DC-presaturated fault current limiter for high voltage direct current transmission systems

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Abstract
The authors present a 500 kV real-dimension DC-presaturated fault current limiter (PFCL) with a steady-state rated current of 2 kA for limiting large fault current of 8 kA with high rate of rise. These characteristics of the fault current can be a threat to high voltage direct current (HVDC) transmission systems, and hence PFCL design and performance improvement are investigated through three-dimensional, time-domain, magnetic-field and electric-circuit coupled model using finite element simulation of COMSOL Multi-physics package. The nonlinear magnetic characteristics of the soft magnet ensure variable inductance depending on demagnetisation magnetomotive force generated by the line current. This DC-biased PFCL can replace the traditional smoothing reactor during the normal operation of the system by controlling the level of presaturation. In addition, PFCL is a self-triggered device and therefore it can automatically limit the fault current and reduce its value below the interruption rating of the used HVDC circuit breakers (CBs). Moreover, the rate of rise of the fault current can be controlled to ensure the compatibility with the available type of HVDC CBs. The dynamic performance of PFCL is investigated during fault condition through the fault current clipping ratio and rate of rise of the fault current, and during steady-state operation through the voltage drop across PFCL and its power losses. It is found that the proposed PFCL presents adequate capability in limiting large fault currents with extremely low values of voltage drop and power losses during the steady-state condition. However, the switching transient overvoltages that appear at terminals of PFCL coils during the fault duration have been successfully suppressed by carefully selected ratings of zinc-oxide surge arresters.

1 | INTRODUCTION

High voltage direct current (HVDC) systems are widely used in the electrical networks for power transmission due to their tremendous advantages as compared with those of the high voltage alternating current (HVAC) systems, especially for bulk-power transmission over long distances with lower capital costs and lower losses than those of HVAC. The recent and wide penetration of different distributed energy resources with multi-terminal interconnections continuously increase the fault current level, which can threaten the power system reliability [1–5]. Such levels of fault current represent a challenge near the switchgear and/or circuit breakers (CBs) ratings [6–9]. Consequently, their endurance must be upgraded to conserve the system reliability and full protection against inevitable increase of fault current level. This upgrade process is a costly solution and time-consuming process.

Currently, the superconducting fault current limiters (SFCLs) and solid state FCLs (SSFCLs) represent well-known categories of HVDC FCLs. Therefore, the continuous progress in superconducting technologies and solid-state power semiconductor switches raises the application importance of SFCLs and SSFCLs in HVDC networks. In SFCL, the fault current can be limited by the sharp rise in the superconductor impedance to a remarkable high value due to fault current effect. However, the accompanying cryogenics for SFCLs [10–12], and inevitable delay of fault detection/clearance due to the accompanying control circuit for SSFCLs [13] can be considered as operation difficulties that limit the reliability and application of these categories.

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HVDC smoothing reactor is still used to relieve the severe rise behaviour of the fault current [12, 14]. Moreover, inductive-type FCLs have attracted many considerations by researchers due to their increased ability and reliability of limiting fault current in AC networks with self-triggering behaviour [15–19]. The detection-free strategy, high voltage withstanding capability, and fast response increase the importance of such presaturated FCL (PFCL) to be used in the electrical networks [2–8].

During the fault condition, the soft magnet is forced to operate in the linear zone of its B-H characteristics, with extremely high value of relative permeability, and hence is promoted to higher insertion inductance value leading to fault current clipping. This can be achieved by the provided magnetomotive force (mmf) from either superconducting/simple copper DC-energised coil [6–12], or permanent magnet (PM) [16, 17, 19].

This work proposes a HVDC PFCL through three-dimensional (3D), time-domain, magnetic-field and electric-circuit coupled model using finite element (FE) simulation of COMSOL Multiphysics package [20]. The rate of rise of the fault current (fault current slope) is calculated and hence its compatibility with various types of HVDC CBs can be determined. Moreover, comprehensive FE simulations have been conducted to study the effect of the controlling parameters on the dynamic performance of the PFCL. Finally, a design flowchart has been proposed, taking into consideration the relative effect of such parameters, to summarise the design process of PFCL for HVDC transmission networks.

2 | BASIC CONFIGURATION AND OPERATING PRINCIPLE

The main objective is to introduce a simple design of PFCL having extremely low power losses and voltage drop across it under steady-state conditions. In addition, PFCL can be used to replace the traditionally used current smoothing reactor and to reduce the current harmonics generated by the converters’ operations. This implies that PFCL must have a reasonable inductance even under steady-state conditions. Moreover, the controllability of the damped fault current enables users to adjust the fault current slope and ensure of having high fault current clipping ratio. On top of all the aforementioned constraints in the design of HVDC PFCL, there are important challenges, namely, both the fault and the steady-state currents are too high and the ratio between them is four for the ±500 kV, 2 kA HVDC system [8, 21–23]. In addition, the DC current through the presaturation coil must be as low as possible to have low power losses.

