Inductive Fault Current Limiters in VSC-HVDC Systems: A Review

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ABSTRACT Fast emerging fault current levels in high voltage direct current (HVDC) systems has always been a significant obstacle to building a safer and more reliable grid. Inductive fault current limiters (FCLs), compared with its resistive counterpart, are very effective in restricting the fault rising speed that causes major damage during the whole fault process. In this study, a comprehensive review of the methods used for building inductive type FCLs in HVDC systems is presented. The fault current characteristics of the modern HVDC system is discussed to obtain the basic requirements for the FCL. On the basis of different technological domains, various inductive-type FCL topologies and devices are well categorized and analyzed. After the overall discussion and comparison, representative works, as well as new progress and future prospects, are conveyed in detail. One may find the content of this study helpful as a detailed literature review or a practical technical guidance of this field.

INDEX TERMS Fault current, fault current limiter, HVDC system.

I. INTRODUCTION

Due to the rise in global energy consumption in recent decades, the high voltage direct current (HVDC) technology has been widely employed for bulk power transmission over long distances [1], [2]. Compared with traditional high voltage alternating current (ac) systems, HVDC transmission is considered advantageous and, in some cases, superior to ac in applications such as long underwater cable crossings, long distance bulk power transmission, stable ac interconnections, renewable power integration coupling systems with different frequencies and long-distance underground cable systems [3]–[8]. Through continuous progress of high voltage high power switching devices, power electronic technologies used in HVDC systems have experienced technological leaps in recent years. As a result, from traditional line-commutated converters (LCCs) to recent voltage source converters (VSC), the prosperous development of HVDC systems is changing toward a more efficient, flexible and reliable power transmission solution [1].

Despite the huge benefits offered by the HVDC technology, the major drawback has been fault ride-through capability during direct current (dc) faults due to low dc impedance and the absence of natural zero crossings of fault current. These factors make dc fault levels extremely high and rise very fast, thereby posing a threat to the grid [9]–[12]. Therefore, the main focus of the HVDC industry has been the development of reliable protection schemes with fast fault detection and effective fault current limitation to prevent further severe damage and maintain normal power transmission after the fault clearance.

According to the survey conducted by CIGRE [13], the most serious issue of the fault current is that the rising rate of it is too high and it reaches the top within several milliseconds. Hence, it is imperative to add extra facility to limit the steep rising rate of the fault at its early stage. A promising solution to this problem, which has drawn significant attention in recent years, is the application of fault current limiters (FCLs). The research and development of various types of FCLs has been conducted worldwide [14]–[19]. Insights into FCL concepts and technologies can be classified by the principle of operation and key technological components used.
Generally, FCLs can be implemented with passive nonlinear elements [20]–[22], inductive devices [23], [24], semiconductor switches [25], [26] and hybrid approaches [10], [27], [28]. The technical feasibility of such FCLs has already been demonstrated with prototypes or scaled down models. However, due to power limits and strict application requirements of both semiconductor and superconducting (SC) devices, few of them are applicable in HVDC systems.

When it comes to external electrical feature of the FCLs, there are resistive type FCL and inductive type FCL that are proposed previously [18], [20]. Resistive type FCL often uses SC coil to generate variable resistance and limit the fault current [22]. Some typical topologies are shown in Fig. 1. Series connected type (Fig. 1(a)), magnetic shielding type (Fig. 1(b)) and flux lock type (Fig. 1(c)) are presented. The resistive type FCL can limit the peak value of the fault current. However, given that the resistance part $R$ can not be easily changed in the HVDC system and resistive type FCL helps little to restrict the rapid rising rate of the fault current [29], the breaking point of the fault current issue lies in the inductor.

For a dc fault current, the waveform is consisted of a high frequency fault component. Considering that a large inductor can present extremely large impedance to system with high frequency component, inductive FCLs, which have developed rapidly in recent years, offer a promising way of solving the fast transient problem of HVDC fault current [11], [12]. For a dc fault current, the waveform is comprised of a high frequency component, inductive FCLs, which have developed rapidly in recent years, offer a promising way of solving the fast transient problem of HVDC fault current [11], [12].

