A Review survey on fault current limiters

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Abstract -This paper presents an summary on fault current limiters (FCLs) technologies in power systems. First, the FCLs are classified into four groups: superconducting FCLs (SFCLs), solid-state FCLs (SSFCLs), hybrid FCLs (HFCLs), and other technologies. Then, for every group, the literature is reviewed, and therefore the technical characteristics of every cluster are specified. Also, the technical development barriers of the FCLs are described. supported these characteristics and specifications, the FCLs are compared. At last, the FCLs future trend is discussed supported the papers analysis, investigated in IEEE and SCOPUS databases, and patent analysis, investigated within the US Patent and Trademark Office Database , European Patent and Trademark Office Database , and considering patents in queues. The pioneer countries, universities, and researchers during this field also are distinguished.

***Key Words*:**An influence system protection short Fault current limiter Technical aspects Statistical analysis

1.INTRODUCTION

Power systems should provide reliable electricity for different sorts of loads. As a posh system, the last-long power systems con- stitute an outsized number of different components with various char- acteristics [1,2]. the mixing of renewable resources with inter- mittent behavior, like turbine and photovoltaic (PV) systems, within the conventional power systems has added more complexities to the facility systems [3,4]. Considering other agents e.g., environmental ef- fects like weather etc., this complex system is usually exposed to different faults. The short-circuit (SC) faults are the foremost common failures which occur within the power systems [5–8]. A SC may be a low- impedance path resulted from the connection of two nodes with dif- ferent potentials in an circuit [9]. During a SC fault, the fault current

Generally, the negative effects of the SC fault on power systems are: 1- power interruption, 2- damped mechanical oscillations on the gen- erators and motors' shaft, 3- negative rotational inertia and stress on the damping windings of synchronous machines, 4- increase within the reactive power demanded by inductive impedance of the transmission lines and leakage impedance of power transformers, 5- drop in buses with voltage-sensitive loads, 6- torque reduction in induction motors; this also increases the demanded reactive power, 7- thermal stress on equipment, 8- voltage swell and voltage sag in un-faulted buses, 9- electromagnetic interference, 10- increased unsupplied energy and economic losses, 11- corrosion within the connection area, and 12- reduc- tion in power grid reliability and power quality indexes [10].

The short capacity (SCC) is defined because the maximum current flowing through the fault point [11,12]. Usually, the installed equip- ment during a power grid have specific tolerable fault current limits (TFCLs). If TFCL for a component is less than the system SCC, then the element is exposed to wreck . Therefore, to avoid malfunctions and failures, a redundant capacity within the ratings of the equipment must be considered which successively dramatically increases the prices [13]. On the opposite hand, the contribution of some equipment during a SC fault in- crease the fault current.

Ordinarily, the fault current is fed through: 1- synchronous gen- erators installed at neighbor buses, 2- large induction motors, and 3- distributed generation units (DGs). The synchronous generators have a serious effect on increasing the magnitude of the fault current within the steady-state condition. However, the massive induction motors have a dominant effect on increasing the transient components of the fault current [14]. The DGs contribution within the fault current is different considering the DG type. for instance , if a SC fault occurs at the output terminals of the inverter-based DGs, like PVs, the utmost fault current is about 1.2 times of the nominal current whereas this fault current may reach to six times of the rated current for doubly-fed in- duction generator (DFIG)-based wind turbines [15].

During a SC fault within the distribution systems, the DGs may cause the subsequent problems: 1- unwanted trip thanks to function of the protection relays, 2- blinded protection, and 3- unintentional islanding.

To overcome these problems different measures are taken within the literature. As a primary solution, some researchers have proposed to pack up the DGs which contribute within the fault current [16]. The prominent merit of this strategy is that the protection settings of the protective devices don't change. However, disconnecting the DGs may reduce the system reliability in terms of voltage instability, and power quality problems like flicker etc. Readjustment of protection relays and redesigning the protection schemes are proposed to co- ordinate the protection relays [17]. The disadvantages of such schemes are that they're supported complicated and time-consuming algorithms. Also, these strategies might not be economically feasible in some cases [18]. for instance, within the meshed networks with tons of DGs and nonlinear loads (for example, the electrical drive systems which basi- cally use power electronics components), there are harmonics, bidir- ectional power flows in some branches etc. In such networks, re- designing the protection schemes is expensive. The adaptive protection supported artificial intelligent concepts, has also been proposed to affect the issues caused by the DGs in distribution systems [19,20]. However, these schemes also are complicate and commonly need the predefined data of the system for different conditions. The multi-agent- based complicate and commonly need the predefined data of the system for different conditions. The multi-agent- based algorithms are described as new solution to stop the DGs effects on the fault current and their interference with the distribution system protection scheme [21]. Nevertheless, the multi-agent- based strategies are highly dependent of the communication links wont to transfer date among agents. Therefore, these strategies may fail thanks to communication link loss.