2.1 | System geometry

Figure 1 shows the typical dimensions of the proposed PFCL suitable for ±500 kV HVDC system [8, 23]. The steady-state current value \(I_{ss}\) of such line is equal to 2 kA, while the prospective fault current peak value \(I_f\) without any FCL can reach to 8 kA. This PFCL consists of rectangular soft magnet comprising two simple DC coils wound on the outer legs in the same direction to provide opposing mmfs through the soft magnet, as shown in Figure 1. The line coil has number of turns \(N_L\) and is connected in series with the HVDC line under protection. This coil carries the line current, either under steady-state or fault conditions and should be designed to withstand high transient overvoltages. The other presaturation coil has number of turns \(N_P\) and is connected to a separate DC current source \(I_p\). Such current source enables the control of presaturation mmf by controlling \(I_p\). This coil is responsible to drive the soft magnet into presaturated state depending on the steady-state and fault currents.

Figure 2 shows the basic electrical circuit, which comprises the PFCL with a fault representative switch. PFCL, presaturated fault current limiter
The soft magnet nonlinear $B$-$H$ characteristic is selected as nongrain-oriented steel (NGO-35PN250), see Figure 10 later. However, this material requires a relatively small magnetic field intensity to reach the saturation magnetic flux density. The relative permeability of such material reaches up to $\sim 8272$ in its linear part of $B$-$H$ characteristics, which warrants adequate clipping of the fault current. Additionally, the low power losses exhibited by this material during the steady-state condition encourage its application in FCL devices [6, 7, 15–17].

The convergence stability of simulation and its accuracy are increased using non-uniform process of mesh refinement neighbouring the boundaries. However, the mesh of minimum size has higher gradients which can affect the simulation accuracy. Accordingly, this minimum size of mesh is devoted to a parametric study to reduce the error difference lower than $10^{-4}$ between two consecutive runs, without affecting the magnetic field distribution inside the soft magnet bulk. To increase the accuracy of simulation, the relative tolerance of solution convergence criteria is set to be 0.0001 with time step of 0.1 $\mu$s. This has an opposing consequence of longer simulation time and increased memory requirements. However, to ensure reaching the steady-state value of the current, the fault is started at $t = 200$ ms and cleared after 10 ms, which represents the operating time of different HVDC CBs [24, 25], with a total simulation time of 500 ms.

### Table 1

| Symbol | Quantity | Value |
|--------|----------|-------|
| $V_{dc}$ | DC source voltage | 500 kV |
| $R_{Line}$ | Line resistance | 62.5 $\Omega$ |
| $R_{Load}$ | Load resistance | 187.5 $\Omega$ |
| $N_L$ | Line coil number of turns | 150 |
| $N_P$ | Presaturation coil number of turns | 6000 |
| $l_{coil}$ | Coil length for both coils | 13 m |
| $A_c$ | Coil cross-sectional area | 36.52 $m^2$ |
| $\sigma_{c,coil}$ | Line coil’s wire cross-sectional area | 500 $mm^2$ |
| $\sigma_{c,coil}$ | Presaturation coil’s wire cross-sectional area | 200 $mm^2$ |

Abbreviations: HVDC, high voltage direct current; PFCL, presaturated fault current limiter.

#### 2.2 Principle of operation

Generally, a small inductance for the PFCL is required in the steady-state operation. On the contrary, when the magnetic field strength due to the line current is increased, PFCL inductance should be spontaneously increased to limit the fault current. The DC presaturation coil generates $mmf$ that can magnetise the soft magnet and drive it into sufficient saturation level with lower values of relative permeability. However, increasing the magnetisation $mmf$, $F_P = N_P I_P$, would result in a deeper saturation state of the soft magnet because of shifting the operating point to the right-hand side. Hence, this reduces the inductance of the presaturation coil. During the steady-state condition, the imposed counter ‘demagnetisation’ $mmf$, $F_L = N_L I_L$, due to the line current, is unable to completely demagnetise the soft magnet, as shown in Figures 3a,c, provided that $F_P \geq F_L$. Therefore, the PFCL experiences nonlimiting effect with extremely low value of the insertion inductance due to small value of relative permeability in the saturation level. During fault occurrence, the demagnetisation $mmf$, $N_L I_L$, caused by the fault current is comparable with the presaturated $mmf$. This fault demagnetisation $mmf$ forces the soft magnet into the linear region with remarkably high values of relative permeability leading to limit the fault current, as shown in Figures 3b,d. Faster transients and higher magnitudes of the fault current are inherent characteristics in HVDC system. Consequently, intermediate rising PFCL inductance is tremendously helpful in limiting HVDC system fault current [2].

