy sources like hot water, natural steam, and geo-pressured reservoirs. Geothermal energy is extracted from about 6400 km below the Earth's surface, where the temperature reaches 5000 °C. Therefore, there are few places considered as suitable geothermal resources, although this type is available and easy to exploit. The average geothermal gradient in France is 4 °C/100 m, while it reaches 30 °C/100 m in Iceland and volcanic regions [23].

2.5. Biomass (Bioenergy)

The term biomass, or bioenergy, is defined as a renewable energy resource derived from living or recently living organisms. This type of energy has many applications as it is burned directly to produce heat or power, and it can be converted into liquid biofuels. There are three main types of biomass [26]:

(1)Solid biofuels and renewable waste.

(2)Biogas (landfill gas).

(3)Liquid biofuels like biogasoline and biodiesel.

2.6. Fuel Cell (FC)

Fuel Cells are basically batteries in which electrical power is generated, with thermal power and water as co-generation through an electrochemical process. FCs are well known from the early 1960s as they were implemented in the modulated states' space program in addition to many automobile industry companies [2]. Its output ranges from kW to MW as it is used for both mobile and stationary applications. Additionally, it can operate at different pressure levels. There are different types of FCs, such as Proton Exchange Membrane (PEMFC), Alkaline (AFC), Phosphoric Acid (PAFC), Melton Carbonate (MCFC), Direct Methanol (DMFC), and Solid Oxid (SOFC) [27]. The challenge that faces the operation of FCs is the existence of hydrogen sources, as FC, unlike batteries, which are limited by stored chemicals, can work until there is a source of hydrogen [28]. Accordingly, both MCFC and SOFC have high operation temperatures, which are directed at turning hydrocarbon products into hydrogen. This means that the cell can operate self-independently. Looking at the charger carrier, it differs in MCFC and SOFC. For MCFC, carbonate CO_3^{-2} represents the charger carrier, while it is the oxide O^{2-} in SOFC [27]. For control purposes and converting the DC component accompanied by some of these DG units, all of them are integrated into the distribution network through a voltage source converter (VSC).

3. Fault Current Limiters (FCLs)

3.1. FCLs Applications and Conditions

FCLs, devices that reduce prospective fault currents to a lower, manageable level [29], are regarded as applicable and effective tools. They depend on inserting impedance into the grid, limiting high fault currents. With FCLs integrated into power systems, the procedures have the opportunity to avoid equipment replacement and damage and use a lower fault-rated one [30]. Moreover, FCLs form a low impedance at normal operation where the power flow is unobstructed. They have several applications as they can be applied in transmission [31][32] and distribution networks [33][34]. Additionally, they can be utilized in both alternating and direct current systems [31][35]. To enhance the system stability [36] and fault through capability [37], FCLs are used as well. However, there are certain conditions in which FCLs are vital in these applications, such as [30][38]:

(1)Sufficient low impedance at normal operation whilst possessing large values during fault conditions.

(2)Quick appearance when the fault occurs, as they should work within the first cycles of the fault current, and also, at the same time, they should return rapidly to their initial values after fault elimination.

(3)Reliable current limitation.

(4)Can withstand any current magnitude or any kind of fault.

(5)Do not affect the coordination of protective devices.

(6)Small size, low cost (operational and maintenance), and long lifetime.

3.2. Development of FCLs

Work on enhancing the properties of FCLs is continued, but there are three major technologies which in turn help in ameliorating the quality of FCLs. They can be clarified as follows [29]:

(1)The purification of Yttrium Barium Copper Oxide (YBCO) superconductors for coated conductors with a reasonable cost.

(2)Advancement in the development of Magnesium Diboride (MgB2) superconductor wire designed specifically with FCL properties.

(3)The development of a Silicon Carbide (SIC)-powered electronic device.