Stage I (Capacitor Discharge): This stage occurs as the dc-link capacitor discharges and the equivalent circuit shown in Fig. 2(b). Due to the low internal impedance of the HVDC system, the precondition can be given as $R < 2\sqrt{L/C}$. Hence, the solution of the second-order circuit natural response gives an oscillation and the fault parameters can be calculated as:

$$v_c = \frac{v_c(\omega_0)}{\omega} e^{-\delta t} \sin(\omega t + \beta) - \frac{i_0}{\omega C} e^{-\delta t} \sin \omega t$$

(1)

$$i_f = C \frac{dv_c}{dt} = -\frac{i_0}{\omega C} e^{-\delta t} \sin(\omega t - \beta) + \frac{v_c(\omega_0)}{\omega L} e^{-\delta t} \sin \omega t$$

(2)

In (1) and (2), the initial condition can be given as:

$$\begin{cases} v_c(0) = v_c(\omega_0) \\ i_f(0) = 0 \end{cases}$$

$$\begin{cases} R = 2L_L \omega = 2L_L \omega_0 \\ \delta = R/2L_0 = 2\sqrt{1/LC} - (R/2L_0)^2 \\ \omega_0 = \sqrt{\delta^2 + \omega^2} = \arctan(\omega/\delta) \end{cases}$$

(3)

Stage II (Fremwheel Diode Continuous Charge): This stage is initiated when the dc-link voltage reaches zero and the dc
inductance drives the current around the freewheel path. The fault circuit is solved using the first-order equivalent circuit, as shown in Fig. 2(c).

\[ i_f = i_0 e^{-\frac{R}{L}t} \]

In (4), \( R \) and \( L \) can be found in (3), while \( i_0 \) is the current derived from (2) when the \( v_c \) in (1) decays to zero.

Stage III (AC Grid Current Feeding): During this stage, the fault current is a forced response with ac grid current feeding and dc-link capacitor inductor oscillation. However, because this stage has already reached the steady state of a fault, it is not our priority to calculate the exact fault current at this stage.

B. FAULT ANALYSIS AND FCL REQUIREMENTS

During the fault transient process, it is obvious that stage I of the dc PTP fault is the most serious stage among the whole fault process. The most important factor of the fault current issue in VSC-HVDC system is that current increases very rapidly (less than 10 ms to the top) during the stage I shown in Fig. 2(a), causing destructive damage to the whole system. Therefore, for VSC based HVDC systems, it is necessary to limit the fault current rising speed in order to protect the system more efficiently [12].

A typical VSC-HVDC system was built in MATLAB/Simulink and a PTP fault was conducted to verify the deductions mentioned above. Table 1 shows the parameters of the VSC system and Fig. 2(e) shows the variation of current and voltage under different \( L_{dc} \) conditions. It is obvious that although the practical VSC-HVDC system has self-block strategy that can protect the system from further damage caused by dc fault, the current rising speed is still too fast in the first few milliseconds. Although the latest modular multilevel converter (MMC) based HVDC system that have the capability to block the converter station after the fault was detected, it still takes about 3 ms for the protecting strategy of the system to react and block the whole converter station. The fault current issue can be alleviated by the strategy, but the fault can still harm the station due to the fast rising speed of the fault current.

In this case, the self-block strategy is not sufficient for the safety operation. Large smoothing reactor can alleviate this situation but the dynamic response of the system will be threatened and LC oscillation problem might occur [34]. Moreover, both extra room and cost will be brought by a larger smoothing reactor. The HVDC circuit breaker, on the other hand, cannot withstand the large fault current up to 30 kA level in practical HVDC system and the total price is extremely high. Hence, an FCL device that can restrict the rising trend of the fault current is really helpful. From (2) and (3), it is obvious that the decay factor \( \delta \) of the up-rushing dc fault current depends on both the \( R \) and \( L \) of the fault routine. In this case, a fast-changing inductor that can have an immediate inductance rise is very effective in limiting the rising trend of a dc fault current [11], [12].

There is no FCL installed in ac side and the focus point lies in the dc side. The simulation results in Fig. 2(e) shows that the larger inductance is, the lower fault current level can become. From the deductions mentioned above, in order to reduce the fault current increase rate, the dc inductor \( L_{dc} \) shown in Fig. 2(a) can be replaced by an inductive type FCL that can present variable inductance to the system. In normal state, the FCL can present inductance with fixed value and act as a necessary smoothing reactor in the dc side of the system. When a fault occurs, the inductance of the FCL can rise immediately and the fault rising rate can be restricted effectively.