Another problem, which has concerned the facility plants also as

utility engineers, is that the increase within the SCC level of the transmission systems [22]. this is often thanks to the very fact that the facility systems are extended considering their generation capacity and cargo level. There- fore, the circuit-breakers in many substations, could also be utilized near their maximum SCC limits leading to a significant reduction within the power grid reliability margin. One costly solution to unravel this pro- blem is replacement of existing circuit-breakers with ones with higher ratings.

A widely-recognized measure to counteract all of the above-men- tioned problems, is that the fault current limiting, which may be a good solution for the transmission and distribution systems. This measure can resolve the issues raised by the DGs in distribution systems. Fig. 1 shows the classification of fault current limiting measures [23]. the essential idea altogether of those approaches is to limit the fault current within the specified limits

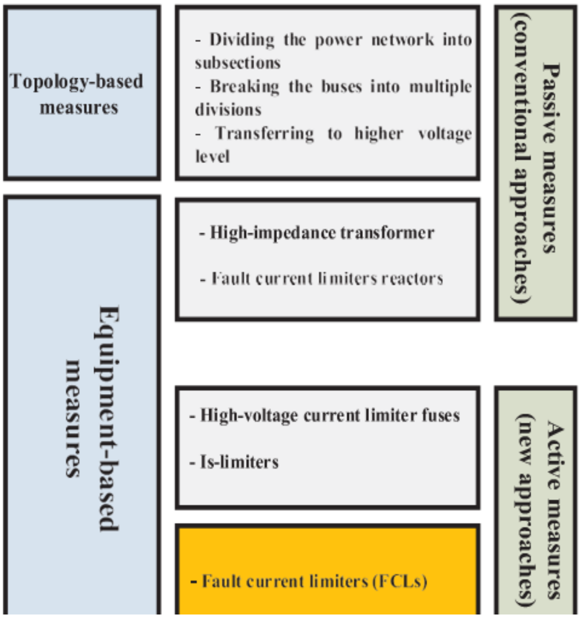

Fig. 1. Classification of fault current limiting measures [23]

either either by reducing the SCC level or adding a high-impedance within the fault path. consistent with Fig. 1, these measures are often classified as ac- tive or passive.

The term “passive” is acknowledged to the fault current limiting measures which don't apply any changes to the limiting scheme, neither within the normal condition nor within the fault condition. for instance , when the SCC level has increased during a typical substation, the buses are often broken into multiple divisions to scale back the SCC level. Therefore, the system impedance will increase but the topology is fiXed, before and after fault [24]. Dividing the facility network into several sections has an equivalent effect. A system/subsystem with low SCC are often fed from an upstream system with higher voltage. during this way, the SCC level of the weak subsystem improves. These three passive measures are supported changing the system topology. Therefore, they're classified as “topology-based measures” as shown in Fig. 1. Two other passive measures are the appliance of high-impedance transformers and fault current limiters reactors. By increasing the transformers impedance, the fault current are often limited. The limiting reactors also can be added to strong systems to scale back the fault current magnitude [25]. Their effect is that the same as increasing the transformers impedance. These two mentioned passive measures are classified as “equipment-based measures” since they need used/added/modified an equipment. All of those aforementioned measures are often classified as “conventional approaches” of fault current limiting.