3.3. Types of FCLs

Work on the modification of FCLs' performance has attracted a lot of researchers. This helps in finding new enhanced types that match with the applications of higher ratings. Generally, FCLs can be classified as:

3.3.1. Fault Current Limiting Reactor

It is the simplest one that consists of a limiting coil [35]. This coil has large inductive reactance and low ohmic resistance [29]. Such FCLs can be divided into two types: air core and iron core, where the limiting impedance depends on the magnitude of the fault current. Unlike the iron core, the air core does not suffer from saturation, so its impedance is independent [29].

3.3.2. Pyrotechin Fault Current Limiter (Is-Limiter)

The Is-Limiter, which was created in 1995, consists of an ultrafast-acting switch and a contactor connected in parallel to a high interrupting fuse [29]. At a fault condition, a high external trigger provides the main path for the fault current to transfer to the fuse. This fuse can limit the fault current to 0.5 ms and then interrupt it in the next zero-voltage moment [39]. Finally, the Is-limiter is disconnected after operation by the service. This operation needs an electronic measurement device as an additional circuit to determine if the passing current needs to be interrupted or not. This limiter can let the existing devices run as they are not replaced but it is not non-resettable [29].

3.3.3. Superconducting Fault Current Limiters (SCFCLs)

Superconducting materials are those that can carry electrons from one atom to another without any resistance [39]. These materials have two states, the normal and superconducting states, where the transition from one state to another mainly depends on the current, magnetic field, and temperature. Below the critical current [40], the material has no resistance (superconducting state), while, when the current increases until it reaches its critical value, the quench operation occurs, and the material transfers to its normal state. In this state, there is a great resistance besides high temperature, so a cooling system must be created. According to the temperature generated, superconductors can be categorized as low-temperature superconductors (LTSC) and high-temperature superconductors (HTSC) [41][42]. For LTSC, the transition temperature is below 25 Ko, and the cooling system, which is liquid helium, reduces the temperature to 4.2 Ko. The new version of superconductors, HTSC, can be cooled by liquid nitrogen and can operate at 77 ko [29].

The nature of the superconducting materials has been harnessed to be implemented in FCLs where the first SCFCL is 12–100 FCL. It can operate at 12 kV and 100 A. This has been fabricated by Nexans superconductors (NSC) GmbH and installed in Bamber Bridge, UK as a busbar coupler. The second one has been developed to work in 12 kV and 800 A systems. It is the first HTS device to work in a thermal power plant. Both SCFCLs have been used since the last quarter of 2009 [43]. According to the structure and operation, SCFCLs can be divided into inductive and non-inductive-type SCFCLs. Non-inductive-type SCFCLs consist of two superconducting coils, which can be formulated as a current-limiting coil and a trigger coil. The two coils are connected antiparallelly and magnetically coupled [17]. There are many configurations, such as coaxial coil and bifilar winding, which are superior as they have a high impedance ratio. On the other hand, the inductive type consists of primary and secondary coaxial coils with a magnetic core [44]. The primary coil is made of copper, while the secondary one is made of HTS.

Inductive Shield SCFCL

It is about the secondary side, which is the superconducting coil (SC coil) and the bypass winding lapped around the iron core, and the primary side as the power line [29]. During the normal operation, where the material appears in its superconducting state, the secondary coil shields the iron core from the primary coil. This means that the magnetic flux generated by the primary is not able to penetrate the iron core, so the impedance transferring to the primary is very low. On the other side, the superconducting coil losses its superconductivity at the fault condition so the magnetic field can pass through the iron core, forming a high impedance at the primary side. In this state, bypass winding can provide a path for the flowing current. This in turn reduces the energy produced in the SC coil and produces a counter-induction, reducing the current in the primary coil. Generally, the idea of this device depends on the full diamagnetism of the superconducting materials, which was first discovered by Meibner and Oshsenfeld [29].