From the characteristics mentioned above, some technical aspects of the inductive type FCL must be taken into consideration. Fig. 3 shows the diagram that defines different parameter indexes of inductive type FCLs.

1) INDUCTANCE CHANGING RATIO \( k \)

For an inductive type FCL device, the clipping inductance changing ratio \( k \) must be considered as one of the most important parameters that affect the performance. The \( k \) can
be defined as:

\[ k = \frac{L_f}{L_0} \]  

where \( L_f \) is the inductance value of the FCL in fault state, while \( L_0 \) is the normal inductance value of the FCL. Under the same \( L_0 \) condition, the larger the \( k \) is, the larger \( L_f \) can be, so the slower fault current will rise and a better clipping performance can be achieved. Therefore, the inductance changing ratio \( k \) is chosen as one of the key parameter indexes to judge the performance of an inductive type FCL.

2) INDUCTANCE CHANGING TIME \( t_c \) AND RECOVERY TIME \( t_r \)

Apart from the \( k \) mentioned above, the inductance changing time \( t_c \) is also crucial. Since the rising speed of the fault current is quite fast, the inductance of the FCL also need to change as fast as possible to reach its maximum value when a fault occurs and limit the fault transient issue. Whether the fault detect device and fast switch are necessary or not, the total period of time when the clipping inductance reaches its peak value from the normal value, which is defined as inductance changing time \( t_c \), can reflect the fast response feature of an inductive FCL. Indeed, this rising feature of the inductance value looks quite like the “quench” mechanism in resistive type SFCL. But the meaning of them are not exactly the same. In fact, taking account of fault detecting time, switching time, rotating and shifting time of magnetic domain wall and other time before the FCL’s inductance value reaches its maximum value, every type of FCL in the VSC-HVDC system has time delay on the inductance changing period. Considering that, the inductance changing time \( t_c \), shown in Fig. 3, becomes another crucial index to measure the performance.

Moreover, when the fault clearance is completed, the inductance of the FCL needs to change to its original value \( L_0 \) as fast as possible, so as to restore the normal operation of the whole system. In this case, although the inductance recovery time \( t_r \) is not directly related to the fault clipping performance, \( t_r \) is another choice of index that needs to be taken into consideration.

3) OTHER FACTORS

There are, of course, some practical indexes such as price, volume and so on, to also consider. These factors will also be included to decide the performance.

III. CATEGORIES OF INDUCTIVE TYPE FCLS

Significant efforts have been devoted to building different kinds of inductive FCLs. In order to analyze their principles and compare their performances, inductive FCLs will be divided into different categories according to the types of technology. Figure 4 illustrates the categories of inductive FCLs.

Figure 4 illustrates the inductive FCL classification, namely, flux coupling, iron core and solid-state. Based on different coil topologies, the first category can be sub-classified into different coil shapes and topologies. Meanwhile, the iron core type can be sub-classified into different core, coil, material and other topology designs. The solid-state type FCL is usually combined with power electronic devices and is complicated. Therefore, different hybrid structures of this kind will be introduced and analyzed. It is worth mentioning that SC coils are widely used in building FCL devices, so these categories of FCLs that use both SC technology and non-SC technology will be applied and included in the following study.

IV. FLUX COUPLING INDUCTIVE TYPE FCL

Flux coupling inductive type FCLs mainly consist of induc-tors that have different coil shapes and circuit topologies. Due to the loss problem and magnetic coupling effect, SC coils are often chosen as proper material for flux coupling type FCL. Figure 5 shows the basic principle of this type of FCL. In the normal state, the switch \( K \) is closed and the coils are maintained in the superconducting state. The FCL’s impedance is determined by the operating impedance, which can be calculated as:

\[ Z_{FCL} = j\omega \left( \frac{L_1 + M}{L_2 + M} - \frac{M}{L_1 + L_2 + 2M} \right) \]

where \( L \) and \( M \) are the self and mutual inductance of the coil, respectively. In this case, the equivalent inductance is almost zero in the SC state. When a fault occurs, the switch \( K \) detects it and opens. Herein, the electromagnetic repulsion mechanism (ERM) may be applied in the switch \( K \), and a high-speed DC switch prototype with an ERM can open within 0.5 ms from the trip signal [36]. Since the flux between the two windings can no longer cancel out each other, the non-inductive coupling will be destroyed, and the equivalent inductance \( L_{FCL} \) will become \( L_2 \), which is much
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**FIGURE 5.** Basic principle of flux coupling inductive type FCL.

