Saturated-core fault current limiters for AC power systems: Towards reliable, economical and better performance application

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Abstract: With the continuous expansion of power grid capacity, the problem of short-circuit current exceeding the standard is becoming increasingly serious. Fault current limiter is a promising solution and is gradually becoming a research hotspot. In this study, fault current limiters are classified into four categories. And saturated-core fault current limiters are emphatically introduced, including its working principle and comparison with the other three categories. Saturated core fault current limiters are divided into four branches according to the ways leading the core saturated. A comprehensive review of the research activities and emerging technologies of saturated-core fault current limiters for AC power systems is presented in this study. The working principle and typical structure of DC-biased-, permanent-magnet-, superconducting- and hybrid-type saturated-core fault current limiters are introduced. The advantages and disadvantages of four types of saturated core fault current limiters are compared in detail from the aspects of current-limiting performance, iron core size and DC magnetomotive force. Real grid application examples of some types of devices are presented, as well as new progress in the techniques, are covered and discussed in detail. One may find the content of this study helpful as a detailed literature review or as practical technical guidance.

1 Introduction

Economic growth has created an exponentially increasing demand for electrical power [1]. With the continuous development of power systems and the increase in installed capacity, the short-circuit current level of the power grid has increased significantly. Among the numerous faults occurring in power systems, short-circuit faults are probably the most destructive [2].

In some cases, a short-circuit fault may generate a fault current >20 times the maximum nominal current. The increasing level of short-circuit current causes great harm to the power grid [3]. On the one hand, it will affect the selection of power grid equipment, such as circuit breakers and greatly increasing investment. When approaching or exceeding the interruption capacity of switchgear, it will seriously affect the safe and stable operation of the system. On the other hand, the magnetic field generated by fault current will cause the failure of the communication system or other signal systems. The increase of contact voltage and step voltage near the line or in the substation will endanger the safety of humans and livestock.

There are several traditional approaches to manage the fault current in power systems [4–6]. System-level measures mainly include the layered and partitioned operation of the power grid, bus segmentation, increasing voltage level, HVDC transmission technology and rational planning of the power supply access mode. These measures mainly lie in rational planning of the power grid structure, which is the fundamental measure for the growth of fault current in the control system. However, it is difficult to implement them. Equipment-level measures mainly include high impedance transformers and generators, transformer neutral point connected small reactance, series reactors, current-limiting fuses, fault current limiters (FCLs) and so on. The former three will increase the system impedance under normal and fault conditions and affect the stability of the system. The current-limiting fuse is simple. It has low cost and good current-limiting effect, but it needs to be used in conjunction with fast interruption current-carrying equipment, zinc oxide resistance and so on. It has limited interruption ability and a low voltage level. Thus, it is not possible to apply it in power transmission system at present.

An alternative solution to the problem, which has received much attention in recent years, is the application of a FCL [7–11]. After >40 y of development, with the efforts of researchers worldwide, great progress has been made in the research, design and development of FCLs, and a few prototypes have entered the stage of experimental demonstration [12, 13]. The recent trend of deregulation and restructuring of the power grid has invoked a renewed interest in FCL technologies for the implementation of reliable and economically feasible commercial devices.

An insight into FCL concepts and technologies can be found in several excellent works [14–16]. FCLs may be classified by their principle of operation and key technological components used. Generally, FCLs can be divided into solid-state FCLs, superconducting FCLs (SFCLs), saturated-core FCLs (SCFCLs) and hybrid FCLs. Hybrid FCLs means that they combine some key technologies or working principles of the former three, mostly superconducting technology and other technologies. For example, the solid-state FCLs which combine high-temperature superconducting (HTS) coils with power electronic devices and the SCFCLs which use superconducting materials in windings. The characteristics of such FCLs have been shown in the literature and some have already been demonstrated with full-power prototypes or scaled models.

