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Design and Analysis of Fault Current Limiter Based on Air Core Variable Series Reactor

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ABSTRACT With the ongoing growth of the interconnected electric power systems and the increase of the short circuit current level in the power network, electric power equipment that are capable of limiting the fault current are gaining interest. Hence, this article proposes a novel fault current limiter based on air core variable series reactor (FCL-ACVSR). The proposed design limits the fault current within a short time frame (e.g., less than half a cycle), while featuring structural simplicity. It consists of two movable, coaxial, concentric air core reactors to increase the inductance of the device during the fault. At normal operating condition, the voltage drop and the reactive power consumption is minimal and therefore, the device does not impose any operational burden on the network. The structure of the proposed FCL is introduced, the operating principle is analytically explained, and finite element (FE)-based electromagnetic performance analysis is presented. Finally, FE-based simulation results are supported with detailed theoretical discussion.

INDEX TERMS Air core, fault current limiter, short circuit current, variable series reactor.

NOMENCLATURE

V	Network Voltage.
λ	Flux Linkage.
L_{Line}	Line Inductance.
L_{FCL}	FCL Inductance.
R_{Line}	Line Resistance.
R_{FCL}	FCL Resistance.
x	Position of Moving Reactors.
v	Speed of Moving Reactors.
e	Induced Voltage.
V_m	Peak Amplitude of the Network Phase Voltage.
α	Network Voltage Phase Angle.
θ	Network Impedance Phase Angle.
ω	Network Frequency.
Z	Thevenin Impedance of the Network.
F	Electromagnetic Force between Two Reactors.
$F_{gravity}$	Gravity Force.
F_{spring}	Spring Force.
m	Mass of the moving Reactor.
a	Acceleration of the Moving Reactor.
k	Constant of the Spring.
g	Acceleration of the Gravity.
v_0	Initial Speed.
x_0	Initial Position of the Moving Reactor.
L_{11}	Self Inductance of Outer Coil.
L_{22}	Self Inductance of Inner Coil.
L_{12}	Mutual Inductance between Coils.

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I. INTRODUCTION

With the expansion of the electric power systems and the subsequent rise of short circuit current level fault currents may reach or even in some areas exceed the nominal values of the power equipment. This may cause irreversible damage on the power equipment and necessitate their replacement [1]. Therefore, alternative methods/equipment that can effectively combat the increase of short circuit current in the power network has become an attractive choice for utility companies. Current limiter reactors (CLRs) [2]–[5], and fault current limiters (FCLs) [6]–[14] are the two most prominent equipment frequently used for this cause. These devices are connected in series with the line to curb the fault current. CLRs exhibit a fixed reactance in both normal and faulty operating conditions. Therefore, despite their simple structure they impose a significant voltage drop on the network during normal operating condition.

Conversely, FCLs are variable impedance devices (with low impedance at normal and high impedance at faulty operating conditions) and therefore, are more desirable choice for limiting the fault current. According to their design structure, FCLs can be further classified into different subgroups such as power electronic based FCLs [15]–[20], inductive core saturation FCLs [21]–[24], IS limiters, PTC (Positive Temperature Coefficient) [25], superconducting FCLs [26]–[28], non-superconducting FCLs [29], [30] and series resonant limiter. There are certain limitations pertaining to each subgroup. For example, superconductor resistance devices must be kept in environments with certain temperature. Regarding the IS limiter, the connector and fuse components must be replaced after each fault, which is not desirable. Power electronic based FCLs are costly and their design and control are complex.

Literature includes some innovative design structures in the field of FCLs. References [31], [32] introduce a high-temperature superconducting FCL with ferromagnetic core, which operates based on the magnetic saturation concept. However, the structure includes a large dc power supply with a large turn number of winding to saturate the core. Hence, it requires further design considerations regarding safety and material insulation. In addition, using the superconducting conductors for dc coils is costly and requires frequent maintenance. Moreover, the performance of the device entirely relies on the coil and dc supply. If the dc structure fails, the FCL loses its functionality, which undermines the reliability of the devise. It is also noted that the dc current may cause noise in the network. In [33], [34] a three phase common core, triangular winding FCL with a new core structure and improved magnetic coupling between the phase windings is proposed. In [35], a multi-function saturated-core FCL is presented. It includes an E-I core, a magnetic valve and dc/ac coils. In normal conditions, dc coils provide necessary *magneto motive force (MMF)* to saturate columns of coils and keep the impedance low. When the fault occurs, columns of core gets unsaturated in each half-cycle and the impedance increases rapidly. Reference [36] presents a compact structure for FCL with permanent magnets to decrease the amount of dc power supply. In [37] a simple series variable reactor is proposed with a stationary core, and a movable core. In normal conditions, the length of air gap is large and thus, the inductance of the device is low. When the fault occurs, a high amount of current passes through the coil and attracts the moving part to the stationary part. As a result, the air gap reduces and inductance rises rapidly to curb the fault current. The drawback of this scheme is that the reactor core becomes rapidly saturated under the large amount of fault current and therefore, a huge volume of magnetic core is needed to prevent the saturation. In [38], a six-leg three-phase saturated-core fault current limiter (T-SCFCL) is presented to reduce the volume of the ferromagnetic material. The T-SCFCL consists of an iron core with six limbs, two permanent magnets, six AC coils and six DC coils. Each limb wound by two concentric coil that the inner coil is a DC coil and outer coil is an AC coil. However, the use of high-energy permanent magnets could be costly. In addition, a special insulation must be placed between AC and DC coils. In [39] a three phase structure of a saturable-core FCL is proposed with all three phase coils being wrapped around one common core. However, the FCL performance is strongly dependent on the DC circuit and also the impedance of the three phase windings are not the same.

