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SATURATED CORE FAULT CURRENT LIMITER IN ELECTRICAL POWER INDUSTRY: A TOPOLOGICAL SURVEY

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Abstract:

The power industries worldwide have witnessed a large growth in demand, and the emergence of cost effective distributed generations leads to the interconnections of power networks. The modern grids thus are complex. The handling of the inevitable short-circuit current became a serious concern as it may cause enormous damage to the costly power components. The conventional measures to handle these harmful faults degrade the efficiency of the system operation. The Saturated Core Fault Current Limiter (SCFCL) is an advanced FCL technology solution, and its effective implementation may allow optimal resource utilization. The paper aims at a comprehensive topology survey of SCFCLs including the features and the drawbacks, and the review is based on the standard publications in recent times. The selection of the topology is an engineering problem for the optimized performance of the SCFCL application in the power sector. For the increased market adoption, the development of a compact topology with the improved performance envelope has been a long way research. Therefore, the study will act as the foundation for the researchers and scholars to work on this enabling technology in the electrical power sector.

Keywords: configuration, distributed generation, fault current limiter, saturated core fault current limiter, topology

1. INTRODUCTION

Economic growth with industrialization and urbanization lead to an extensive increase in power demand. It forced the utilities to add power generating facilities to cause the necessary demand-generation balance. The modern trend is also to make use of the cost effective generating sources especially solar and wind. Thus penetration of DG is on the rise [01]. All of these measures though found to be beneficial to utilities have posed one serious problem in terms of an increase in the fault or short circuit level. The short-circuit current in modern power systems has grown to a very high level and it almost now becomes unmanageable by the existing hardware of the network mainly circuit breakers (CBs)[02]-[03]. At some places in the world, the short-circuit current became so high that it even reaches the maximum available breaking capacity of the CBs [04]-[06]. Therefore, the power network components are in danger unless it is either replaced or upgraded [07]. However, both of these options are highly uneconomical.

There are traditional efforts to limit the magnitude of short-circuit current. There can be topological measures or apparatus measures that can restrict the excessive flows of short circuit current [08]-[10]. Splitting of grids or bus bars be affiliated to the topological measures while application of current limiting reactors, installation of high impedance transformers, pyrotechnic breakers, and fuses belong to the apparatus measures.

Splitting of bus bars or grids prevents one segment of the system from contributing to a fault in an adjoining section. The splitting of the sub-grids or bus bars is generally preferred in rapidly growing areas. Although it prevents the contribution of one subarea to the other, it adds the network complexities along with the complex protective schemes. However, the splitting measures also diminish the reliability of the supply system as the number of generators which may feed the healthy part of the system decreases in the case of fault. The practical viability of splitting measures also demand more parallel paths between the load and the generation that involve huge investment, and not a financially viable option [11]. The system operators are generally reluctant to this strategy as it is totally empirical and highly case-dependent.

Another commonly employed measures are the introduction of the current limiting reactor (CLR) or the high impedance transformer. They increase the system impedance perceived by the short-circuit current leading to the obstruction of a fault current. CLR may be of two types, viz. air-core or iron core type. Since the high fault current may saturate the core resulting in the lower limiting reactance, the iron-core type is generally avoided. The air-cored reactor shows more desirable characteristic and therefore are commonly employed [09]. These measures as persistent (permanent) even under the steady-state, normal system operation, which leads to higher impedance, in this case, that contributes to the system losses and voltage drops. It results in a reduction of the critical fault clearing time as required by the generators. However, it also absorbs a large space in the substation area while complying with the safety norms. The use of high impedance transformers, although results in fault level reduction, significantly affect the voltage stability and transient stability. However, the replacements of transformers are not also financially viable to the system operators.

The other most simple and cost-effective apparatus measure, commonly employed for the fault current control is the use of high-voltage fuses. However, the manual substitution of fuse wires is needed after each fault event, and the reconnection of the detached load is, consequently delayed [12]. The auto-reclosing principle of protection may not be allowed along with the application of fuses. Their applications, however, are also technically constrained to the nominal system operating conditions (40 kV voltage and 200 A current). All of these barriers discourage their use and their viability.