The term “active” is mentioned those measures which may be en- abled during a fault. Concisely, the active fault current limiting mea- sures are the present limiting schemes which are disabled in normal conditions. When a fault occurs, these schemes become enabled and limit the fault current, usually by adding a high-impedance to the system or directly limiting the fault current. for instance , the high- voltage fuses directly limit the fault current and are commonly used as a cheap protective device against SC faults for distribution transformers, motors, capacitor banks etc. [26]. The Is-limiters are

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RRecently, the fault current limiters (FCLs) have getting more at- traction in power systems and that they are considered because the state-of-the-art devices to limit the fault currents. The FCLs also are classified as active fault current limiting measures. Also, they belong to the equipment- based group. The FCLs are utilized in many power grid appli- cations. for instance , in [27] a resistive superconducting fault current limiters has been utilized in offshore boring platforms. The authors in [28] have presented a case study supported fault event which has been occurred on a floating production storage and offloading. This problem has led to severe damage and its consequences on operation conditions are analyzed. In [29], a price effective inductive shielded super- conducting fault current limiter are proposed for industrial ap- plications. Also, in [30], the appliance of superconducting fault cur- rent limiters in power systems are reviewed. Application of a resistive superconducting fault current limiter during a distribution grid has been indicated in [31]. a perfect FCL is predicted to possess no losses during normal system condition. However, when a SC fault occurs, the FCL inserts a series high-impedance into the fault path to limit the fault current. The classification and technical advantages/disadvantages of every FCL are described within the next sections intimately . However, by limiting the SC current using FCL, the subsequent advantages are often achieved [24,26,32]:

-The power grid equipment like circuit-breakers, current transformers (CTs) and potential transformers (PTs), and measure- ment devices etc. are often designed with lower SC ratings and this reduces the prices .

-After each operation, the weather of FCLs don't usually require replacement.

-In the steady-state conditions, the FCLs don't impose a consider- able overvoltage or inject harmonics into the system.

-The power grid main equipment, like synchronous generators, motors, and power transformers are ready to operation without a substantial thermal stress until the circuit breakers and protective relays remove the fault.

-They have almost no power losses or drop during the traditional operation.

-The development investment cost of the facility system are often postponed.

-The transient stability of the facility system is improved.

-The fast voltage reduction are often prevented and therefore the voltage stability is improved.

-The stability of induction motors connected to the faulted bus or near buses is enhanced.

-The instant large reactive power, which is demanded by the reactive impedances of the system during a SC fault, is reduced.

-Most of FCLs have a brief recovery time, making them fast enough to act during successive faults.

Some general disadvantages of FCLs, counting on the FCL type, are as follows [23,26,32,33]:

-High cost (specifically, for the superconducting type FCL (SFCL)) and initial investment.

-Relatively high failure rate (for solid state type (SSFCL)).

-Need to fault detection algorithms (exclude, for instance , the su- perconducting FCL.

-Wrong trips in some cases.

-Recovery time (especially, for the SFCLs).

However, these problems are considerably improved by re- cent progress in FCL technology. The advantages/disadvantages of every specific sorts of FCLs are going to be detailed within the next sections of this study. Besides limiting the fault currents, the FCLs are often also utilized in appli- cations which require large transient current limitation. for instance , an FCL has been utilized in [34] to limit the starting current of induction motors. during this case, the FCL reduces the transient voltages, harmonics and thermal stress on the shaft. they will even be wont to protect dis- tributed generators [35].

To develop FCLs, many research studies and experiments are conducted in academic and industrial levels. These efforts have resulted in novel FCL structures or improvement of previous topologies. Many universities like Soongsil University, Ohaio State University etc. and also research institutes like electrical power Research Institute (EPRI) within the us are developing the FCLs. On the opposite hand, large companies like General Atomics, Southern California Edison, IGCS Super Power, and National Laboratory of Los Alamos , ABB, Beijing Innopower Superconductor Cable Co, Silicon Power etc. have manu- factured different sorts of FCLs. Several papers and technical reports have tried to overview these academic and industrial works. In [36], the authors have presented a review on application of SFCLs. Mainly, the SFCLs are divided into resistive and inductive types and their characteristics are briefly described. A report of CIGRE work group A3.10 has classified the FCLs and overviewed the essential char- acteristics of different FCLs [23]. A review of different sorts of FCLs has been also given in [37]. the normal methods of the fault current limiting and a quick review of latest methods, like SFCLs, are presented. The authors have also described a technical comparison of different SFCLs. The EPRI has also published some surveys on FCLs[38,39]. the most features of several industrial projects on FCLs are described in those reports. In [40], a review on FCLs types and applications are presented. Some technical characteristics of FCLs are also compared and therefore the specifications of some installed FCLs are presented. a brief review of development of FCLs has been described in [41], where the operational principles of some FCLs are discussed. A report on FCLs has been prepared by University of California, Irvine for California Energy Commission [24]. during this report, the small print of FCLs projects developed by EPRI, this report, the small print of FCLs projects developed by EPRI, Zenergy power service , and Silicon power service are provided.