At present, there are many reviews on solid-state FCLs and superconducting FCLs, but few on SCFCLs. This review presents an overview of research activities, recent advancement and emerging SCFCL (including hybrid FCLs with similar working principle) technologies for power systems, as well as describing the concepts and principles of the operation of several potential SCFCLs and discussing their main features and advantages.
The development of solid-state current limiters has been vigorously promoted. The main advantages of solid-state FCLs are their short action and short recovery time. They are feasible to apply in high voltage and large capacity fields [21]. However, their limiting effect restricts their commercial application. In particular, the high-power DC bias power supply and additional energy consumption required to saturate the core are the most significant problems [22–24].

As mentioned above, FCLs can be divided into four types. In this section, the SCFCL is compared to other FCLs and the working principle is also introduced.

With the development of power electronic devices, the development of solid-state current limiter has been vigorously promoted. The main advantages of solid-state FCLs are their short response time and good current-limiting performance. However, statically and dynamically realising voltage and current sharing of devices is a major challenge for solid-state current limiters. The on-state loss of power electronics leads to thermal management problems. Signal isolation issues also need to be addressed. At present, solid-state FCLs are only suitable for distribution networks [17]. SCFCLs are a hotspot in the field of current limiters. There are many branches according to different working principles. Among them, resistance type and hybrid type are popular at present [16, 18–20]. Currently, these devices are mainly limited by refrigeration systems, high maintenance requirements and high costs. SCFCLs have fast action and short recovery time. They are feasible to apply in high voltage and large capacity fields [21]. However, their volume, weight, consumption of magnetic materials and current-limiting effect restrict their commercial application. In particular, in high voltage and large capacity fields, the high-power DC bias power supply and additional energy consumption required to saturate the core are the most significant problems [22–24].

The ideal FCL has a small static loss when the system is in normal operation, and the whole FCL presents small impedance, which will not affect the normal operation of the system. After the short circuit fault, the FCL responds quickly and presents a large impedance in the system, which plays a role in limiting the short-circuit current. Two important parameters of FCL are the clipping factor and the response time. The clipping factor is the ratio of fault current without SCFCL to that after installing SCFCL. The response time means the period during which impedance changes from minimum to maximum. After the fault is removed, it quickly restores to small impedance.

SCFCLs are developed on the basis of magnetically controlled reactors. Their basic principle is to use the non-linear change of the magnetic permeability of the core material to limit the short-circuit current of the system.

SCFCLs generally consist of two cores, I and II. There are an AC coil and a DC bias coil wound on each core. The DC coils are wound in the same direction, while the AC coils are wound in opposite direction. Therefore, at any half-cycle of the current, the direction of AC and DC flux in one core is the same, while in the other core, the direction of AC and DC flux is opposite. The two AC coils are connected in series with the system. The DC magnetomotive force (MMF) generated by the DC coils leads two cores in deep saturation. Under normal working conditions, the AC current flowing through the SCFCL is the rated current of the power system, which is very small relative to the short-circuit current. The AC MMF generated by the AC coils 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 of the system. After the fault occurs, the AC MMF generated by the sudden increase of short circuit current leads the two cores out of saturation alternately at positive and negative half-cycle waves. At this time, the SCFCL presents large impedance, which plays a role in limiting the short-circuit current. The typical structure of SCFCL is shown in Fig. 1. In addition, the inductance of the AC coils in this structure can be changed by controlling the DC power supply to realising the function of controlling the power flow [25].

The SCFCLs operate quickly, have short recovery time and are feasible to be applied in high voltage and large capacity fields. To improve the performance of SCFCLs, experts and scholars have carried out theoretical research and topological improvements.

### 3 Classification of SCFCLs

This study suggests classifying the SCFCL topologies into four major groups: the DC-biased, the permanent magnet-biased, the superconductive and the hybrid types. The following concepts are reported in the literature and to date seem feasible methods for the implementation of practical SCFCLs.