The pyrotechnic breakers, commonly known as Is-limiters are designed to enhance the nominal current rating of the fuse. It consists of two parallel current paths, a conductor and a fuse wire in parallel. Under normal operation, a conductor carries a major portion of the line current. Under the fault condition, the conductor is opened due to high stress recruiting the current to the fuse wire, which also eventually melts down. This mechanism augments the normal current carrying capability of a fuse typically to 5kA. However, their use is also subject to the maximum operating voltage constraint of 40kV [09].

Therefore, it was essential to limit the implications of fault occurrences wherein the normal system impedance is not increased, the fault current is effectively controlled and, the availability of the power is unaffected. Such desirable characteristics can only be imposed by the integration of FCLs.

FCLs are devices that limit the short-circuit current to an acceptable value, and can avoid or at least defer the necessary replacement or up gradations. The addition of FCL can enhance the life of power network components such as T & D lines, transformers, cables, and switchgear equipment. It also enables the cost-effective expansion of generation facilities with the improved stability and reliability of power systems.

There are many proposed FCL technologies in the literature but the most promising, practically realizable, and commercially viable technology is SCFCL[13]-[17]. The significant features of this technology are an instantaneous reaction to the fault, instantaneous recovery from the fault, and compatibility with the existing hardware. However, there are few major engineering challenges to be addressed in this original design of SCFCL (1) Massive use of iron in the device result in large size, high weight, and more cost. (2) AC to DC coupling which causes high induced emf across the DC coil that may damage the supply (3) Laboratory or field testing of the suggested SCFCL concepts to ensure its practical viability, etc. Researchers all over the world are working on the topology aiming at reducing size, cost, AC-DC coupling, and increasing the limiting ability of the device.

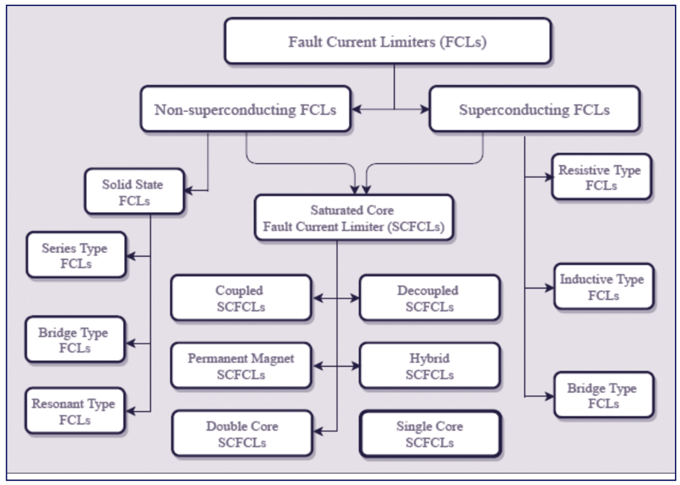
In this paper, a comprehensive survey of SCFCL topologies including the features and the drawbacks has been carried out. The selection of the correct topology is an engineering problem for the optimized performance of the SCFCL application in the power sector. The review is based on the standard publications in recent times. And, it aims at narrowing the search for the practically realizable, and commercially viable topology option. Therefore, the study will act as the foundation for the researchers and scholars to work on this enabling technology in the electrical power sector.

The dominant FCLs are classified, and their features are compared in Section 2. Section 3 describes the general principles of the SCFCLs. In Section 4, several configurations reported in the literature are reviewed and logically grouped. Section 5 describes the future challenges in the developments of SCFCL. Conclusions are drawn in the last section of the paper.

2. CLASSIFICATION OF FCL TECHNOLOGY

In general, the FCLs are broadly classified into three technology groups as superconducting, non-superconducting(solid-state), and saturated core. The number of derivations, in this context, have been studied and reviewed. Fig.1 shows the classification of the FCLs. This division is technical and each class has its own positive and negative features as regarded to the current limiting performance.

Fig. 1. Classification of FCL technology



Superconducting Fault Current Limiters (SFCLs) rely on the property of superconductor material as toggled resistance. Under normal operation the resistance of SFCL is nearly zero. And upon the inception of the fault, the resistance increases to a high value that limits the fault current. SFCLs are further classified as resistive, inductive, bridge SFCLs, etc. Most of the SFCLs are self-triggered and do not require external fault detection circuits. However, there are certain drawbacks like the high cost of the superconductor and its cooling, which are barriers in this application development [18].