**FIGURE 6.** Typical coil shapes of flux coupling inductive FCL. (a) Flat shape; (b) pancake shape.

**FIGURE 7.** Different coil connection in [43]. (a) In parallel; (b) in series.

larger [37]. Therefore, the large inductor is connected into the system and limit the fault effectively.

Based on the flux coupling and decoupling principle mentioned above, various types of flux coupling inductive FCLs were developed and the relevant research is mainly aimed at the following two objects: coil shapes and circuit topologies.

**A. INTERNAL COIL SHAPE ANALYSIS**

In [39], a flat type SC coil shape was developed and different cylinder modules were analyzed to find a better combination between layers and structures. The results shows that the novel flat type FCL has the advantage that it can be easily built up to make a compact FCL with a high inductance changing ratio $k$. To further increase the inductance changing ratio $k$ of the FCL coil, detailed magnetic analysis, calculation and experiments were carried out in [40]. Moreover, the parallel connection and transformer connection of SC flat coils were also introduced and compared to make this FCL obtain better fundamental characteristics, as explained in [41].

As for the pancake shape shown in Fig. 6(b), [42], [43] proposed a pancake shape FCL with modularized multiple parallel branches, shown in Fig. 7, which is suitable for HVDC application, while [38], [44], [45] analyzed its feasibility in large dc impulse application as well as electromagnetic, force and recovery features. Moreover, a 10 kV/400 A prototype [46] was analyzed, designed and tested to verify the proposed structure. Results show that this topology can limit the peak fault current from 12.5 kA to 5.8 kA, which is quite effective. The research mentioned above is much more comprehensive, but they still lack the characteristics of practical HVDC systems, which can be discussed and explored in future.

Furthermore, other kinds of pancake coil shapes like single pancake, double pancake, bifilar pancake [47]–[49] and stack shapes [50] are also developed and analyzed. Even some hybrid type combining inductive and resistive component into the FCL also emerges [51].

From the previous study, the $k$ of these types of FCLs has exceeded from 4 to 23, which is impressive. The time feature $t_c$ and $t_r$, on the other hand, have been considered and $t_c$ is often less than 5ms, while $t_r$ is often larger than 100 ms [11], [52], [53]. In this case, the recovery time needs improvement for further application.

**B. EXTERNAL CIRCUIT TOPOLOGY ANALYSIS**

When it comes to the external circuit topology of the flux coupling type FCL, different combinations of coils and devices are presented. In the following study, some typical topologies will be introduced and analyzed.

Chen et al. [54] firstly proposed a modified flux coupling FCL, shown in Fig. 8. Over-voltage issue is another important issue needs to be fixed. From Fig. 9, a metal oxide arrester (MOA) is a proper choice to suppress the switching and impulse overvoltage, which is connected in parallel with the upper coil. When a fault occurs, the fast switch $S$ will open, $R_{SC}$ and $L_2$ will be connected into the fault circuit. In this case, the impedance of FCL is:

$$Z_{FCL} = R_{SC} + j\omega L_2 + \frac{(kn\omega L_2)^2}{(R_{MOA} + n^2j\omega L_2)^2}$$

(7)

where $k = M/\sqrt{L_1L_2}$ and $n = \sqrt{L_1/L_2}$. Since $R_{MOA} \gg n^2j\omega L_2$, so (7) can be rewritten as:

$$Z_{FCL} \approx R_{SC} + j\omega L_2$$

(8)
This kind of FCL was proposed and applied into the renewable energy integration process. Relevant studies are shown in [55]–[58]. The fault current reduction rate can be 25.8% under 100 mH \( L_2 \) case and with the rise in \( L_2 \) value, the current can be reduced more effectively.

Jin et al. [59] proposed a SC air-core dc reactor that is designed for both voltage smoothing and fault current limiting applications. Yan et al. [60] proposed an improved FCL that uses two switches \( S_1 \) and \( S_2 \) instead of one switch in Fig. 8, which can decrease the necessary capacity of the switch. Different winding methods of this FCL were also analyzed and experimental results are shown in [61].

According to the principle, this kind of topology often has a fixed current limiting inductance \( L_2 \) and the simulation results in [54]–[61] revealed that the clipping performance mainly depends on this inductance. From (7) and (8), since the non-inductive state of \( L_0 \) can be achieved in normal state [62], the \( k \) calculated from (5) can be much larger. The react time, in the meanwhile, is depended on both switch \( K \) and the SC material. The \( t_c \) can be 1~5ms, while the \( t_r \) still remains in second level.