After fault clearance, the soft magnet restores its initial state of presaturated saturation depending on the time constant $\tau = \sqrt{(L(\Delta)} / (R_{Line} + R_{Load})$ of the circuit, especially its time-varying inductance $L(\Delta)$. In such case, the HVDC PFCL may replace the required smoothing reactor during the normal operation of the system, as well as it can immediately and automatically react to the fault during its incidence. Obviously, the line coil nonlinear relative permeability ($\mu_{rL}$) depends on soft magnet $B$-$H$ characteristics and can be expressed as follows [16, 19]:

$$\mu_{rL} = \frac{\Delta B}{\Delta H}$$  \hspace{1cm} (1)

where $B$ is the magnetic flux density in (T) and $H$ is the magnetic field intensity in (A/m). Therefore, the nonlinear inductance of the line coil ($L_L$) can be given by [9]:

$$L_L(B, H) = \mu_0 \mu_{rL}(B, H) \frac{N_L^2 A_c}{l_{coil}}$$  \hspace{1cm} (2)

where $\mu_0$ is the permeability of free space. Furthermore, the induced voltage or voltage drop across the line coil ($\Delta V_{FCL}$) can be calculated as follows [15]:

$$\Delta V_{FCL} = R_L i_L(t) + \frac{d\lambda_L}{dt}$$  \hspace{1cm} (3)

where $R_L$ is the dc resistance of the line coil, $i_L$ is the line current, and $\lambda_L$ represents the total flux linkage of the line coil. Equation (3) can be rearranged to calculate the line coil flux linkage as follows:

$$\lambda_L(t) = \int (\Delta V_{FCL}(t) - R_L i_L(t)) \, dt$$  \hspace{1cm} (4)

Consequently, the current through the line coil can be expressed as follows [15]:

$$i_L(L, t) = \frac{\int (\Delta V_{FCL}(t) - R_L i_L(t)) \, dt}{L_L(\lambda_L(t))}$$  \hspace{1cm} (5)
where $L_L(i_L(t))$ represents the time varying inductance of the line coil. Similarly, the inductance of the line coil can be calculated as follows [15]:

$$L_L(t) = \int \left[ \frac{1}{i_L(t)} \left( \Delta V_{FCL}(t) - R_L i_L(t) - L_L(t) \frac{di_L(t)}{dt} \right) \right] dt$$  \hspace{1cm} (6)

Nevertheless, the inductance of the line coil in (Equation (6)) strongly depends on the number of turns of such coil and the instantaneous location of the operating point on the $B$-$H$ characteristics of the soft magnet in Equation (2). Therefore, the dynamic performance of the HVDC PFCL during the fault condition can be revealed through Equations (2), (3), and (6), where the inductance of the coil has a considerable value.

Similar relations can be realised to investigate voltage across the presaturation coil and its inductance $L_P(t)$.

The fault current clipping ratio ($k$) can be calculated as follows [5–17]:

$$k = \frac{\hat{I}_f - \hat{I}_L}{\hat{I}_f}$$  \hspace{1cm} (7)

where $\hat{I}_L$ represents the limited peak value of the DC fault current at the interruption instant of CB ($t = 210$ ms). However, the acceptable values by utilities for the fault current clipping ratio range between 45% and 55% or higher [19].

In HVDC networks, the rate of rise of fault current increases and it is difficult to control it. Consequently, the associated arc seems to be problematic to control, since the fault current has no natural zero-crossing value in the
HVDC system. HVDC CBs should be capable of interrupting and reducing the current to zero within certain time. Before interrupting of the fault current, its instantaneous slope ($S_i = \frac{di}{dt}$) is a function of the growth rate and frequency of oscillation that may vary over a wide range [24]. Hence, special concerns should be considered for limiting the high value and sharpness of such fault current [21–23]. In practical HVDC network, the installed CBs in the station DC side have often operating times of 10 ms or lower. The major problem associated with such CBs is the inability to interrupt tremendously large fault current with high current rate of rise. Once the fault current is limited to an acceptable value by the PFCL, the CB can effectively act and interrupt it at early stages. Thus, the good coordination between PFCL and CBs improves the performance and reliability of the network.