Solid-state Fault Current Limiters (SSFCLs) are also referred to as power semiconductor-based FCLs, where the semiconductor switches are used for the implementation of the device [19]. There are many advantages of SSFCLs such as flexible and modular structures which are adaptable to the capacity expansions, comparatively low costs, low normal-state impedance, simple cooling mechanisms, low weight, low maintenance, etc. However, the steady-state power losses are comparatively higher than the SFCLs. Also, the requirement for ancillary circuits adds the complexity and cost of the SSFCLs designs [20].

The drawbacks of the SFCLs (the significant cost and maintenance) and SSFCLs (considerable losses, voltage limitations, and power quality issues) have triggered the research of Saturated Core Fault Current Limiters (SCFCLs). Quick response and recovery after having the short-circuit, adaptability to the MV, HV, and large capacity fields are the significant characteristics of the SCFCLs, and therefore, the topic has recently been at the center stage of the research [19].

Table 1. Summary of general pros and cons of FCLs

Features / Characteristics	SFCLs	SSFCLs	SCFCLs
Response	Fast	Slow	Immediate
Recovery	Slow	Fast	Immediate
Voltage adaptability	LV	LV to MV	LV, MV & HV
Power loss	Low	High	Moderate
Cooling system	Complex and costly	Complex and moderate cost	Possibility of cheaper conventional cooling
Size	Large	Small	Moderate
Cost	High	Low	Moderate
Fail safe operations	No	No	Yes

The significant features of the above-mentioned technology groups are compared in the Table 1. It can be inferred that the SCFCLs are the leading candidates for providing acceptable solutions to the high fault current problems in the modern power system.

3. SCFCL: GENERAL PRINCIPLES

The operating principle of the SCFCL can be found in [21]. The SCFCL realized with superconducting bias has been, mostly referred to with the superconducting saturated core FCL in the literature. In this case, the superconductor is used to bias the core to keep it at saturation during normal operation with low power losses. However, the recent research explored the possibility of a bias with the normal copper conductors. This possibility has opened the doors towards the commercialization of the SCFCLs [22]. The ruggedness, null reaction, and recovery delays are the most significant characteristics of the SCFCLs. While following the development of these devices for real-world MV and HV application, the component cost (core and the coils), the large footprints (size), and the magnetic coupling between the coils during a fault have been the major engineering challenges. Keeping these aspects at the center stage, several topological structures are proposed in the literature. The designs can be differentiated in terms of magnetic core geometries, biasing mechanisms, bias coil arrangements, and their applications.

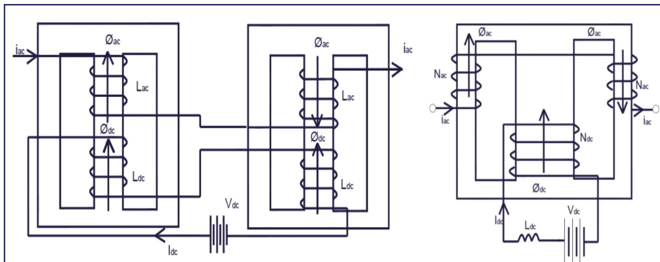
4. TOPOLOGICAL STUDIES

Several configurations reported in the literature are reviewed and logically grouped in this study to arrive at the narrow search for the practically realizable, and commercially viable topology. These SCFCLs configurations are logically grouped in terms of the coupled SCFCLs, decoupled SCFCLs, open-core SCFCLs, permanent magnet and hybrid SCFCLs, and the three-phase SCFCLs.

4.1 Coupled SCFCLs

The magnetic design originally proposed by Raju et *al*[23] is shown in Fig. 2(a). The simplicity of the design, ruggedness and fail-safe performance are the advantages of this magnetic design. However, the considerable size of EE core makes it very difficult to employ the device at MV & HV applications(the larger dimensions at the distribution level voltage) since it requires a total of six cores for the three-phase application. Moreover, the cooling design in this structure also becomes challenging besides the original bulky structure.

