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SATURATED CORE FAULT CURRENT LIMITER: A TECHNOLOGY TO HANDLE SHORT-CIRCUITS IN THE MODERN POWER NETWORKS

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Abstract:

The power industry world-wide has seen aggressive power demand growth in the pursuit of economic development of the countries. The power sector, in general, has also gone through reforms in the last decades and the decentralized power generation, transmission, and distribution made the control diversified. Green energy generation technologies are penetrating the power grids, and the parallel addition of bulk power generation plants is also in order. These modern power system requirements lead to complex systems where unforeseen incidents - faults challenged the power utilities to control extensive short circuit currents. The short-circuit levels reached or even exceeds the manageable limits of applied protective gear especially, costly circuit breakers. However, the time-bounded upgrades or replacements are also not financially viable. Saturated Core Fault Current Limiter(SCFCL) technology, a commercially viable option, is considered as a prospective solution to the problem. This paper report the concept validation work in the laboratory and the current limiting performance of the test model. The SCFCL technology development work world-wide with the on-site grid applications of some pilot projects has also been presented. The researcher may find the contents supportive as technical guidance.

Keywords: clipping factor, distributed generation, fault current limiter, short circuit.

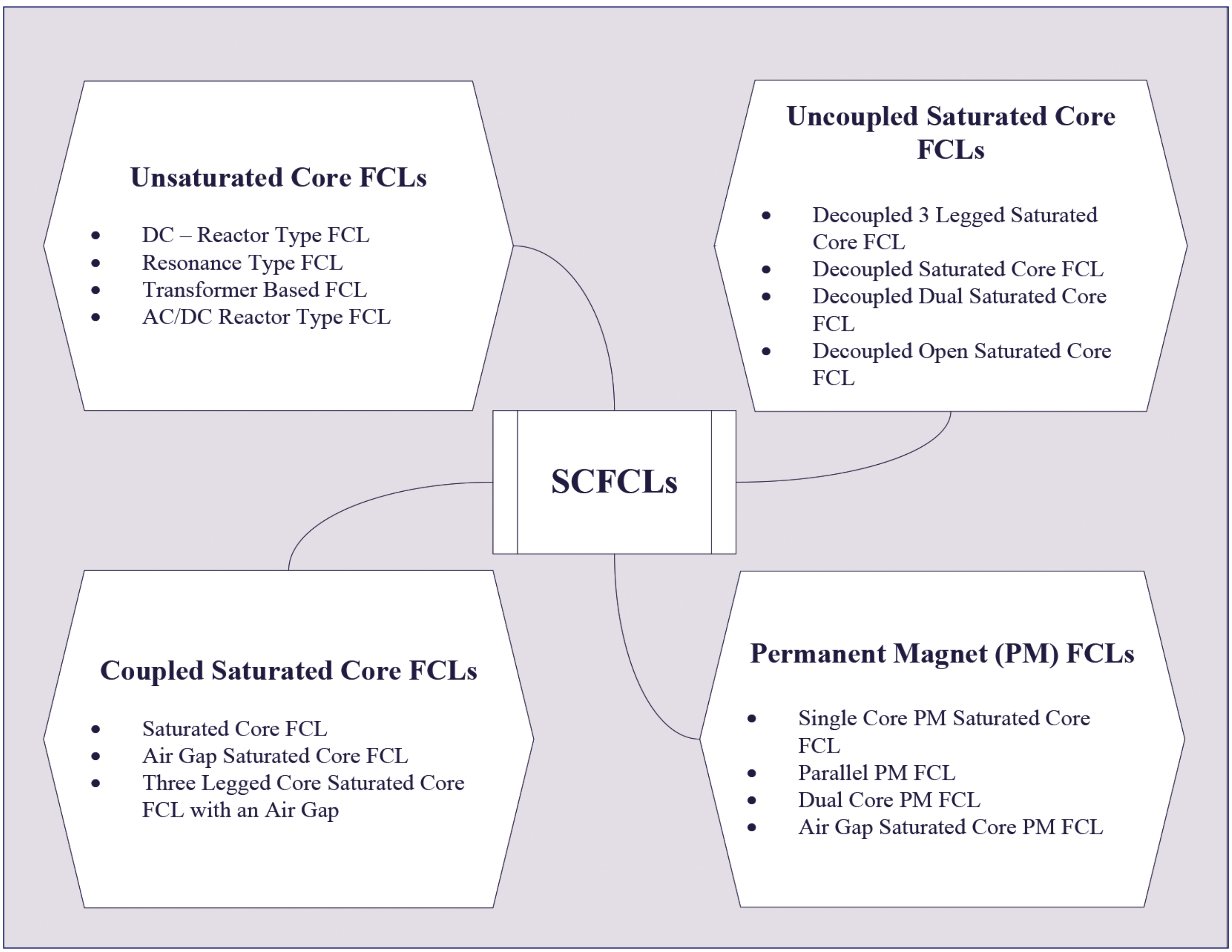
1. INTRODUCTION

With the rapid industrialization and urbanization during the last few decades, the demand for electrical energy has gone up many folds. Many distributed generation (DGs) technologies besides the addition of bulk generation are integrated into the main grid. The need for parallel operation of the transmission networks for reducing the cost of energy and to enhance reliability is rising. All of these efforts increased the short-circuit current, almost at the unmanageable levels. The power network components are under intensive thermal and mechanical stress and their operational life has been endangered [1]. Especially the circuit breakers to handle these short-circuit currents are just not capable to perform the over duty. Many traditional approaches to handle short-circuits have been proposed in the past, which includes the use of high-rated circuit breakers, high impedance transformers, current-limiting fuses, air-core reactors as equipment level measures. Some of the system-level measures have been the partitioned operation of the power grid, increasing the voltage level, and reconfiguration of the system such as splitting of power buses [2]. None has proved to be efficient or economical. Usually, circuit breakers are expensive, cannot interrupt fault currents until the first current comes to zero, and have limited lifetimes. The high impedance transformer with its high losses makes the system inefficient. The fuses have a very low withstand able fault current and it has to be replaced manually. The air-core reactors are subject to large voltage drops, incur substantial power loss during normal operation, and require capacitors for volt-ampere reactive (VAR) compensation. The system reconfiguration using bus-splitting, besides adding cost, reduces the system's reliability and its operational flexibility [3].