The purpose of this paper is to offer a review of FCLs supported the technical aspects and from statistical analysis point of view. The orga- nization of the paper is as follows: Section 2 provides a literature overview considering the structure of different sorts of FCLs. The technical specifications and development barriers of every FCL group are presented in Section 3. The futurology of the FCLs technology is in- vestigated in Section 4. during this section, the papers are investigated using IEEE and SCOPUS databases, and therefore the patents are analyzed considering the US Patent Office, European Patent Office, and patents in queues. Finally, Section 5 concludes the paper.

2.Classification of FCLs

In this work, consistent with the technology, the FCLs are classified into four groups; these four groups are superconducting FCLs (SFCLs), solid-state FCLs (SSFCLs), hybrid FCLs (HFCLs), and other technologies. Fig. 2 shows the classification graph supported brain- storming approach. consistent with this categorization, absolutely the fre- quency curve of the amount of FCLs installed in power systems throughout the planet until 2018, is shown in Fig. 3. This figure illus- trates that the SFCLs have taken the foremost attraction among other sorts of FCLs. the most element within the SFCL is that the superconductor material. this sort of FCL is characterized by their low-loss and automatic fault limiting properties. The SSFCLs operate supported the facility electronics switching principals. The HFCLs are recognized as a mixture of SFCLs and SSFCLs. Finally, other sorts of FCLs are categorized here supported the very fact that their operation principal isn't almost like other three classes. The FCLs with core also can be classified into two general types: 1- closed-loop core, and 2- open-loop core. The closed-loop core provides a closed magnetic path whereas the open- core topology doesn't . Both of those topologies are im- plemented in different FCLs schemes developed by the researchers and industrial companies.

3.Technical Aspects, development barriers and comparison of FCLs

during this section, for every class of FCL, the technical aspects and development barriers are presented. At last, all FCLs classes are compared.

3.1. SFCLS

One of the most objectives of implementation of superconductors in power grid is loss reduction (when the superconductor is connected serial with the line). during this field, the subsequent two main objectives are pursued:

a) Energy losses reduction: Since the RFCLs are and can be utilized in many parts of power systems, and therefore the RFCLs are connected serial with transmission lines, using the superconductor (with approXi- mately zero resistance during its normal operation) reduces the energy losses considerably.
b) The superconductor inherent behavior limits the fault current. The resistance of a superconductor in normal conditions is near zero. When a fault occurs, the superconductor temperature increases, leading to a high-impedance path within the fault current. This im- pedance increment appears automatically due to the super-conductivity properties.

The technical characteristics of SFCLs are as follows:

-Operating voltage: the voltage level of installed SFCLs is within the range of 220 V-510 kV AC and 500 kV DC. The voltage level is restricted by insulation problems, cooling strategies, and semi- conductor switches.
-Rated current: the rated current of SFCLs is from a couple of amperes (experimental cases) to a couple of kA (for example, 5 kA, for the SFCL installed in power grid of Russia). The rated current is restricted by superconductor thickness, material, thermal management and cooling system.
-Production technology of superconducting material: the super- conductor is that the key element in SFCLs. The superconductivity properties mainly appear in low-temperature. Until now, many re- searches are tried to extend the superconductivity tem- perature (high-temperature superconductors) and present a strong molecular structure for superconductive materials. the most su- perconductive materials utilized in SFCLs are given in Table 1.
Superconductive materials commonly utilized in SFCLs [38]