Fig. 2. Structures of the coupled configurations



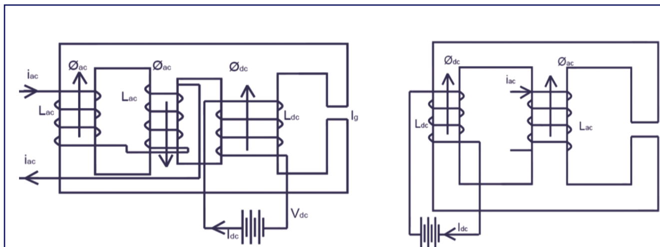
(a) Original conceptual configuration by Raju (b) Saturable FCL by Yanxia

Another coupled configuration [24] is constructed with a pair of EE cores, as shown in Fig. 2(b). It enables the use of a non-superconducting coil for biasing. Also, the cost of maintenance of ancillary systems is reduced. However, it demands larger AC turns leading to increased window dimensions for the given magnitude of current limitation. It also results in objectionable voltage drop across the AC terminals. The concern of AC-DC magnetic coupling further demands their isolation (AC-DC) resulting in an additional increased in the dimensions.

4.2 Decoupled SCFCLs

Considering the magnetic coupling between the AC and DC winding and subsequent high induction voltage across the DC biasing source, a concept of decoupled topology is proposed in the literature [25]. It has been introduced earlier to that presented in[23]. The magnetic structure of the design is shown in the Fig. 3(a). The magnetic decoupling between AC and DC comes at the cost of asymmetry with increased complexity and manufacturing difficulty. However, nothing is mentioned about the three-phase application of the design in the said literature.

Fig. 3. Structures of the decoupled configurations



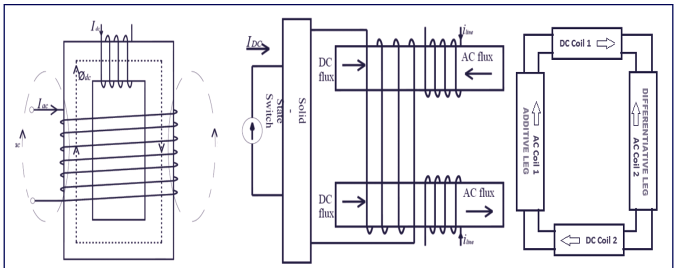
(a) Saturable FCL by Oberbeck (b) Saturable FCL by Cvoric

To reduce the size and transformer coupling effect between AC and DC coils, the original Oberbeck decoupled design [25] was further improved in[26] and is as shown in Fig. 3(b). Since the AC flux is diverted through the desaturated air gap limb under the faulted operation, the coupling effect substantially reduces. This results in a low induced voltage across the DC bias source. However, the addition of a limb with an air gap leads to an asymmetric structure, in addition to the high volume and cost. The same authors also had proposed another variant of a single-phase topology with a pair of EE cores with the air-gapped middle limb in[27]. The addition of the central leg though reduced the bias coil material with a reduction in the coupling effect, the problem of considerable volume and weight of the core remains in the design.

4.3 Open-core SCFCLs

Another class of topologies is an open-core topology which has many significant features compared with the closed core(one which has a magnetic return path), like reduced material requirements for similar performance. It is a very important feature as it enables the open core configuration for higher-rated real-world, MV, and HV applications. Also, the current limiting ability is comparatively higher in this case.

Fig. 4. Structures of the open-core configurations



The authors in[28] present a novel, compact, single-core, and single AC coil configuration, see Fig. 4(a), that overcomes several drawbacks and enables the commercialization prospects for the device. The size, naturally, approximated to half of the original design [23] leading to the compact design. Also due to the orthogonal coil placements, the AC-DC transformer coupling effect substantially reduces. However, the high bias requirement of this design for the given amount of current clipping is observed as a significant drawback [29].

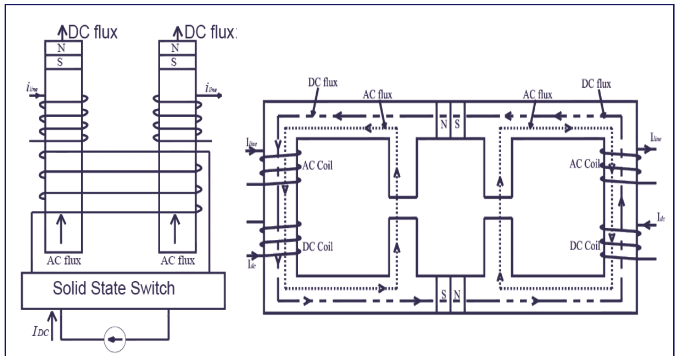
One more open core topology investigated in[14] consist of two iron cores(bars) which are wound with the two AC coils in opposite directions, as shown in Fig 4(b). This open core configuration has better current limiting characteristics and requires less amount of core material making it suitable for high voltage applications. However, the serious drawback is again the requirement for a very high DC mmf to drive the core saturation.