Deployment of the fault current limiter (FCL) to mitigate the ill effects of short-circuit current is an alternative, effective, and reliable technological solution. It offers low impedance and hence low-voltage drop during normal conditions. However, it immediately triggers the high impedance to limit the fault current after the appearance of the fault in the power system. Besides, the application of FCLs improves the power quality, fault ride-through capability, better coordination between protection equipment in the systems integrated with dispersed generations[4]-[7]. Several excellent works on FCL concepts have been earlier reported in the literature [8]-[10]. Based on the operating principle and the components used the various FCL types may categorized in to solid-state FCLs(SSFCLs), superconducting FCLs(SFCLs), saturated-core FCLs (SCFCLs) and hybrid FCLs(HFCLs). With the advancement of power semiconductor technology, the development of SSFCLs has been actively encouraged. The main advantages of solid-state FCLs are their low cost and compact structure with good current limiting performance. However, the high power loss is a major challenge for solid-state current limiters that lead to heating. It also requires an external trigger circuit for fault detection that results in delayed operation. Also, the solid-state FCLs deployment has the working voltage restriction [11]. There are many types of SFCLs like resistive types, inductive types, and hybrid types [12]-[14]. However, these devices suffered from the high cost of superconductors and their cooling systems with their maintenance requirements. Hybrid FCLs combine the features of the former three types, mostly the superconducting technology. Among different FCL technologies, SCFCLs have recently been the research hotspot due to their comparatively superior characteristics, particularly their suitability for HV applications. There are various types of SCFCL working on the nonlinear magnetic properties of the iron core [15]. The four classes, based on inductive effect, identified as unsaturated inductive FCLs, coupled saturated core FCLs, uncoupled saturated core FCL, and the permanent magnet-based FCLs. Further sub-classification of these groups is shown in Fig. 1. The differentiating features of these classes lie in first peak reduction of fault current, real and reactive power loss under normal operation, operational delay, recovery time, voltage drop in normal operation, control coil voltage induction, required solid-state switches, core losses in normal operation. The desirable requirements of FCLs are - 1. Small steady-state loss when the system is in normal operation 2. The small impedance, which will not affect the steady-state operation of the system 3. Ability to act on short circuit fault immediately to presents high impedance for limiting the short-circuit current 4. After the ceasing of the fault, it should quickly restore the original state. Also, the significant performance indices of any FCL are the clipping factor and the response time. The clipping factor, the ratio of fault current without FCL to that after installing FCL, is to be maximum and the response time, the period during which impedance changes from very low to high, is to be minimum.