Consequently, the current slope is a vital parameter in determining the suitable type of HVDC CB in interrupting such high value of DC fault current, depending on the HVDC technology. Typically, mechanical CBs are suitable for fault current slope of 1.6–2 kA/ms with voltage rating lower than 400 kV and interruption capability between 2 and 16 kA. Solid-state and hybrid CBs are suitable for 47 and 2.9–6.7 kA/ms with voltage ratings of 132 and 500 kV with interruption capabilities of 19 and 26 kA, respectively [21, 22]. More details about the interruption limits of various HVDC CBs technology and the process of current interruption can be found in [24, 25]. It is worth mentioning that hybrid HVDC CBs combine the advantages of mechanical HVDC CBs which have low-on state losses, and solid-state HVDC CBs which have fast and accurate trip [26].

Since the PFCL performance can be represented by a multi-parameter function, the relative effects of the controlling parameters are studied to explore their effects on the dynamic performance of the PFCL. Generally, the dynamic performance of the HVDC PFCL can be interpreted through the fault current clipping ratio ($k$ in percentage) and its slope ($S_i$ in kA/ms). Additionally, the voltage drop across the line coil (3) and the power losses ($\Delta V_{\text{FCL}}$ and $P_{\text{Loss}}$, respectively), are in percentage of 500 kV source voltage kV and 1000 MW source power, during the steady-state condition. They are vital parameters that control the feasibility of using PFCL in HVDC networks.

3 | EFFECT OF DESIGN PARAMETERS ON THE DYNAMIC PERFORMANCE OF HVDC PFCL

3.1 | Peak value of prospective fault current

The peak value of prospective fault current is a controlling parameter which determines the demagnetisation effect related to the line coil. However, it can be changed through $R_{\text{Line}}$, but constant total resistance ($R_{\text{Line}} + R_{\text{Load}}$) ensures constant value of steady-state line current and without any change in the other parameters of Table 1. The reference case (the best combination) is defined by the following parameters $I_f = 8$ kA, $I_s = 2$ kA, $N_L = 150$ turns, $I_p = 50$ A, and $N_P = 6000$ turns. Figure 4 shows waveforms of the limited line current with different imposed fault currents up to 30 kA, but with constant value of the steady-state line current ($I_s = 2$ kA). It can be observed that all the currents have reached to the steady-state value of 2 kA before fault occurrence and after fault clearing. Increasing the peak value of fault current would result in increasing the demagnetisation mmf of the line coil, and hence dragging the operating point towards higher values of relative permeability on the $B-H$ curve. This increases the inserted fault inductance and hence increases the clipping ratio of fault current. After fault clearance at $t = 210$ ms, the currents decay to their pre-fault value of 2 kA in different times depending on the exact time-varying inductance given in (Equation (6)).
In a practical HVDC system, for example, modular multilevel converters (MMC) HVDC system, fault current can rush to more than 20 times of rated value within 5 ms if no protection strategy is applied [27, 28]. The proposed PFCL demonstrates its ability to handle such high fault current levels. Moreover, HVDC CBs can cut the fault current up to 26 kA level, and in this case the proposed PFCL might be not that necessary. However, that kind of HVDC CB is awfully expensive and not so reliable. Therefore, if the proposed PFCL can cope properly with such HVDC CBs, the total cost and reliability of this combination can be significantly enhanced.

Figure 5 shows the dynamic performance of the HVDC PFCL when changing the peak value of the fault current at $I_a = 2$ kA, $N_L = 150$ turns, $I_p = \Lambda$, and $N_P = 6000$ turns. This configuration offers an adequate value of $k \approx 51.2\%$ for the parameters summarised in Table 1 and for 8 kA of fault current (reference case). It shows an increase in the clipping ratio (up to $\sim 75\%$ for $I_f = 20$ kA) with increasing the fault current peak value due to the increase of demagnetisation $mmf$. Similar trend has been observed for the current slope ($S_j$), as shown from Figure 5, due to the increasing inductance of PFCL with increasing the fault current as in Equation (6). This can be attributed to the increase of the time constant ($L_C/R_{\text{Line}}$), which increases the rate of rise of fault current. In terms of CBs type, $S_j$ shows that solid-state and hybrid CBs are suitable for interrupting such levels and slopes of fault current [24, 25].