As mentioned above, the high-power DC bias power supply and additional energy consumption required to saturate the core are the most significant problems of SCFCLs. The development trend of SCFCL is also towards solving this problem. Compared with the traditional DC-biased SCFCLs, the inner resistance of the superconductor coil is smaller, the current-carrying capacity is larger and the excitation loss is lower. Permanent magnet FCLs (PMFCLs) do not need DC excitation. However, at present, the maintenance cost of superconducting materials is high, and the bias ability of permanent magnets is insufficient. Hybrid current limiters use a variety of excitation modes, which can achieve deep saturation and reduce losses through optimisation.

#### 3.1 DC-Biased type

3.1.1 Open-Core SCFCL: Open-core SCFCLs are one of the most classical SCFCLs. The basic configuration of an open-core SCFCL is shown in Fig. 2 [26–28]. It consists of two iron cores surrounded by two separate copper coils wound in opposite directions, carrying the same AC line current (AC windings). A winding carrying the DC bias current encompasses both iron cores and is utilised to saturate the cores.

Under the normal state, the MMFs set up by the AC load current are too small to drive the cores out of saturation. Hence, the relative permeability of the iron cores approaches unity and the AC-side coils act like air-core inductors. During a fault event, the magnetisation forces set-up by the fault currents are high enough to
3.1.2 Closed-core SCFCL: Compared with the open-core SCFCL, the closed-core SCFCL has the advantage of low-loss under normal conditions. The loss of DC-biased type SCFCL is mainly from the DC coils made of the conventional conductor. Since the open-core SCFCL requires higher DC MMF and its DC coil also produces a higher loss. A closed-core SCFCL topology and its clipping performance are discussed in [32–34]. As shown in Fig. 4, the topology of closed-core SCFCL is composed of a magnetic core with three columns, current-limiting inductance and DC bias source. AC windings 1 and 2 are connected in series to a power line and wound in opposite direction in terms of magnetic flux. DC bias winding 3 and current-limiting inductance is connected into the DC circuit. A three-phase full-bridge controlled rectifier provides DC bias current for the FCL.

In this structure, there-column core and coils act as a magnetic-controlled switcher together. Under the normal operation state, the DC bias current is adjusted to make the side column core in a deep saturated state. The current-limiting inductance has no obvious effect. The AC circuit, the impedance of the FCL is very low and the voltage drops on the AC windings are low. At this time, the working state is equivalent to switching off the magnetic-controlled switcher which connects L to the AC circuit.

When a fault occurs, the amplitude of the fault current is increased and generates an AC MMF large enough to counteract the DC bias MMF and desaturate the side column core. In the negative half cycle of the AC current, the right-side column will be unsaturated. Since the middle limb and yoke are always unsaturated, strong electromagnetic induction occurs between the DC coil ‘3’ and the right AC coil ‘2’. The current-limiting inductance \( L \) will be converted into the AC circuit to limit the fault current automatically. Two side columns are used here for the fault current limitation in the positive and negative half cycles of the AC current alternatively. The working state is equivalent to switching on the magnetic-controlled switcher.

The section area of the yokes and middle column are larger than that of the side columns. This kind of design has two advantages. The first is that the side columns can be easily be driven into saturation by the bias current while the middle column and the yokes are in an unsaturated state. The second is that when the side columns are desaturated after the fault, strong electromagnetic induction occurs between the DC coil and the AC coil immediately and automatically. The current-limiting inductance \( L \) will be connected into the AC circuit to limit the fault current. Harmful AC voltage is induced on the DC winding. Due to the current-limiting inductance in the DC circuit, the harmful voltage across the DC power supply is greatly reduced, which can effectively ensure the safety of the DC power supply.

When the working voltage of the current limiter is 400 V rms, the clipping factor of the structure in Fig. 4 is 2. The response time is about 10 ms. Compared to the open-core SCFCL, closed-core SCFCL needs more ferromagnetic material because it has a middle limb. Besides, an external inductance is added in the closed-core prototype. The inductance is 22.86 mH. To make the core deeply saturated, the DC magnetising force is set to be >8000 AT [32].