The SCFCLs have interesting properties like instantaneous action, fast recovery, and also adaptable to high voltage applications with large ratings [16], much of worldwide research focus recently was on the development of technology. In [17], the SCFCL inductance versus the line current characteristics are obtained with the experimental measurements as well as FEA simulations with good agreements. A developed non-linear inductance model, then incorporated in the grid is simulated to show that the limiting current has a dynamic component that significantly contributes to the current controlling property of the device. The equivalent magnetic circuit which can accommodate the varying core dimensions employable in the commercial software such as MATLAB/PSCAD as an alternative to FEM solution has been suggested in[18]. The transient performance in the grid is then calculated using MATLAB by introducing the NR method in the study. Recently the application of permanent magnet as an assisting bias has been suggested by some of the researchers. The authors [19] have investigated and compared the performance in terms of SCFCL current reduction ability, voltage drop contribution, and losses with two compatible models, one with conventional DC bias and the other with the application of PM bias.

Fig. 1. Classification of SCFCLs

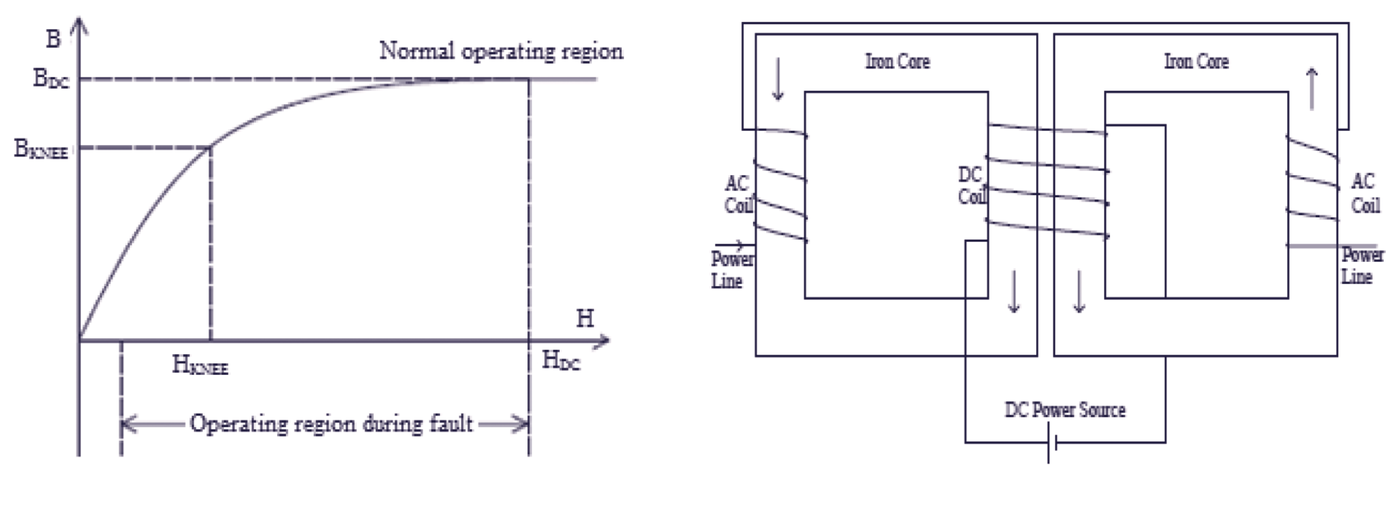


The COMSOL Multiphysics simulations have shown that the PM bias can improve the losses and coupling problems in the conventional designs. It has been investigated [20] that the application of PM bias and its stability may be endangered by high power losses due to eddy currents and subsequent heating. The 2-D FEM analysis with the coupled 3-D analytical model of PM evaluated the performance in terms of eddy-current losses. It has been demonstrated in the work that the PM width segmentation improves the eddy current losses in the device. The work presented in[21] a modeling methodology in terms of the non-linear flux linkage-current characteristics to study the dynamic behavior of the device. The characteristic is plotted with FEM simulations initially and then the analytical and fast numerical solution is proposed. Experimental validation is also carried out in this work. The performance of the existing dual-core topology and the 3-leg configuration have been compared with the proposed novel 5- leg configuration [22]. The COMSOL Multiphysics software simulations have shown that the high material requirements, as well as the transformer coupling effect between the DC-AC winding along with the high power losses in the earlier designated designs, can be considerably improved in the novel 5-leg design. However, the huge requirements for magnetic materials and AC-DC magnetic coupling effect, in