Saturated Iron Core-Type SCFCL

It is composed of two iron cores (each for a half cycle), AC windings, superconducting DC winding wrapped around each core, DC power, and a control circuit [29]. During normal operation, the DC source can feed the superconducting winding which in turn produces DC magnetic field. This field saturates the two iron cores; therefore, there is no impedance, whereas when a disturbance occurs, the control circuit plays its role as it can disconnect the DC magnetizing coil just after the fault happens. This fault current produces a large inductive electromagnetic force in the two AC coils, which in turn limits the current. This type has superiority, as the superconducting material does not have to transfer to its normal state.

Transformer-Type SCFCL

The primary side of the transformer is connected in series with the load, while the secondary one is connected in series with superconductors [39]. The transformer is connected to a vacuum interrupter as a switch, where L1 and L2 are the self-inductance of the primary and secondary, respectively, and M is the mutual inductance between the two coils. During normal operation, the material can exist in its superconductivity so there is no impedance. However, at the fault condition, quench operation occurs, and the current is limited in the secondary side, so it is limited dependably in the primary one. This type is implemented to enhance both the system stability and reliability, as in [45]. The transformer type has some advantages as it provides isolation between the power line, and the current-limiting part beside it has a flexible design [46].

Resistive-Type SCFCL

Such a type is used to enhance the transient stability of the system as it suppresses the fault current in a quick and efficient manner [47]. It consists of two resistances which are known, according to their function, as stabilizing and superconducting resistances beside a series-connected coil [17]. During normal operation, the resistance keeps its superconductivity, so it does not pose losses where the coil has a small value as well that forms small AC losses. However, the resistance is quenched and limits the fault current in the faulty condition. This type has a high length of superconductor which makes it uneconomical.

Hybrid SCFCL

This type can be used to improve the dynamic performance of the system [48] besides solving the difference of the critical currents among the units, which can be observed in the resistive and inductive types. This type [48], is composed of the primary winding and several secondary windings which are connected in series with superconductor resistance. This resistance is obtained through normal operation, so its value is zero while it is transformed to its normal state to limit the fault current during the fault condition.

Flux Lock-Type SCFCL

Flux lock SCFCL, [17], consists of two parts: a current-limiting part and a current-interrupting part. The first part has two parallel connecting coils with one connected with HTSC, whilst the current-interrupting part is composed of an over-current relay, which takes its signal from one coil, in addition to a circuit breaker. During normal operation, zero voltage is deduced across the coils whilst the current is limited during the fault condition throughout the voltage deduced across the two coils. Flux lock SCFCL has less power burden compared between the other SCFCLs.

Magnetic Shield-Type SCFCL

This type consists of a primary coil (copper coil) and a secondary coil (HTSC tube), which are wound around a magnetic iron core[49]. At the steady state condition, the flux does not penetrate the iron magnetic core, as the HTSC tube is sited between the copper coil and the magnetic core, so there are no losses at this state, while in the fault condition, the HTS tube is quenched, transforming into its normal operation, so its resistance increases, and consequently, the resistance of the primary coil increases the limiting of the fault current.

3.3.4. Non-Superconducting Fault Current Limiters (Solid)

Unlike SCFCLs, FCLs can be implemented with passive nonlinear elements as inductors and switches. Such FCLs are known as non-superconducting fault current limiters (non-SCFCLs). The revolution of semiconducting switches helps in developing non-SCFCLSs with minimal cost as compared to superconducting ones. Within the distribution current level, non-SCFCLs are exposed to high thermal stress, so they should be cooled using either forced air or liquid cooling. Additionally, the voltage, during switching, rises sharply in a short time; therefore, properly tamed snubbers are used beside the bypass and clear switches to take FCLs out from service for maintenance or fixing [50]. There are different types of solid-state FCLs, such as:

Series Switch-Type FCL

It is composed of a bidirectionally controlled semi-conductor switch (Sss) and bypass network [50]. This network consists of a normal bypass (Sbp), fault current resistance (Zf), overvoltage protection (Zno), and a snubber circuit. The normal bypass is about a low resistance path for decreasing both switching losses and waveform distortion, while (Zf) is used to limit the fault current. Zno is important to provide an alternative current path to limit the voltage across switching as well as absorb some of the energy stored in the inductance, while the snubber circuit function is to keep with allowable limits [50].