Seeing that the above topology research mainly focuses on the application of the FCL, more detailed optimization like thermal, force and electromagnetic features studies are suggested for further discussion. Other kinds of flux coupling FCL topology that use iron core to have a larger coupling coefficient will be elaborated in the next section.

To summarize for the flux coupling inductive type FCL, significant work, including both theoretical and experimental aspects, has been done on this type of FCL. However, this research regarding both coil shape and circuit topology is limited within their own technology areas. Hence, the combination of these two research areas is suggested for further study.

V. IRON CORE INDUCTIVE TYPE FCL

Iron core is widely used in the FCL field for decades due to the permeability variation between unsaturated and saturated states. However, the mainstream direction of the iron core FCL is in the aspect of the ac system. Until recently, some research regarding dc system iron core inductive type FCLs has been observed and proved effective in HVDC systems. In the following study, these researches will be elaborated in detail.

There are many kinds of core structures in the ac FCL field, such as closed [63], open [64], [65] and hybrid loop cores [66]. In the dc system field, in order to obtain larger inductance changing ratio \( k \), the closed loop core is frequently used to avoid fixed large magnetic reluctance provided by the air gap.

A closed core FCL structure was proposed in [67] and its topology is shown in Fig. 10. SC coil is used in the dc excitation circuit. As for this type of FCL topology, the dc current source is connected in series with the coil to generate large dc bias current. Since the flux of system current and dc bias current is in the opposite direction, the equivalent B-H curve of the core will be shifted from the ordinary red line to blue line, as illustrated in Fig. 10(b). In this case, the iron core can present low permeability \( \mu_u \) under normal current and rush up to large permeability \( \mu_u \) when current goes unusually large. The coil inductance can be derived as:

\[
L_2 = \frac{N_2 S_2}{l} \left( \mu - \frac{N_1 i_1 - N_2 i_2 + \mu}{d_2} \right) \tag{9}
\]

where \( N, S, l \) and \( \mu \) are the coil turns, cross-sectional area, length of the total magnetic loop and permeability of the core, respectively. The result shows that the maximum fault current value and drop velocity of dc voltage can be reduced effectively in the VSC-HVDC system [67]. Moreover, the inductance calculation scheme was proposed and verified in [68] to guide the design of the parameters.

Based on this topology, a coil and circuit optimized topology was proposed in [69], which is shown in Fig. 11. The single SC coil was replaced by parallel connected SC coils, while MOA and fast switching device was added for device protection. These modifications were dedicated to decreasing the over-voltage issue on the SC coil and protecting the dc source when a fault occurs. In addition, the parameters matching and constrains between the FCL and direct current circuit breaker (DCCB) were also carried out in [70], [71]. Both theoretical and simulated results show that the \( k \) of the FCL is over 1000 since the initial inductance is almost
zero, while the react time $t_c$ is less than 1 ms. In a practical VSC-HVDC system, fault current can be reduced from 15 kA to 9 kA within 5 ms. The overvoltage issue of the source and coil, in the meanwhile, can be relieved.

Except for traditional single core structure with two windings [67]–[71], many other FCLs concerning the iron core structure and topological design are proposed in HVDC system. Wei et al. [34] proposed an FCL based on magnetic shielding of the SC rings, shown in Fig. 12(a). Parameter optimization of this FCL presents promising performance with $k$ over 50 and $t_c$ less than 1 ms. Dual core structure was also utilized in [72]. When combining the iron core with semiconducting devices, some topologies like bridge type [29] and auto-transformer type [73], shown in Fig. 12(c) and (d) respectively, were proposed in HVDC system. Semiconducting switches are used in these topologies to alter the current path before and after a fault. Both react and clearance time are fast (within 1 ms) and the fault current can be restricted below 50% according to the simulation results, which is very promising.

Apart from the ordinary dc bias source that is used to drive the core into saturation, rare earth permanent magnets (PMs), developed rapidly recently, have been an alternative choice for the dc bias source. There is significant research regarding PM energized FCL devices in the ac FCL field [63]–[66] and its development in the dc field is also emerging.