the case of SCFCLs restricted their commercial take-off. The high DC bias power to saturate the core and the steady-state energy consumption is the most significant problem [22]-[23]. In this work, the concept of SCFCL technology is experimentally validated to study the performance in terms of current reduction rate and the voltage drop contribution. The transient performance has also been investigated. It also presents an overview of the developments in SCFCL technology, including classification, application areas, and worldwide technology developments. The current challenges before commercialization and the research opportunities are also briefly discussed.

2. SCFCL: PRINCIPAL OF OPERATION

SCFCLs exploits the nonlinear change of the magnetic characteristics (See Fig. 2(a)) of the core material to limit the short-circuit current of the system. The original design[24] consists of two iron cores, two AC coils, and a DC bias coil wound over the cores as shown in Fig. 2(b). In each half-cycle of the AC wave, the direction of AC and DC flux in one of the cores is the same, while the AC and DC flux in the other core is opposite. The AC coil circuit is in series with the line, which is to be protected. The strong DC mmf generated by the DC coils forces both the cores into deep saturation. Under steady-state operation, the relatively small AC load current will not lead the core out of saturation, and the impedance of the SCFCL is very small. The SCFCL has little effect on the normal operation and the device acts transparently to the system. After the fault occurs, the AC demagnetizing force generated by the sudden increase of short circuit current leads the two cores out of saturation alternately at positive and negative half cycle waves. The SCFCL, at this time, presents a large impedance, which controls the rate of rising and magnitude of the short-circuit current. Quick response and recovery after having the short-circuit, adaptability to the HV and large capacity field application are the significant characteristics of the SCFCLs, and therefore, the topic has recently been at the center stage of the research.

Fig. 2. Saturated core fault current limiter
(a) Typical B-H curve of the magnetic core (b) Dual-core configuration of the SCFCL

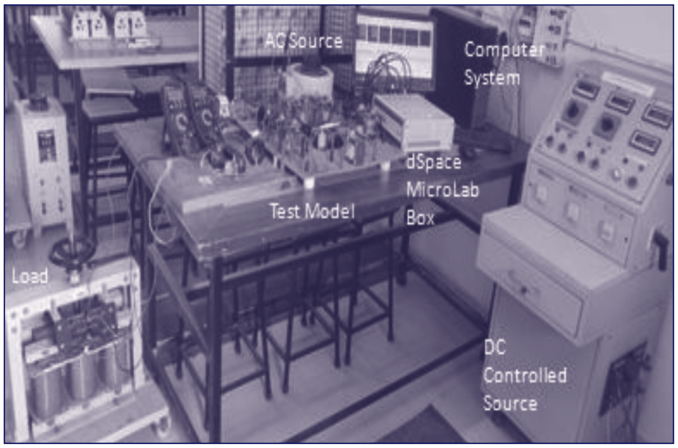


(a) **(b)**

3. SCFCL: PROOF OF THE CONCEPT

The SCFCL test model has been incorporated between the source and the load. The actual image of a laboratory experimental setup is shown in Fig. 3. It has DC controlled source to bias the core, an autotransformer as an AC source, the inductive load bank as load, a contactor to create artificial short circuits across the load, and the dSpace Microlab Box to capture the real-time parameters like voltage and current at locations.