Figure 5 shows constant behaviour of the voltage drop $\Delta V_{\text{FCL}}$ across the PFCL terminals with increasing the fault current, during the steady-state condition. However, this value of $\Delta V_{\text{FCL}}$ is calculated just before the fault occurrence and it is recommended to be kept as low as possible, for example $<0.05\%$. Irrespective of different value for $I_f$, constant value of $\Delta V_{\text{FCL}} \approx 0.044\%$ can be attributed to the constant total resistance ($R_{\text{Line}} + R_{\text{Load}}$) and $I_s$ during the steady-state condition. Additionally, the power losses are of constant value $\sim 0.047\%$ due to the same steady-state current during pre- and post-fault durations.

In HVDC PFCL, a special attention should be given towards the induced voltage across the DC coils due to the high flux variations inside the soft magnet. Figures 6a,b show waveforms of the induced transient overvoltage across both the line and the presaturation coils for different values of $I_f$. Figure 6c shows the peak value of the induced voltage, with changing the fault current peak value. Increasing the peak value of the fault current would in turn increase the induced transient overvoltage across the two coils, as shown from Figures 6a,b, due to the increase of the line coil inductance and high current slope during the fault duration as shown in Figure 5 [15]. However, the induced transient overvoltage across the presaturation coil reaches an extremely high value, in megavolts, as compared to that of the line coil. This can be attributed to the transformer action ($N_P/N_L$), since the number of turns $N_P$ is much greater than $N_L$, as given in Table 1. These high values of induced transient overvoltage can be considered as the main drawback of such DC-biased PFCL [5–9], due to the necessity of increasing the insulation of each coil to support such high voltage levels. Consequently, metal oxide surge arresters [29, 30] can be used to dissipate the associated energy with such transient overvoltages and hence limiting their magnitudes to acceptable and safe values.

### 3.2 Steady-state current value

The steady-state current value can be changed through changing only the load resistance, while the line resistance is kept constant to ensure constant peak value of fault current. To avoid the loss-of-life expectancy of reactors and oil-cooled transformers, the overload practical value should not exceed
120% for one hour. On the contrary, this can significantly affect the thyristor valve design [31]. However, the redundancy of cooling can be extended from one hour to continuous overload depending on the particularity of design. Alternatively, a minimum DC current level should be included in the HVDC specification. A 10% of rated current can be considered as a common value, while other systems have stipulated 5% of such value [31]. Obviously, the cost the DC side filtering equipment can be significantly affected by the minimum current selection criterion. Consequently, it should be as high as
the planned system operations will permit. Therefore, the variation of the steady-state current is taken as 90%–120%, that is, 1.8–2.4 kA.

Figure 7 shows the effect of changing the steady-state current on the dynamic performance of the HVDC PFCL. It can be seen that increasing $I_a$ will in turn decrease the clipping ratio of the limited fault current. This can be referred to the slight decrease in the line coil fault inductance as in Equation (6). This slight decrease will be reflected in the rate of rise of the fault current, as shown in Figure 7.

During steady-state condition, $\Delta V_{FCL}$ linearly increases with the increase of $I_a$ because of constant line coil resistance. This can be referred to the comparable effect of resistive voltage drop compared with the inductive term in Equation (3), which is vanished at the steady-state value of the inductance. Moreover, the power losses show the traditional behaviour of increasing with the square value of the current, as shown in Figure 7.

3.3 Number of turns of line coil

The number of turns of the line coil is a crucial parameter, which controls the demagnetisation $mmf$. Figure 8 shows the effect of increasing $N_L$ on the limited fault current value. When the demagnetisation $mmf$ ($F_L = N_L I_a$) is much lower than magnetisation $mmf$ ($F_P = N_P I_p$), the soft magnet stays in the saturation state as long as the resultant $mmf$ ($F_P - F_L$) remains high enough. This will result in lower limited fault current and consequently lower clipping ratio, as shown from Figure 8, for example, the case of $N_L = 50$ turns. A further increase of such demagnetisation $mmf$ has the same effect of reducing the
limited fault current due to its effect in driving the soft magnet in deeper saturation state. Therefore, good damping performance of this PFCL can be achieved when $F_p \geq F_L$, that is, when $N_L \leq 150$ turns, and vice versa. In other words, for high values of $N_L$, the fault current can drive the soft magnet into deeper saturation state with lower fault inductance value. When the magnetisation and demagnetisation mmfs are comparable, the PFCL shows adequate limiting behaviour of fault current (i.e., $k \geq 45\%$), as shown in Figures 8 and 9 for $135 \leq N_L \leq 155$. Additionally, increasing $N_L$ will reduce the rate of rise of fault current due to the increase of line coil inductance, as shown from Figure 9. In such case and irrespective of increasing $N_L$, the line coil inductance is strongly dependent on the relative permeability value due to the location of the operating point on the $B$-$H$ curve as in Equation (2). Consequently, the relative ratio ($F_p/F_L = N_p I_p/N_L I_o$) is an important parameter which controls the capability of PFCL in limiting the fault current with adequate characteristics as shown in Figure 9.