Yuan et al. [74] proposed a PM biased FCL in a HVDC system. A Nd-Fe-B type PM was used to generate a strong bias flux that drives the limbs of the FCL into saturation when the system operates normally. In the fault state, the large magneto-motive force generated by the non-SC dc system coil will make the limb desaturate and the inductance will rise automatically. Compared with the dc source excitation type FCL, this PM energized FCL can have a much smaller power loss during normal operation and lower total cost compared with iron core FCL with SC coils.

After solving the equations in Figs. 13(b) and (c), the equivalent clipping inductance $L_{FCL}$ can be derived:

$$L_{FCL} = \frac{4N_{dc}^2}{\sum_r r} = \frac{4N_{dc}^2}{r_{el} + r_{ce} + 2r_m + 4r_u}$$

(10)

where $N_{dc}$ is the turn number of the dc coil and $r_{el}$, $r_{ce}$, and $r_u$ are the magnetic reluctance of limb, PM and yoke, respectively. Different soft magnetic materials and their combination in this FCL topology were also tested and optimized in [75]. Three limb topology was also developed to further increase the inductance changing ratio $k$ [76]. The $k$ of this FCL derived from (5) and (10) can be up to 10, while the $r_c$ and $t_c$ can still below millisecond level. The fault current can be reduced by over 50% within 10 ms.

Given that the bias source is indispensable in this kind of FCL topology, the combination of both PM, dc source and other devices can be considered to have a faster and more cost-efficient solution. Moreover, flux lock type [77]–[82], PM hybrid type [66], [83] and many other ac system iron core FCL can be modified and optimized to fit the dc environment.

For the iron core inductive type FCL, relatively less work has been done in dc systems. Considering that iron core can be a perfect carrier for a variable inductor, more topological improvements, including coil design, core structure optimization, multi-physics simulations, HVDC system combination and protection relay cooperation, can be achieved in future.
VI. SOLID-STATE INDUCTIVE TYPE FCL

Recent advances in high power semiconductor technology, such as new thyristors with higher voltages and higher current ratings, and emerging SiC devices, have increased the feasibility for the implementation of commercially viable solid-state FCLs [16]. There are numerous structures and topologies of solid-state FCLs and in the following study, the inductive type of them will be elaborated and analyzed.

A. BRIDGE TYPE SOLID-STATE INDUCTIVE FCL

Bridge type FCLs, firstly revealed in 1999 for ac system protection [84], are a large branch in the solid-state FCL field. Recently, applications of this type of FCL has appeared in dc system, which can be found in the following part.

Figure 14 shows the working principle of a typical bridge type FCL. For this topology, it can be applied into both ac [84] and dc system [85]. SC coil and a dc voltage source is used to generate a dc-bias current. During normal operation, as long as the dc biased current $i_b$ is larger than the absolute value of the dc line current $|i_{dc}|$, $(i_b + i_{dc})/2$ and $(i_b - i_{dc})/2$ are both positive and thus all the diodes $D_1 - D_4$ can stay in the conducting state. Meanwhile, the current flowing through the dc reactor $L_B$ remains constant as $i_b$. In this situation, the dc reactor is bypassed from the dc line, thus having no influence on the dc grid normal operation.

After a dc fault, the dc fault current rises rapidly. As shown in Fig. 14(b), when $i_{dc} > 0$ and it exceeds the dc-biased current $i_b$, $(i_b - i_{dc})/2$ will be negative. This means that the series diode groups $D_2$ and $D_3$ will be turned off automatically. Thus, the dc reactor is connected to the fault circuit to limit the fault current. Similarly, if $i_{dc} < 0$, the series diode groups $D_1$ and $D_4$ will be turned off automatically, allowing the dc reactor to be in the fault circuit as well. This means that the bridge-type FCL can deal with the bidirectional fault current limitation in the dc grid. In this topology, the equivalent normal impedance of the FCL is almost zero, while the equivalent fault impedance of it is the value of $L_B$.

He et al. [85] proposed this type of FCL in an HVDC system and analyzed the coordination between the FCL and DCCB to find the best parameter combination of the FCL. A capacitor modified type was proposed in [86] and both fault current and low-voltage ride-through issue can be solved by applying this FCL into wind farms. In [87], a parallel branch with a fully controllable semiconductor switch and resistor were added in the inductor circuit, while the control strategy was applied to detect the fault and insert the $r_p$, so as to use $L_d$ and $r_p$ to restrict both severe fault rising rate issue and peak current value. In addition, the fault ride through scheme of a wind turbine and low voltage ride through the strategy of the grid were also investigated in [88], [89]. Experimental result reveals a 37% reduction rate for the bridge type FCL under fault condition. Regarding the performance index $k$ and $t$, since the limiting inductor is bypassed in normal state, $k$ derived from (5) can be extremely large. The time indexes, on the other hand, are below the millisecond level owing to the fast switch used.