Baichao et al. [35] improved and developed the configuration on the basis of the above topology. This configuration was named the bridge-type SCFCL (BSFCL). As we can see in Fig. 5, the BSFCL consists of three limbs, four windings, a limiting inductor \( L_0 \) and a DC-biasing source. Cores I and II each have two identical windings. The AC and DC share the same windings, which are connected in a bridge-type structure. The limiting inductor and the DC biasing source are inserted into \( df \) as a DC biasing circuit.

During a fault event, in the positive half cycle of the fault current, because the AC and DC MMFs in the two windings of core I flow in the same direction, core I will still remain in

Take a prototype designed to limit fault currents in low voltage systems [up to 415 V root mean square (rms)] as an example, the clipping factor of open-core SCFCL is about 1.8. The response time is about 10 ms. The cores were constructed using grain orientedM4 electrical steel, with a cross-sectional area of 225 cm² and overall height of 90 cm. To make the core deeply saturated, the DC magnetising force needs to be >8000 AT [26].
In addition, a limiting inductor in series with the DC biasing circuit is proposed to improve clipping performance. Hence, compared with traditional existing types of SCFCL, the BSFCL has the advantages of a better economy and fault clipping performance.

The clipping factor of the structure in Fig. 5 is 2.5. The response time is about 8 ms. This structure also has three limbs. And there is an external inductance in this structure. The inductance is 4.5 mH. To make the core deeply saturated, the DC magnetising force is set to be 5500 AT [35].

In addition to the single-phase structure mentioned above, some three-phase topologies have also been proposed. Ahmadvand et al. proposed a three-phase structure of a saturable-core FCL based on the common core for all three phases [23]. Fig. 7 shows its basic principle. In this structure, the windings of all three phases are wrapped around one core, which leads to a reduction in the volume and weight of the core of the FCL. As a result of the three phases negating each other, FCL inductance decreases during the normal operation of the grid and therefore, the voltage drop across the FCL decreases. However, under the symmetric fault condition, three-phase fault currents also negate each other. The sum of AC flux in the core is zero and the core is still saturated. So, it cannot work under the symmetric fault condition.

The clipping factor of this structure reaches 4.04. The DC magnetising force is set to be 10,000 AT. It saves two-thirds of the ferromagnetic material and DC source because of the three-phase structure. The core is similar to other structure introduced above [36].

A novel five-leg design of a non-superconducting, three-phase, pre-saturated core FCL is proposed in [25]. The proposed design of the FCL has superior properties in limiting any type of fault currents with the reduced volume of the magnetic iron core, total power loss and the induced voltage across the DC coil terminals in comparison with those of the well-known dual-core design. However, the magnetic flux leakage of the design is serious.

### 3.2 Permanent magnet type

In 2000, Mukhopadhyay et al. [37] proposed a method of using permanent magnets to provide DC bias MMF in an SCFCL and proved the clipping performance of PMFCLs. A new type of PMFCL was proposed in [38].

On the basis of the above methods and topological structure, several competent topologies of PMFCLs were introduced in [39, 40], and the advantages and weaknesses of each topology were also analysed. Four parallel-biased PMFCL structures are shown in Fig. 8.

Parallel-biased PMFCLs consist of two sets of C-shape cores, one permanent magnet and two AC current windings. The permanent magnet in the middle biases the two C-shape cores and forces them into saturation under normal conditions. Each C-shape core is used for one of the half-power cycles. The two windings around the two core limbs arranged magnetically in the opposite direction function as a bipolar current limiter to suppress the large current flow in the AC circuit. The series biased mode I is much more economical than the parallel-biased PMFCL in terms of the topology design. The permanent magnet is divided into two pieces in series with the two cores. As the magnetic field direction in the two cores is opposite, the windings around the two cores are magnetically in the same direction. The magnetic structure of the series biased mode II is similar to that of the series biased mode I; however, there is only one winding around the two cores for the series biased mode II, where the winding functions to limit the fault current at every alternative power cycle. A comprehensive mode PMFCL is the synthesis of a parallel biased mode and a series biased mode II, in which the permanent magnet is separated into three parts and its middle limb is twice as large as the other two side limbs.