As noted, existing structures are fairly complex and often require multiple components with a relatively high manufacturing cost. Hence, an innovative solution that can blend the structural simplicity of the CLRs and operational excellence of FCLs into one product is desired.

This paper presents an innovative design for developing the next generation FCLs based on air-core variable series reactor. The proposed structure is simple and does not require a magnetic core, which avoids dealing with the saturation problem. Furthermore, it does not contain a dc excitation source. Thus, it improves the operational reliability of the device. Section II presents the structure and the operating principle of the proposed device, followed up by detailed analysis and discussion in section III.

II. FAULT CURRENT LIMITER BASED ON VARIABLE SERIES REACTOR (FCL-ACVSR)

The structure of the proposed FCL is shown in Fig. 1. It consists of two coaxial and concentric air core reactors at close proximity (i.e., outer reactor, and inner reactor) with axial mobility. The two reactors are connected in series but with opposite current directions. Each reactor has two terminals; one terminal is the input/output terminal of the reactor and the second terminal is connected to the other reactor. Thus, the whole set has two terminals. The four terminals shown in Fig. 1 are only the connections points between the coils and the springs. The portable feature allows the mutual positional displacement between the two reactors. From the network's perspective, this transpires into a device with variable inductance.

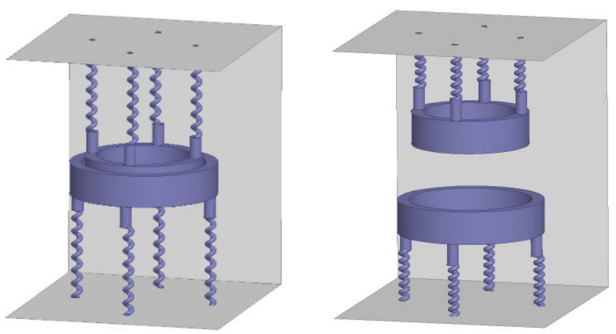
In normal operating condition, the two reactors are aligned (maximum overlapping space), and therefore the mutual inductance between the two reactors is maximum. The total inductance of the device is equal to the sum of the reactors' self-inductance and their mutual inductance as given by relation (1). Considering the opposite excitation currents of the inner and outer reactors, the mutual inductance has a negative/opposite sign with respect to the self-inductance, and thus, the total inductance and the impedance of the device is minimum at the normal operating condition. Therefore, from the network perspective, the device exhibits a low inductance. Since the device is connected in series with the network, the voltage drop and the reactive power consumption is minimal at this operating state. Conversely, with the rise of reactors' current during the fault, the two reactors behave like two magnets with opposite polarity. This exerts a significant repulsive electromagnetic force between the two reactors, which results in transition from aligned to unaligned position.

At this stage of operation, the mutual negative inductance is minimum and thus, the device exhibits a high inductance to limit the fault current. Although, the fault current can potentially exert strong forces between the coils, these forces are not localized (but rather distributed along all layers of the coil), and both coils can move freely. Therefore, it does not cause an unbearable mechanical tension on the coils. Nevertheless, the mechanical structure should be properly designed to withstand such potential forces. In particular, the housing should properly seal the coils to form a rigid structure. The mechanical structure should also include mechanical or electrical damper to stop the moving reactors after they reach to desired position. On the other hand, the spring specification should be properly calculated to ensure that the spring force can return the moving reactors to the initial position.

$$L_{FCL} = L_{11} + L_{22} - 2L_{12} \tag{1}$$

where, L_{11} is the self-inductance of the inner coil, L_{22} is the self-inductance of the outer coil, and L_{12} is the mutual inductance.