In addition, there are more hybrid bridge structures in the ac field, like the flux coupling type in [90], the fully controllable switch type in [91] and other hybrid bridge types in [92]. They combine the bridge structure with other topologies to achieve better performance. In order to apply them to the dc field, more investigations need to be completed.

B. OTHER TOPOLOGIES OF SOLID-STATE FCLS

For other topologies of solid-state inductive FCLs, it is more about the combination between inductor, fast semiconductor switch and MOA. Some typical topologies are shown in Fig. 16.

Figure 16(a) shows a novel FCL that combines both fault current limit capability and a DCCB device [93]. In the normal state, the branch breakers are closed and the non-SC inductors $L_1$, $L_2$ and $L_3$ are connected in parallel. The total equivalent inductance of them is $L_1//L_2//L_3$ and it is very small, thus causing no harm to the normal operation of the system. When a fault occurs, the branch breakers are forced to open, letting the fault circuit shift from previous parallel status to the series status. Considering that, the equivalent
inductance becomes $L_1 + L_2 + L_3$ and it is much larger than its original form. After the fault limiting stage, the main breaker can cut the fault effectively. The $k$ of it can be 9 and higher, depending on the parallel structure. The time index is about 1–3 ms due to the combination and coordination of the breakers.

Recently, superconducting magnetic energy storage (SMES) technologies have been research hotspots for renewable power integration in HVDC system. Fig. 16(b) shows a SMES type solid-state FCL [94], [95]. In this topology, SC coils are used. By switching the relevant semiconductor switches and apply the control strategies, it can achieve three different modes, i.e., SMES charging, SMES discharging and SMES FCLs. Since the impedance of the FCL was inserted into the circuit when the FCL mode was activated, the $k$ still depends on the SMES coil. Different current paths are shown in Fig. 16(b). In this case, power fluctuation generated from wind farms can be relieved and dc side fault current can be limited effectively. Other SMES FCL topologies in wind farms and photovoltaic generation units are proposed and analyzed in [96], [97].

In summary, for the solid-state inductive type FCL, the multifunctional topology, good controllability and fast reaction time are some advantageous points compared with other types of dc inductive FCLs. However, this type of FCLs need complex control strategy and indispensable fault detecting device. In addition, the relatively low voltage and current level of single semiconductor devices results in a large number of device combinations to adapt to high voltage system. Anyway, with the fast development of power electronics technology and the integration of the hybrid FCL structure, the solid-state inductive type FCL in the HVDC system will have another leap in the near future.

### VII. PERFORMANCE COMPARISON AND CONCLUSION

In this study, different types of dc inductive FCLs, i.e., flux coupling, iron core and solid-state types, have been organized and relevant comparative studies have been presented. Taking account of the performance indexes mentioned at the end of section II, a brief summary is put forward in Table 2 to show these categories of FCLs and discuss their advantages and disadvantages.

From Table 2, it can be seen that these three types of FCLs have their own unique merits. The flux coupling type FCL is easy to build and efficient in performance. The iron core type FCL is free from fault detection and easy to withstand the HVDC system. The solid-state FCL is fast in reaction speed and flexible in function. In contrast, there are also reliability issues related to the control and coordination of semiconductor devices.

| Categories          | $k$                  | $t_0$ & $t_r$                      | Other indexes, advantages and disadvantages                                                                 |
|---------------------|----------------------|-----------------------------------|------------------------------------------------------------------------------------------------------------|
| **Flux coupling**   | $37–52$              | $1–5$ s level (depending on coil structure) | a) Easily built topology; relatively small volume.  
                                                | $54–61, 90$                         | $100$ ms level (SC coil recovery time) | b) Strongly rely on the fault detecting device and fast switch; dependent on SC coil; lack experimental analysis. |
| **Iron core**       | Up to several hundred (depending on core material and saturation point) | $1–5$ s (core inductance rising)  | a) Automatic fault limiting capability; better high-voltage compatibility; relatively small volume.  
                                                | [34, 67–83]                         | $<5$ ms (core desaturation automatically)                         | b) Ordinary power loss of dc bias source (if used); insufficient relevant research for dc field; lack experimental analysis. |
| **Solid-state**     | Up to several thousand (from zero to the inserted inductance value) | $1$ ms (depending on the fast switch)        | a) Fast speed; multi-functional topology; better dc system adaptability.  
                                                | [85–92]                             |                                   | b) Rely on the fault detecting device and fast switch; hard to withstand high voltage and current situation. |