The experimentally tested closed DC open AC configuration(CDOA)[22] also belongs to the open core category as the AC mmfs are counterbracing each other at the center of the DC(short) leg of the core. The use of single-core and orthogonal placement of the AC-DC windings are the most superior features of this topology that has eventually enabled the commercial prospect for the SCFCL application.

4.4 Permanent Magnet and Hybrid SCFCLs

For the SCFCLs, reducing the bias requirements has been a topic of research over a long way. The bias power supply in the case of a higher rated device may be a significant cost driver over the lifespan of the device. Also, the subsequent DC power loss in the device may be substantial. The concept of simultaneous bias with DC coil and permanent magnet (PM), sharing a burden of saturating mmf, is a new research area following the SCFCL application development. In this case, the major portion of the saturating mmf/flux is provided by the PM and the supplementary requirement is fulfilled by the small DC bias coil.

Fig. 5. Structures of the PM and Hybrid bias SCFCLs



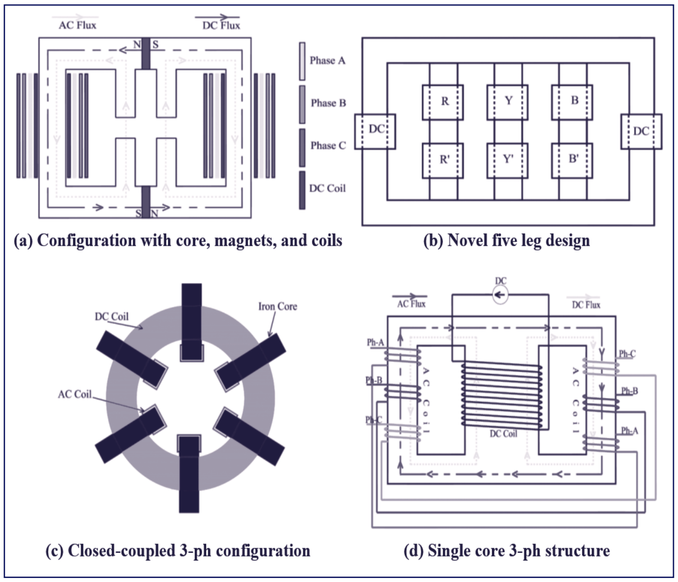
The authors [30] suggested a hybrid way of core saturation to attain steady-state core saturation. It uses a combination of NdFeB magnets and a traditional DC coil (copper) for biasing the core, as shown in Fig. 5(a). The simulation result demonstrated that the same performance for hybrid SCFCL can be achieved with 50 % reduced steady-state energy loss. The current clipping performance is noted inferior due to the large leakage flux in this design. However, the handling of large PMs for the practical voltage levels of distribution and transmission may impose the footprint constraint of the device.

The problem of conventional permanent magnet FCL (viz. thermal stability due to eddy currents), can also be addressed [31] in the novel hybrid configuration of SCFCL, as shown in the Fig. 5(b). the reliability of the PM biasing can be enhanced with an effective fault current clipping. However, the three-phase practical realization of the concept should be tested along with the handling of the permanent magnets.

4.5 Three-phase SCFCLs

The three-phase design [31] proposed is an extension of the work prescribed in [32]. The proposed structure is as shown in the Fig. 6(a). The amount of core material and hence the cost is significantly reduced due to the common core. Also, the PM assists the core saturation process under the steady-state that leads to a reduction of the amount of DC basis current and/or the number of turns resulting in further saving in the cost of components. However, the use of common core results in a significant drawback in terms of limiting only single-phase (phase-to-ground) faults. Also, the parameter selection in the design of the structure is very critical due to the insertion of the air gap, and largely affects the limiting performance of the device

Fig. 6. Structures of the three-phase SCFCLs



(a) Configuration with core, magnets, and coils (b) Novel five leg design (c) Closed-coupled 3-ph configuration (d) Single core 3-ph structure

Another three-phase, non-superconducting, novel five-leg configuration is recently suggested in[33]. The topological structure is as shown in the Fig. 6(b). It has been found that the overall core volume requirements were significantly reduced, in addition to low power loss and induced voltage across DC under fault conditions. However, the current limiting ability was found compromised compared with that of the conventional dual-core design.