Fig.3. An actual picture of test set up for the SCFCL model



The single-core configuration[16], as shown in Fig. 4(a), has been realized in the laboratory in terms of the test model to validate the concept. The experimentally plotted B-H curve for the core, as shown in Fig. 4(b), has been useful to select the DC bias value of 1A, which was necessary for forcing the magnetic core in the deeply saturated region under the normal operation. The same has also been validated with the analytical calculations. The elongated core, M4 grade electrical steel material, was selected for the experimentation and the dimensions are specified in Table 1.

Fig. 4. (a) Closed DC Open AC configuration (b) Experimental B-H curve

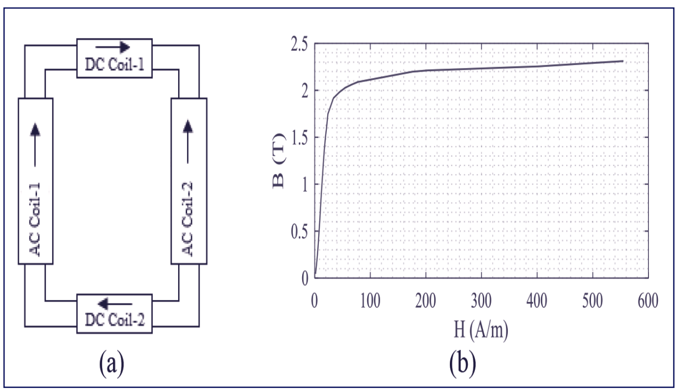
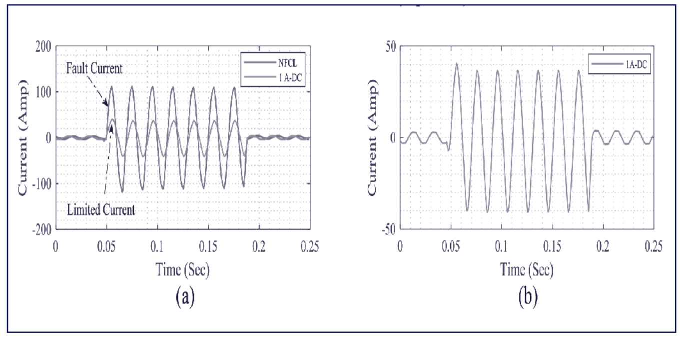


Table 1.The physical parameters of the SCFCL model

Core dimensions in mm	
Core limb width	16
Core limb depth	30
Core mean width	54
Core mean height	138
Area of cross section of the core(mm^2)	480
Mean length of the core	384
Number of DC Turns	150
Number of AC Turns	100

It has been investigated that the prospective short circuit current (fault current without SCFCL) has been reduced considerably with the test model introduced in the circuit. The first peak value of the short circuit current noted was 119.1 A, which has been limited to almost 40.5A. The amount of current reduction is specified in terms of the current reduction rate (C.R.R.), which in this case was noted to be almost 66%. The prospective short circuit current superimposed with the limited current (with SCFCL in the circuit) is shown in Fig. 5(a), whereas the limited current waveform is shown separately, in Fig 5(b).

Fig. 5. (a) Prospective short circuit current superimposed with the limited current (b) the limited current(separate)



Another significant performance parameter is the non-limiting state voltage drop(voltage drop under normal operation of the system also called the insertion voltage drop). It has been measured as 3.55 % which is well below the general limits of the statutory requirement. The sudden rise in the voltage drop during the faulted operation was obvious as the SCFCL impedance triggered to high value under fault operation and the drop has thus increased. The immediate response and recovery after experiencing the short circuit are also evident from the waveform shown in Fig. 6. It has also been observed that the SCFCL fault handling is not smooth, as the impedance during fault inception and ceasing undergo the transients. The transient nature of the SCFCL impedance is shown in Fig. 7, for which the describing parameters have been registered in Table 2. The other performance parameters of the SCFCL test model system have been recorded in Table 3.