Material	Critical temperature (K)
MgB_2	39
YBCO	92
BSCCO	108

-Time response: for the installed SFCLs, it's been reported from 2.5 to 10 ms. This parameter depends on the superconductive ma- terial type, quench time, and cooling system.
-Percent of transient overvoltage: its range is 0.6–2.3%, as re- ported in [38,40].
- Weight: for the SFCLs installed in power system (medium and high voltages), this parameter range is from 3 to 36 tones.
- Physical dimensions: the peak is from 1 to three .6 m, and length/ width from 1 to 13 m.
- Cooling system: it's supported nitrogen (LN2 Dewer machine which is out there from 2 to 1580 L).
- Cost: the development cost of SFCLs is especially depends on the sort of superconductor and its range is from 40 $/kW (for 400 V) to 21 $/kW (for 230 kV).
- Maintenance: after several operations, the SFCLs must be rechecked by the system operators and monitoring devices. this is often because that the superconductive material properties are affected by thermal effects of the fault current. Also, the rate of depreciation of the cooling system is high due to uninterruptible operation.
- No-load losses: since the cooling system of SFCLs operates con- tinuously, it imposes a substantial power loss on the facility system.
- Voltage droop: for the resistive type SFCLs, since the super-conductor is connected serial with the cable , there's not any drop in normal condition. However, during a transformer type SFCL and saturated type SFCL, the superconductor isn't con-nected serial with the road and a few drop (for example, on the windings of the transformer or other elements) may occur.
-Reliability: the most characteristic of SFCLs is their high reliability because there's not a vulnerable part (semiconductor switches etc.) in their power circuit.

Thedevelopment barriers of SFCLs are often described as follows:

- Implementation of superconductor for SFCL applications in high-voltage levels is restricted . To implement the superconductor in high-voltage level, the length of the superconductor must be in- creased. thanks to the high-cost of superconductive materials, this has not been feasible. However, recently the superconductors are implemented at 500 kV thanks to global discount of super- conductive materials.
- Development of cooling system: during the fault, an enormous amount of warmth is generated by the superconductor. to work properly, the SFCLs need strong cooling system which consumes a substantial no-load power. This increases the no-load cost. Also, the cooling system is typically supported nitrogen which features a high-cost, namely, about 40% of cost of a SFCL. Besides, the cooling system demands special equipment, like nitrogen pressure control, iso- lation, leakage detection and online monitoring system, magnetic field and corona protection schemes.
- Insulation limits: the superconductor is connected serial with the transmission line; therefore, it must have the nominal current capacity of the cable . Also, the SFCLs must tolerate the nominal voltage of the cable . Therefore, the develop-ment of SFCLs in high-voltage levels depends on insulation tech- nology.

- High complexity: the SFCLs need special conditions to figure properly and safely. they have elaborated control schemes and
cooling systems. the planning and coordination of those schemes aren't straightforward.
- High-cost: the most disincentive think about implementation of SFCLs is their high-cost. Although the worldwide price of superconductive materials has been reduced in last decade, however the manu- facturing cost of a SSFCL is a few few million dollars.

3. CONCLUSIONS

The The SC faults are common in power systems. To limit the SC fault currents, many strategies are presented within the literature. to the present end, the final and best solution is using the FCLs. during this paper, the FCLs are divided into four clusters, consistent with the technology type, namely SFCLs, SSFCLs, HFCLs, and other technologies. for every cluster, supported a brainstorming approach, different sorts of FCLs are detected and classified. Then, a comprehensive literature review has been presented for every cluster. The technical specifications and com- parative study have also beenprovided. The futurology study, supported both papers and patents analysis, has also indicated that the FCLs technology is in its growing stage and lots of research works are con- tinuingly conducted to develop new structures or improve the dynamic characteristics of the traditional FCLs. Among all of FCLs, the SSFCLs would be an appropriate solution and thus more prevalent in power grid applications. this is often thanks to their lower cost as compared to SFCLs, flexible structure provided by modular features of power electronics converters, and fast advancement in semiconductor science. Among all kinds of SFCLs, the RSFCLs, due to their relatively simple structure and lower cost, are expected to be commonplace in power systems. For the SSFCLs, the full-bridge and multicell resonance types are good candidates for getting used in different applications. This thanks to their lower harmonics production and modular feature which allows their implementation in higher voltage levels. The hybrid FCLs aren't sup- posed to be used fairly often . However, the bridge-type HFCLs could also be an honest choice for a few power grid applications due to their power electronics-based structure. For other technologies, the new composite- based FCLs, like PTC-resistors, are a preferable choice due to the ever-growing advances in composite materials.

Declaration of Competing Interest

The authors declared that there's no conflict of interest.

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