Compared with the traditional SCFCL, the PMFCL is more economical and practical. For better application, an FCL based on permanent magnet biased saturation was presented in [41]. As shown in Fig. 9, two identical magnetic devices are connected in series with opposite MMFs in order to limit the positive and negative half-wave currents, respectively.

Using the above topology, an algorithm for structural parameters design was established on the basis of an equivalent magnetic circuit method [42, 43]. The feasibility of a high voltage and large capacity PMFCL was analysed in [44], which makes it possible for the commercial application of PMFCLs. Zou et al. [45, 46] researched the permanent magnet stability and economic efficiency of the PMFCL. In Fig. 9. Furthermore, the authors in

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**Fig. 6** Principle circuits under normal and fault conditions. Adapted from [35]

(a) AC and DC loop of BSFCL, (b) Working principle of BSFCL under fault conditions

**Fig. 7** Three-phase structure based on common core. Adapted from [36]
explored the effect of a PMFCL on the transient stability of a power system. The above research and work have promoted the large-scale production and application of PMFCLs.

In recent years, new PMFCL topologies have been proposed continuously. A novel compact permanent-magnet-biased FCL (CPMFCL) is shown in Fig. 10 [31]. The CPMFCL consists of iron cores, PMs and coils. The number of turns of each coil is \( N \).

Compared with traditional PMFCLs, the CPMFCL has only three limbs. The three cores have the same cross-sectional area. PMs are used to drop the cores into saturation under normal conditions. In addition, there is a small section part in cores I and II to improve the uniformity of the flux density distribution of the cores. The cross-sectional area of the small section part is reduced to \( S_b \), which is slightly less than the cross-sectional area of main core \( S_e \).

Fig. 11 shows the basic principle of the CPMFCL. Under normal conditions, cores I and II are both driven into deep saturation by PMs, the saturated inductance of each coil is \( L_s \). Hence, the normal impedance of the CPMFCL is very low. During a fault event, the fault current is large enough to offset the MMF setup by PMs. Hence, cores I and II are alternatively out of saturation. The limiting impedance of the CPMFCL increases largely to limit the fault current.

Compared with traditional PMFCLs, the three-limb structure of the CPMFCL can reduce the size and cost, and the optimal small-section structure can improve the biasing ability of PMs and reduce the usage number of PMs. Moreover, the CPMFCL has fast response and excellent fault clipping performance.

The clipping factor of CPMFCL reaches 3.3. The optimal small-section part can improve the biasing ability of PMs, resulting in a 22.4% reduction of usage of PMs. The response time is about 6 ms [31].

3.3 Superconducting type

Superconducting SCFCL is based on the low resistivity of the materials in the superconducting state. Using superconducting material as DC coils can realise large DC MMF with a small loss. Its development is closely related to the progress of HTS materials. SFCLs based on HTS materials have been a research hotspot in the field of FCL in the past 20 years. Superconducting saturated iron core FCLs are composed of a superconducting DC coil, non-superconducting AC coils and an iron core.

A typical reactive SFCL, illustrated in Fig. 12, is composed of dual iron cores, two non-superconducting AC coils, two superconducting DC coils and a DC source [21, 48–51].

When the AC circuit is energised and the AC line current is flowing at normal values, the iron core is highly saturated and has a low relative permeability. To the AC coils, the iron core acts like air, so the AC impedance is small. When an AC fault occurs, the AC amp turns generated by the AC coils increase linearly with the fault current to force the iron core out of saturation, resulting in increased line impedance during part of every half cycle. This results in a considerable reduction in peak fault current. Essentially, the saturable core-type FCL is a variable inductance, iron-core reactor.