Series Dynamic Braking-Type FCL (SDBRFCL)

It is used in fault rides through the capability enhancement of the wind system [51]. During normal operation, an insulated gate bipolar transistor (IGBT) is tuned on (Vpcc is the voltage of the point of common coupling, and Vref is the minimum voltage on which is the IGBT), and the resistor is bypassed. On the other side, at fault conditions, IGBT is turned off, and the resistor is connected in a series system [44].

Bridge-Type FCL (BFCL)

This type is composed of two parts: the bridge part and the shunt branch part [17]. During normal operation, the IGBT is turned on, and the current has two paths. In a positive half-cycle, the current flows through the LDC, RDC, and D4. However, the path of D2, LDC, RDC, and D3 is considered its path during a negative half-cycle. Additionally, an LDC of a small value acts like a short circuit; therefore, there is a negligible voltage drop, whereas, through the fault condition, the IGBT is turned off, so the bridge is out, and the current is limited by the shunt branch (Rsh + Lsh). Ds, which is the freewheeling diode, can discharge the current through the LDC so it protects IGBT from high voltages.

Modified Bridge-Type FCL (MBFCL)

In MBFCL, the shunt branch in the BFCL is modified as the shunt-inductance LDC is omitted [52]. The LDC discharges when the shunt inductance is disconnected during normal operation. On the other side, the resistance of the shunt branch can limit the fault current when the IGBT is turned off. This type is used in fixed- and variable-speed wind farms to enhance their low-voltage ride [53].

DC Link FCL (DLFCL)

This type is implemented in fault rides through the capability enhancement of an inverter-based DG system [54]. It contains a diode bridge type and a limiting branch of inductance Ld and a small-resistance Rd [17]. During normal operation, the limiting branch is negligible while it can limit fault current and suppress high voltages during fault operation.

Transformer-Coupled BFCL

A transformer-coupled BFCL is used for low voltage rides through the capability enhancement of a doubly fed induction generator (DFIG), as in [55]. During the steady state condition, all the thyristors are turned off, making the reactors bypassed, but they are inserted into the system during the fault condition. This is achieved by turning on the thyristors via a control circuit. Rb is a bypass resistor which absorbs most of the harmonics generated during operation, and it can reduce voltage spikes.

Resonant-Type FCL

Instead of using heterogeneous circuits either for the normal state or fault state, resonant FCL, has switches, which in turn reconfigure the circuit to suit both states, normal and fault [50]. During the normal state, the series resonant tank is tuned to the line frequency, forming zero resistance, whilst this resistance turns to a large value to limit the fault current in the fault condition as the resonance is lost. Despite its simplicity, the resonant-type FCL may cause harmonics [50].

3.3.5. Electromechanical Dynamic FCL

Its nomenclature, dynamic, refers to the fact that its impedance varies with the current magnitude [29]. The electromechanical dynamic FCL adjusts automatically and instantaneously its own resistance depending on the current magnitude. The more the current increases, the more the limiting action exists. That is why it creates a low impedance at normal operation and, therefore, low voltage regulation. Such a type can thermally afford high currents for a definite time. On the other side, it is complex and reconciles high-power capacitive systems [29].

3.3.6. Hybrid FCL

This type is a combination of mechanical switches, solid-state FCLs, superconducting materials, and other technologies to limit the fault currents [56]. It consists of inductance (L) and capacitance (C), which are approximately zero at the nominal power frequency in addition to ZnO that protects both the switch SW2 and TVS (triggered vacuum switch) from high voltage. In normal operation, the TVS and SW2 are off, whilst in fault one, a signal is sent to the TVS, and the contactor turns on the bypass capacitor C1. This makes the reactor L limit the fault current, and both C2 and SW1 form a series compensation [56].

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