The three-phase topology suggested in [34] uses a battery of six cores with an air gap, as shown in the Fig. 6(c). It reduces the demand for DC bias for core saturation under normal operation, and hence the capacity of the DC power supply leading to cost-saving. However, the current limiting ability of the proposed structure is inferior compared with the traditional structure.

Several of the SCFCL topologies suggested for the three-phase application of the device do not meet the cost and footprint criteria, and hence commercial uptake of the device is prolonged. Considering this aspect, recently, a three-phase saturated core topology is proposed in [35]. It uses a common magnetic core for all three phases, as shown in the Fig.6 (d). The desirable features of the topology are reduced size, weight, and volume leading to the low cost of the device. Also, the proposed structure claims a low voltage drop across the AC coil under the steady-state operation. Moreover, the coupling effect is reduced as the DC number of turns required is less. However, the major disadvantage of this structure is that it cannot handle the symmetrical short-circuit. Also, any minor unbalance in the system operation causes a severe voltage drop across the device that could challenge the complete insulation system.

Based on the concept used, the topologies have been grouped in this review study. It will enable further research with a foundation for comparative analysis. However, in most of the topology development studies, software simulations are carried out to determine the effective current limiting performance. For real-time grid applications, the prototyping of the concept along with experimental analysis and the field testing is essential. Among the many conceptual categories, the SCFCLs with open core concepts seem to be close to the essential requirements for the cost-effective, commercial fault current limiting solution, and hence recommended for further analysis.

From the perspective of the increased adoption of the SCFCL in the market, it has been a long way research on the development of topology with the enhanced performance envelope at compact size and light weight. It will address the problem space requirement at substations, particularly in the high-density urban areas. The development of SCFCLs with reduced size also enables the connections for the DGs, which in turn results in lower electricity price, higher availability, and higher power network capacity.

5. FUTURE CHALLENGES

The modern power system networks are highly complex with the penetration of dispersed generations. As all the modern grid(smart) 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 grid stability, power quality, and power system protection should not be hindered at times. It is compelling to determine whether the SCFCL deployment in the system has any deleterious effects on these aspects of power system operation and control. Moreover, the SCFCL technology requires further research [36] 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 three aspects, viz. 1. Core material and topology: The materials with high permeability and saturation density for better clipping performance with fast response and recovery times and fewer energy consumptions are required. The topology having reduced size, mass, and lighter in weight with enhanced performance. 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. However, a topology that enables the bias with copper conductors, and in turn allows conventional oil cooling can also trigger the adoption of SCFCLs in the markets. 3. Prototyping and testing: Since much of the development work has been carried out with the simulation software's, the laboratory and field testing of the SCFCL prototypes is the need of the hour before its integration in the system.

6. CONCLUSION

In this paper, the FCL technologies were classified into three technology groups with their pros and cons. The SCFCL has been categorically introduced as the future current-limiting controller. The recently suggested SCFCL topologies from the literature have been studied including their features and drawbacks. The reviewed topologies have been logically grouped in terms of the design principles such as coupled core, decoupled core, open core, permanent magnet and hybrid bias core, the three-phase core, etc. It has been noted that the performance studies of SCFCL topologies have been carried out either with software simulations or experimental prototyping. However, a larger number of studies belong to the software simulations, especially FEM analysis software. The laboratory and field testing of the SCFCL prototypes is thus the need of the hour before its integration in the system.

Moreover, the general problems identified are in terms of inferior current clipping, response & recovery delays, large footprint, high coupling, high maintenance, high cost, high voltage drop, complexity, high bias requirements, the thermal stability of permanent magnets, high insertion power loss, reliability, asymmetry, three-phase application knowhow, critical design, insulation problem, etc. None of the topologies have addressed all of those issues, and complying to all is far from the practical reality. However, there are certainly few recently investigated configurations (open-core) that have been considered as commercially viable options. This study will be insightful for the researchers working on the saturated core fault current limiting technology.

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