Fig. 13 shows an arrangement in which three single-phase devices are arranged radially with their corresponding inner core limbs inside a single cryostat (silver cylinder) containing the HTS DC bias coil. The copper AC coils (red cylinders) are located on the outer limbs of the iron cores and spaced equidistantly [49, 50].

The clipping factor of this structure is 1.67. The DC power loss is significantly reduced because of the superconducting material. However, the superconducting materials have higher maintenance and operation costs [21].

Reactive SFCLs have become a research hotspot in the world due to their advantages of no detection, automatic triggering, fast response and low voltage loss, with many prototypes having entered the stage of demonstration tests.
The German Zenergy Corporation has developed a 13.8 kV/0.8 kA and a 138 kV/1.8 kA saturated iron-core-type SFCL developed by Innopower company was installed in a transmission network at the Puji substation of the China Southern Power Grid in 2007 [52]. Xin et al. [53] conducted current limiting tests in a live-grid under artificially imposed short-circuit conditions on 20 July 2009. Five tests were carried out either under different grid conditions or with different objectives. Innopower company had successfully developed a 220 kV/300 MV A SFCL prototype, which was installed in the Shigezhuang substation of Tianjin, China, and was put into operation in June 2012 [54, 55]. In 2017, a 500 kV SFCL was successfully developed in the China Southern Power Grid.

Generally speaking, reactive superconducting SCFCLs have been widely studied in high voltage and large capacity fields. However, the development of superconducting magnetic saturation FCLs is mainly restricted by the high loss and high maintenance cost of superconducting materials and cryogenic refrigeration systems [56]. In addition, the problem of over-voltage on superconducting components needs to be solved urgently [57, 58]. At present, the research on this type of SCFCL mainly lies in the structural optimisation, coil design, system simulation and so on. A design methodology that allows modelling and optimising reactive superconducting SCFCLs is presented in [59]. The methodology considers the characteristics of each constitutive element of the limiter while addressing utility requirements and power grid characteristics. The authors in [60] intensively investigated the correlation between the design parameters of coils and iron cores and their influence on FCL characteristics. The effect of the winding density in the AC coils on the performance of a SCFCL was studied in [30]. A methodology to simulate the dynamic behaviour of the saturated core SFCL in an electrical grid was presented in [61]. Its main advantage is a drastic decrease in simulation times when compared with FEM software. Santra et al. [62] presents the AC impedance control of a SFCL, along with the minimisation of undesirable voltage spike across dc biasing coil. The power dissipation analysis on a saturated iron-core SFCL was presented in [63]. For real operation, the power dissipation in the HTS coil of a SFCL should be taken into consideration.

3.4 Hybrid type

To reduce the DC bias power supply SCFCL and additional energy consumption and overcome the problem of insufficient excitation ability of permanent magnets, the research team proposed a hybrid excitation way in [64], which uses a NdFeB permanent magnet and traditional DC coil joint excitation, as shown in Fig. 14. Its working principle is similar to the typical SCFCL. However, the hybrid FCL is found to perform to the same specifications with <50% energy consumption.

Since the large magnetic flux leakage and magnetoresistance of the open core, and the reduction of DC bias capacity and current-limiting performance are unsatisfactory, a series of topology optimisations of hybrid type SCFCLs was carried out in [22, 65–67].

A bridge-type hybrid closed-core FCL is proposed in [65]. Fig. 15 shows a basic configuration of the bridge-type hybrid closed-core FCL. It consists of two magnetic devices in parallel
The AC flux flowed through the permanent magnets and the eddy current loss in permanent magnets is very large, which will lead to the overheating of permanent magnets and affect their stability. A coupled method used for calculating the eddy-current loss of PM in an SCFCL is proposed in [67].