During the steady-state condition, both $\Delta V_{FCL}$ and $P_{Loss}$ linearly increase with the increase of $N_L$ due to the increase of line coil resistance with constant value of $I_o$.

Figure 10 shows the location of the operating points at certain instants of pre-fault, during and post-fault on the $\mu_r$-$H$ and $B$-$H$ curves of the soft magnet. It can be noticed from Figure 10 that the values of $N_L$ (100 and 150) are adequate to operate the soft magnet in the linear zone of the $B$-$H$ curve, which corresponds to higher relative permeability, that is, the PFCL shows limiting capability of fault current. In this case, $F_p \geq F_L$, which is responsible to operate the PFCL in the region of its $B$-$H$ curve where the line coil inductance has considerable value. Increasing $N_L$ will locate the operating points into deeper saturation level with extremely low permeability and hence reducing the limiting capability of the PFCL, as shown in Figure 10 for $N_L = 200$ and 300. Consequently, the line coil number of turns can be considered as a key parameter which controls the relative demagnetisation mmf of the soft magnet and its operating region for adequate fault current limiting effect, as shown in Figures 8 and 9.

### 3.4 Presaturation coil current

Unlike FCLs in AC systems that require to minimise the additional inserted inductance under steady-state conditions, DC systems involve smoothing reactors to prevent fault current rising occasions, reduce the rate of rise of fault current, and reduce current harmonics, that is improving the power quality [5, 8, 32, 33]. Therefore, the proper designed PFCL can replace such smoothing reactor in the DC side for assisting the system normal operating condition as well. Furthermore, the magnetisation level can be helpful in controlling the fault inductance value. For these reasons, the PFCL is designed to avoid the deep saturation state so that it provides adequate inductance values during the normal and fault events.

Figure 11 shows the effect on changing the presaturation coil current $I_p$ on the dynamic behaviour of the PFCL. However, all the design and electrical parameters summarised in Table 1 are kept constant, except for $I_p$. When increasing $I_p$, the line coil inductance will be reduced due to the increase of saturation state level, that is, moving towards lower relative permeability region. Consequently, this leads to the reduction of the fault current clipping ratio, as shown in Figure 11. The fault current rate of rise seems to be constant due to the predominant effect of constant $N_L$. The inductance value is changed only due to the change of $\mu_r$ based on the location of the operating point on the $B$-$H$ curve.

During the normal operation, the voltage drop remains unchanged due to the constant line coil resistance and $I_o$. Consequently, this increase of $I_p$ shows slight square increase in the total power losses during the steady-state condition, as shown in Figure 11.
3.5 Number of turns of presaturation coil

Due to the high values of the steady-state and the fault currents, the number of turns \( N_P \) of the presaturation coil strongly determines the level of saturation of the soft magnet. Improper choosing of \( N_P \) can lead to maloperation of the PFCL. From the operation and the economical point of views, it is preferred to minimise the DC current supplying this presaturation coil over the long term of operation [8, 9]. Accordingly, the saturation level of the soft magnet can be controlled through \( N_P \) as shown from Figure 12. Increasing \( N_P \) by taking into consideration that \( F_P \geq F_L \) can effectively limit the fault current and hence increase the clipping ratio, as shown from Figure 12. Any further increase of \( N_P \) to about 6500 turns would in turn increase the saturation level and reduce the clipping ratio. The principal concern with such high number of turns is the high induced transient overvoltage across its terminals due to the transformer action as mentioned earlier. Lower number of turns \( N_P \) can cause incomparable magnetisation \( mmf \) with the demagnetisation one, and hence the PFCL can fail to effectively operate (maloperation). Similar trend with roughly constant value is observed for the fault current slope as in the case of increasing \( I_p \).

Increasing \( N_P \) has no effect on the voltage drop due to constant line resistance as \( I_m \), as shown from Figure 12. However, any increase of \( N_P \) will linearly increase the total power losses due to the increase in resistance of the presaturation coil.