Table 2. The transient impedance parameters at fault inception

Parameter / Bias	1A DC
Overshoot (%)	83.3
Peak (Ω)	5.03
Peak Time (ms)	6.5
Rise Time (ms)	0.2
Settling Time (ms)	29.7

Table 3. The performance parameters of the test model

Parameter / Bias(A)	1ADC
Limiting state Z (ohm)	2.73
Normal state Z (ohm)	2.48
Fault to pre-fault Z ratio	1.1
C.R.R.(first peak) (%)	66.36
C.R.R.(s.s. peak) (%)	62.89
Insertion drop (%)	3.55

Fig. 6. The non-limiting state voltage drop

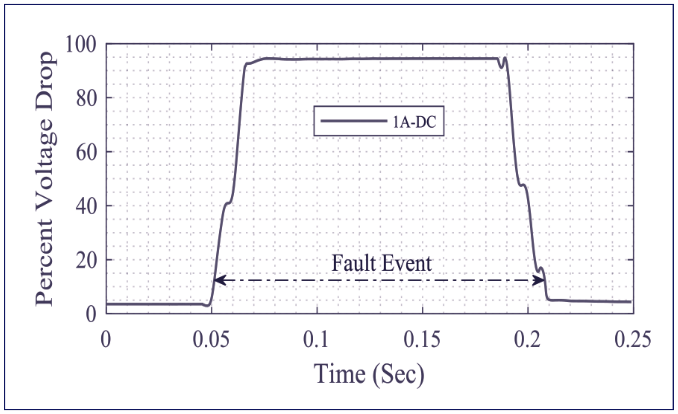
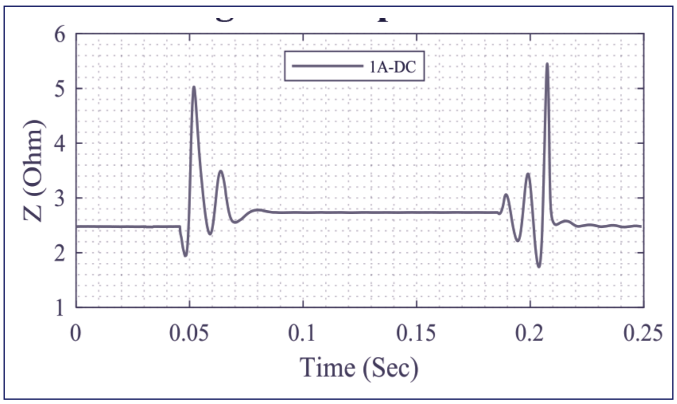


Fig. 7. The nature of limiting and non-limiting state impedance

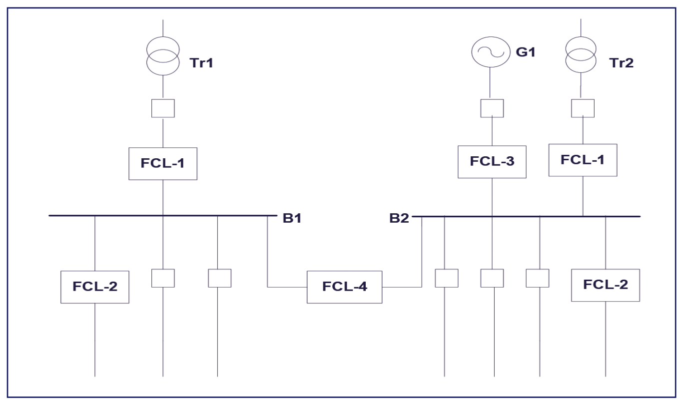


4. SCFCL APPLICATIONS

The integration of SCFCL to an electrical grid avoid equipment damaging, equipment replacement, series reactor, split busses, bus-tie breakers. It also leads to the use of lower fault current rated equipment and improved power grid transient stability. The main parts of power systems are power generation, transmission, and the distribution of electricity. SCFCL, in general, can be potentially used for the short-circuit current limitation in these three components. However, it can be applied anywhere in the system facing excessive fault current. The appropriate locations for SCFCL are decided by the structure of the power network and the aspects such as generators location, type of generators or protective relaying scheme used[25].