To decrease self-heating and possible demagnetisation of PMs produced by induced eddy currents, a hybrid type SCFCL is proposed in [23], as shown in Fig. 16. The structure uses air-gap branches to provide a bypass for AC magnetic flux. The AC flux through a PM is greatly reduced, which can decrease eddy current loss and demagnetisation risk of the PM. It also enhances the operating range of the PMs, which means larger demagnetising current of PMs.

To verify the validity of the proposed topology, a 220 V/50 Hz prototype was fabricated and tested in [65]. The experimental results demonstrated the good clipping performance and reliability of the hybrid SCFCL.

The clipping factor of this structure is 1.83. The DC magnetising force is set to be 3100 AT. It requires a 33.3% less biasing current than the structure without permanent magnet, which means ~45% less energy consumption [22].

Based on the structure in Fig. 16, a three-phase compact SCFCL was proposed in [66]. The amount of ferromagnetic material is considerably reduced as only one common core is used for all three phases. The cost of the FCL is reduced.

The effects of parameters on the performance of a BSFCL was investigated in [68]. The air-gap branch and PM need to be appropriately designed to balance these factors affecting the performance of the BSFCL. The optimisation of the parameters requires consideration of the practical application of the system.

3.5 Comparison of these SCFCLs

Four types of SCFCL are introduced in the previous paper. In this section, their advantages and disadvantages are compared in terms of structure parameters, operation parameters and cost when their working voltage is similar. Some of their parameters are compared in Table 1.

| Type               | Open core | Close core | PM          | Reactive | Hybrid |
|--------------------|-----------|------------|-------------|----------|--------|
| rated voltage      | 415 V rms | 400 V rms  | 380 V rms   | 380 V rms| 380 V rms|
| rated current      | 24 A rms  | 14 A rms   | 10 A rms    | 30 A rms | 30 A rms|
| limiting factor     | 1.8       | 2–2.5      | 2.04        | 1.67     | 1.89   |
| response time       | ~10 ms    | 8 ms       | 8 ms        | 6–8 ms   | 6 ms   |
| DC MMF              | >8 kAT    | 5.5–7.5 kAT| 0           | 10 kAT   | 3.1 kAT|
| core                | dual core | 3-legs core| dual core   | dual core| dual core|
| maintenance cost    | —         | —          | —           | high     | —      |

and one bridge part. Each magnetic device is made up of PMs, core materials and coils. It decreases the energy consumption using a PM and ensures the fault clipping performance using a limiting reactor.

The excitation system: In permanent magnet type, emerging permanent magnets with higher coercively can provide stronger and more stable MMF. For other types, the power electronic devices in the DC source can also be used under fault conditions. For example, the energy of fault current may be fed back into rectifier power supply by changing the working state of power electronics.

5 Conclusions

This paper presents a review of SCFCL technologies for AC power systems from following aspects:

(i) FCL has broad application prospects under the background of increasing fault current. FCLs are classified into four categories based on the working principle.

(ii) The working principle of SCFCL is introduced in detail, and its advantages and disadvantages are compared with the other three types.

(iii) SCFCL is divided into four branches, according to the ways of generating MMF. A variety of prototypes and representative works are presented in detail. In addition to the classical models, we also present some promising new SCFCLs emerged lately. These topologies are compared in terms of core size, current-limiting performance and DC MMF. Some application examples are also listed in this paper.

(iv) At present, SCFCLs still have some limitations and large-scale commercial application has not been achieved. In this paper, the possible future development is speculated from three important parts of SCFCLs.

6 Acknowledgments

This work was supported in part by the Open Project of the State Rail Transit Technology Research Centre under Grant NEEC-2017-A04, in part by the Open Fund of Cascade Hydropower Station Operation and Control in Hubei Province under Grant no. 2017KJX02 and in part by the Shenzhen City Science and Technology Innovation Plan under Grant JCYJ20170306170937861.
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