Therefore, the lower values of voltage drop and power losses during the steady-state operation and the adequate value of the fault current clipping ratio encourage the application of such HVDC PFCL for self-triggering behaviour of limiting fault current.
4 | SUPPRESSION OF COILS' TRANSIENT OVERVOLTAGES USING ZnO SURGE ARRESTERS

Since the PFCL is a series-installed device in the power system, it is essential to suppress the induced transient overvoltage across its coils to avoid hazardous conditions. Installing parallel metal oxide/zinc oxide (ZnO) surge arresters (SAs) to the PFCL line and presaturation coils can successfully be used to suppress such high induced transient overvoltages during the fault duration [34]. The SA reference voltage plays an important role in controlling its performance under surge condition [29, 34]. However, overvoltage clipping occurs when the voltage across the SA exceeds \( V_{\text{ref}} \) due to abrupt change of its resistance to small values.

MATLAB/Simulink is used to model and simulate the whole system and to get the time-varying inductance for both coils based on the detailed procedure mentioned in [15].

Sample waveforms of the circuit, the line coil and the SA currents are given in Figure 13a, for the case of \( V_{\text{ref}} = 200 \) kV. It can be seen that the peak values do not occur at the same instant, however the instantaneous sum of the line coil and the SA currents gives the circuit current according to Kirchhoff’s current law. For the same presaturation coil current and number of turns, the line coil impedance can be considered constant. Since the line coil is shunted by SA, hence the parallel equivalent impedance increases with the increase in the SA impedance (resistance at the high discharge condition). In addition, the SA resistance increases with the increase in the reference voltage for the same reference current. Therefore, increasing SA reference voltage leads to the decrease in both the SA and the circuit current as well as a slight increase in the coil current sharing. Consequently, the shunt SA reference voltage must be optimised to achieve a value of the fault current clipping ratio close to that without SA, and at the same time good suppression of the transient overvoltages at both coil terminals. Figures 13b,c show the effect of SA on fault current and overvoltage clipping when it is connected in parallel with the PFCL line coil. Three values of reference voltage \( (V_{\text{ref}} = 50, 100, \) and \( 200 \) kV) have been considered, while the reference current is kept constant at 500 A. A comparison between the peak values of the voltage and the current with and without SA is shown in Figure 13d. It can be seen that \( k \) becomes 41.25% for SA with \( V_{\text{ref}} = 200 \) kV, which can be considered acceptable for such FCLs. As it can be seen from Figure 13b,c that the SA helps the PFCL to clip the current more, which means higher the reference voltage, the better is the clipping of the fault current. On the contrary, the SA current increases as shown in Figure 13d because SA performance is inherently related to the energy associated to the transient phenomenon.

Recalling Figure 6a,b to calculate the ratio of the voltage peak of the presaturation coil to that of the line coil at the instant of fault clearing (210 ms), it is found that this ratio varies from 35.9 at \( I_f = 4 \) kA down to 31.8 at \( I_f = 30 \) kA. In fact, the corresponding turns ratio for an ideal transformer is 6000/150 = 40 and due to the high frequency effect, it is reduced to (31.8–35.9). Therefore, the transformer action must be considered when installing SA across the line coil terminals, that is, the voltage across the presaturation coil must be scaled down. This procedure helps a lot in suppressing the latter voltage by installing another SA across the presaturation coil terminals as it is illustrated in Figure 14 at different reference voltages \( (V_{\text{ref}} = 200, 400, \) and \( 600 \) kV) and for the case of conserving the SA (with \( V_{\text{ref}} = 50 \) kV) connected in parallel to the line coil with considering the average turns ratio of 33. Lowering this SA reference voltage leads to a wider suppressed voltage although the SA current slightly increases due to the coil high inductance. However, this increase in SA current is not enough to dissipate the same amount of energy. It is worth mentioning that the used MATLAB/Simulink model is highly nonlinear because of the existence of the iron core and hence the inductance of both coils is time-varying, and the use of ZnO SA.
**FIGURE 13** Effect of SA on the fault current clipping and overvoltage suppression across the line coil. $I_a = 2 \text{kA}$, $I_f = 8 \text{kA}$, $N_L = 150$ turns, $I_p = 50 \text{A}$, and $N_P = 6000$ turns. SA, surge arrester

**FIGURE 14** Effect of SA reference voltage on the overvoltage suppression across the presaturation coil. $I_a = 2 \text{kA}$, $I_f = 8 \text{kA}$, $N_L = 150$ turns, $I_p = 50 \text{A}$, and $N_P = 6000$ turns. SA, surge arrester
5 | HVDC PFCL DESIGN FLOWCHART

To achieve the desired design objectives, the following steps must be considered in the design phase:

- Choose the bias point of saturation to optimise relation of insertion inductance to desaturation level at fault state.
- The length of the two DC core limbs affects the level of saturation and the dimensions of the device. In addition, it directly affect the inductance dependency on the current.
- Core cross-sectional area of the line coil side to provide improvement in flux density. Reducing the core cross-section causes the core to saturate at a lower flux bias as well as decreasing insertion and fault inductances. On the other hand, reduced core-section places the device in danger of reverse saturation during a fault, which degrades its limiting performances. The reverse saturation phenomenon is a potentially hazardous condition. In the proposed PFCL this might arise during the high fault condition, where the DC winding is subjected to excessive volt-sec. Consequently, the core operating point may shift into the reverse saturation region. Therefore, the PFCL inductance sharply decreases and the current limiting function is lost as by leading to the equivalent inductance of an air-core inductor.