The SCFCLs may be located in four main sites in the power network as shown in Fig. 8. The main feeder carries the highest current as it is an aggregate of all the downstream feeder currents. The SCFCL when located at the incoming feeder position, it protects the feeder and all downstream equipment as well which are valuable and sometimes is difficult to replace. When it is located at the outgoing feeder position, the SCFCL limits the fault current passing through that feeder. SCFCL in bus-tie position allows two buses to be tied together without significantly raising fault current on either bus. SCFCL in this position would incur lower losses as it does not carry load current in normal operating condition, which otherwise is carried by the feeder positioned SCFCLs.

Fig. 8. Possible SCFCL locations in the grid network



The major worldwide real-time demonstrative projects [26]-[31] using the SCFCL are enlisted in Table 4.

Table 4. Major pilot projects of SCFCL application in the world

Company / Industry	Specification	Location
ASG Pow. Sys.	33 kV/45 MVA	Jordanthorpe, 275/33 kV substation, U.K. Grid.
GridON	11kV/10MVA	UK Power Networks substation, Newhaven, East Sussex.
GridON	11 kV/ 30 MVA	Birmingham, Western Power Distribution Grid, UK.
Innopower	35 kV/ 90 MVA	Puji substation of the China Southern Power Grid.
Innopower	220 kV/ 300 MVA	The Shigezhuang substation of Tianjin, China.
Innopower	500 kV/ 1800 MVA	EHV transmission system - China Southern Power Grid.
Zenergy	11 kV/ 1.25 kA	Northern Power-grid network, UK.
Zenergy	12 kV/ 1.25 kA	CE Electric UK grid.
Zenergy	15 kV/ 1.25 kA	Southern California Edison's, Shandin substation, USA.
Zenergy	138 kV/ 1.3 kA	Tidd substation, American Electric Power, USA.

5. CURRENT CHALLENGES AND THE FUTURE WORK

The recent high penetration of greener generation technologies in the form of solar and wind causes several technical issues especially the high-level of short-circuits. However, the modern power system networks are more complex, and with the advances in digital technologies, all the smart grid / micro-grid system components are working together. It will be a great challenge for the power engineers to secure the stability of such a complex system with a high level of short circuits(fault level). The power system stability, power quality, and power system protection should not be hindered at all times. It is compelling to determine whether the deployment in the system has any deleterious effects on the aspects of power system operation and control. Moreover, the SCFCL technology requires further research[32] in terms of its optimal placement, on-site testing, optimal design, economic feasibility analysis, etc. For the large-scale commercialization of SCFCL application, it essentially needs further focus on the two aspects - 1. Core: The materials with high permeability and saturation density for better clipping performance with fast response and recovery times and fewer energy consumptions 2. Coils: The use of copper in the DC circuit leads to loss and the superconductors to the cost. Therefore, the superconductors employable with the high temperatures(room temperatures) may allow commercialization of the device.

6. CONCLUSION

The modern power industry is facing significant problems in terms of high magnitude short circuit currents. The costly circuit breakers as protective gear have been overstressed. Many conventional strategies to limit the effects of short circuits have been unsuccessful in view of the penetration of greener energy technologies in the power system. The saturated core fault current limiter has recently been the focus of the researchers. The concept validation of SCFCL technology is reported in the paper with the significant performance parameters of the test model. It has been investigated that the SCFCL model can reduce the short-circuit current by 66%, with a voltage drop contribution of 3.55%. Also, the theoretical aspects of SCFCL technology development are discussed in the paper including the conceptual working of the device. The potential implementation areas along with the worldwide pilot application projects are also presented. The prospective research areas in technological development have also been mentioned in the paper.

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