**FIGURE 16.** Other dc inductive type solid-state FCL topologies. (a) Inductor and DCCB hybrid type; (b) SMES hybrid type.
TABLE 3. Cost of different materials and devices.

| Material       | Cu coil | BSCCO | HTS wire | MgB2 |
|----------------|---------|-------|----------|------|
| Wire cost      | 5–25    | 150–180 | 50       | 2–15 |
| Cooling cost   | 0       | 25    | 29.5     | 47.5 |
| Total cost     | 5–25    | 175–205 | 79.5     | 49.5–60.5 |
| (USD/kA*sn)    |         |       |          |      |

Total cost (USD/kg)

| Semiconductor switches of 1.2kV level | Silicon steel | Permanent Magnet |
|---------------------------------------|----------------|------------------|
| Si IGBT                               | 1.75           | 26.25            |
| SiC MOSFET                            | 6.29           | 69.8             |
| Hybrid                                | 76.09          |                  |

TABLE 4. Cost evaluation of different FCL categories.

| FCL Categories | Material used                  | Quantity | Cost * |
|----------------|-------------------------------|----------|--------|
| Flux coupling  | SC coil (YBCO)                | 50 m     | About 3975 USD |
|                | Cooling system cost           |          |         |
| Iron core      | Iron core sheet               | 160 kg   | About 370 USD |
|                | Copper coil                   | 5 m      |         |
|                | Permanent magnet (if necessary)| 0.5 kg   |         |
| Solid-state    | IGBT (SiC MOSFET)             | 4 pcs    | About 900 USD |
|                | dc reactor                    | 1        |         |

*The cost is estimated under the same capacity level, i.e., 1 kV voltage and 100 A current.

Among these FCL categories, the iron core type FCL can automatically limit the fault current and is good in both performance and cost. Still, it lacks practical design experience and detailed topological optimization. In order to realize a fast, reliable and economical application of VSC-HVDC system FCL, it deserves more attention and the technology combination of other types of FCL.

VIII. FUTURE PROSPECT

This work provides a comparative survey of inductive type FCL technologies for dc systems and reports on research carried out in this area. Prior to introducing the methods directly used in the three topics, an overall review on the fault current characteristics of the HVDC system was given, which lays the foundation for the performance target for the FCLs. This study aims to evoke new attention to FCL research and calls for new ideas to be contributed to extend and enrich the available pool of dc inductive type FCLs concepts.

For future research, the following aspects can be considered and further analyzed:

A. DEVICE LEVEL

1) With technological advances in power electronic devices with high power density and efficiency, the combination between power electronic devices, iron core structure as well as energy storage systems can be designed to fully realize instant saturate/desaturate procedure and fault energy storage with charging and discharging control.

2) In terms of material aspect, the next generation of high temperature SC tapes and new soft magnetic materials can be combined to form a hybrid type. Inductance feature, response speed and power loss can be further analyzed. Moreover, the optimization study of the inductive type FCL can be carried out based on multi-physics analysis, coil arrangement, hysteresis analysis and insulation design, etc.

3) The compact and economical design of an inductive type FCL is also crucial for practical installation, which needs more attention. Besides, inductive FCL with multi-function feature like power flow control, voltage compensation and other functions is another promising way to go.

B. SYSTEM LEVEL

1) On the system level, the inductive FCL need to take account of converter/inverter control strategy and relay protection algorithm of the VSC-HVDC system. In addition, how to cope with the operating strategy of the ac/dc breaker of the system is another practical issue to solve.

2) Since the renewable energy are getting their position in the power market, the impact of the unpredictable power fluctuation of renewable generation as well as charging/discharging process of electric vehicle cannot be neglected when the FCL is installed.

3) The placement and layout of the FCLs should be tested under IEEE standard nodes model. Cutting-edge technology on neural network and machine learning can be adopted to...
optimize the performance and cost of the FCL in the actual VSC-HVDC system.

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