The dynamic performance of the HVDC PFCL is significantly controlled through the inserted inductance during both the steady-state and the fault conditions. Typically, industrial specifications stipulate 45%, or more, for the clipping ratio of the fault current, without exceeding the permissible tolerances for the voltage drop and power losses during the normal operation [19]. Consequently, the multi-parameter design process of HVDC PFCL comprises the soft magnet topology, the nonlinear characteristics of such soft magnet and the coils design. Extensive FE simulation outcomes, with the relevant published results [6–8, 15, 23], are used to summarise the design process of such HVDC PFCL based on the most effective governing parameters that affect its dynamic performance, as shown in Figure 15. Starting from the maximum steady-state and short-circuit analyses to determine the maximum values of \( I_{\text{av}}, I_f \) and \( S_F \). These values determine whether PFCL installation is needed or not, and the type of interrupting CB. However, the soft magnet material and its nonlinear \( B-H \) characteristics should be selected in a way such that covering the PFCL working range with very high \( \mu_r \) in the linear zone. The core and the coil dimensions are determined based on the operating voltage and current levels and the coils are wound such that \( F_p \geq F_l \), as shown in Figure 15, to avoid either low or deep saturation of the soft magnet.

The line coil \( N_L \) significantly affects the dynamic performance of the PFCL and can be adjusted to control \( S_f \) and \( k \) during fault condition. In addition, \( N_L \) controls both the voltage drop and power losses, during the steady-state condition. Moreover, the power losses, during the steady-state condition, can be controlled through \( N_L, N_p \) and \( I_p \) as shown from Figure 15. The limitation of both the voltage drop and power losses during the steady-state condition is taken as 0.05% for each.

**FIGURE 15** HVDC PFCL design flowchart considering the most effective governing parameters on its performance. DC, direct current; HVDC, high voltage direct current; PFCL, presaturated fault current limiter

The high induced voltages across the two coils can be considered as the main drawback of such HVDC PFCL. Metal oxide surge arresters can be used as a distinctive solution for limiting these high transient overvoltages or the introduction
of PM in series with the soft magnet to replace the presaturation coil.

6 CONCLUSION

This article presents a self-triggered HVDC PFCL rated 500 kV and 2 kA using magnetic-field and electric-circuit coupled model by FE simulation of COMSOL Multiphysics. Extensive FE simulations have been carried out to study the effect of controlling parameters on the dynamic performance of the PFCL. The number of turns of the line coil is a crucial parameter that significantly affects the insertion inductance and controls the transient rising behaviour of the fault current. The fault current clipping ratio can be increased up to 50% or even greater by adjusting the magnetisation and demagnetisation mmsf ratio and based on the level of both the steady-state and the fault currents as well. In addition, the number of turns and the energisation current of the presaturation coil have some influences on the investigated parameters. The rate of rise of the fault current identifies the type of HVDC CB to be used. Therefore, hybrid CBs are appropriate for interrupting such high levels of fault current in ±500 kV HVDC networks. The major drawback of such PFCL is the high level of the induced transient overvoltages across the presaturation and the line coils during fault duration. The use of metal oxide surge arresters has proved an efficient means to suppress these transient overvoltages across the PFCL line and presaturation coils during the fault duration. Taking the transformer action for the voltage across the presaturation coil facilitates the function of the other SA installed across its terminals. It is worth mentioning that the installation of the SA across the line coil terminals is crucial as it suppresses the transient overvoltages that appear at terminals of both coils. In addition, with a careful selection of SA reference voltage, the fault current clipping ratio can approximately be achieved like that without the SA.

The proposed PFCL represents an excellent means to be used in the case of MMC HVDC systems. In such kind of HVDC systems, CBs are capable to cut fault currents up to 26 kA, but they are awfully expensive, and their reliability is not so good. Consequently, the use of the proposed PFCL is a cost-effective means and it significantly enhances the system reliability.

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