It is noted that the mutual displacement between the reactors is reversible. Once the fault is cleared, the spring force returns the moving reactors to their initial/aligned position. For a proper operation, the two reactors must be concentric (to avoid unbalanced magnetic forces), and slightly displaced at the initial position (to generate enough repulsive force). If the two reactors are fully aligned, the forces may cancel out and the device may not react. It is noted that the passage of the nominal current through the device at normal conditions slightly produces a repulsive force on the moving reactors but the force is negligible and is countered by the spring force. Although, the speed of the spring is not as fast as electrical signals, it does not pose any mechanical misoperation. Only after the fault is cleared that the spring force becomes larger than the electromagnetic force. Therefore, only the transition from the faulty to the normal condition is controlled by the spring. In other words, the spring speed and spring force are only relevant after the fault is cleared. It is worth noting that other fault related equipment in the power networks such as breakers, disconnectors, reclosers, and etc also operate mechanically by (e.g., charged spring or air pressure mechanism). Considering the fact that circuit breakers typically operate between 3 to 5 fault cycles, the proposed FCL can operate within a same time frame or even faster with respect to the operating time of other protective equipment.



(a) (b)

FIGURE 1. The per-phase structure of the proposed FCL at, a) normal condition b) short circuit fault condition.

TABLE 1. Structural and operational features of the proposed FCL.

Structural advantages	
	Does not require ferromagnetic core
	Does not require DC coil
	Does not require power supply
	Does not require sensor
	Does not require replacing component after short circuit
Operational advantages	
	Fast operation when fault occurs
	Fast recovery after fault is cleared
	Does not cause harmonic and noise in the network
	Utilizes the whole equipment to limit the fault current

TABLE 2. Information of the distribution network.

Parameter	Value	Unit
Phase-to-Phase Voltage	20	kV
Frequency	50	Hz
Line Inductance	2.5	mH
Line Resistance	0.03	Ω
Max Load Power	12.5	MVA
Resistance of FCL	0.006	Ω
Phase Nominal Current (rms value)	360	A
Rate of Limited fault current	25	%

The structural and operational advantages of the proposed FCL against the state of the art topologies are summarized in Table 1.

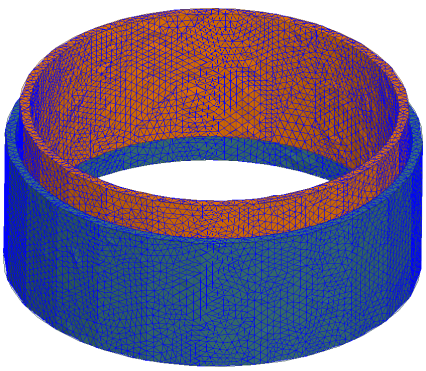


FIGURE 2. The structure of the proposed FCL at normal condition simulated by FE.

III. ELECTROMAGNETIC PERFORMANCE ANALYSIS AND SIMULATION

To investigate the functionality of the proposed FCL, it is applied on a generic distribution network. Detailed specification of the power network is presented in Table 2. Fig. 2 presents the 3-D schematic of the device. This section only includes the electromagnetic design of FCL-ACVSR. The mechanical considerations such as mechanical structure,

TABLE 3. Specification of FCL-ACVSR.

Inner Reactor	Value	Unit	Outer Reactor	Value	Unit
Outer Diameter	1120	mm	Outer Diameter	1200	mm
Inner Diameter	1060	mm	Inner Diameter	1140	mm
Height	400	mm	Height	400	mm
Turn Number	24		Turn Number	24	
Current Density	4	A/mm^2	Current Density	4	A/mm^2
Mass	170	kg	Mass	180	kg

forces acting on the coils, and tensions will be the subject of a different article.

The initial distance between the two reactors is set to 100 mm to provide sufficient repulsive force at faulty condition. The geometrical parameters (i.e., size/dimensions, turn numbers) of the device are presented in Table 3. These parameters are chosen based on the design data of existing FCLs with fixed inductance in the power network.

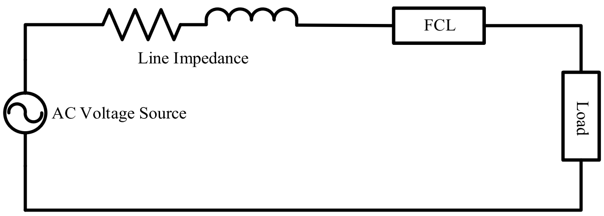


FIGURE 3. One line diagram of the distribution network.

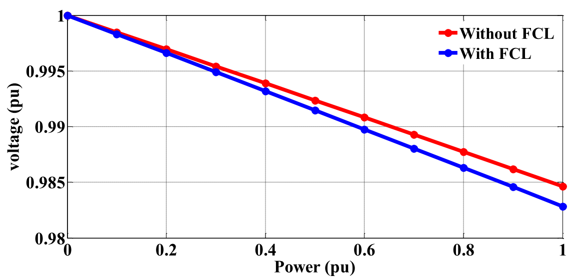


FIGURE 4. FCL current waveform.

The coils must be placed inside a structure to move freely along the axial direction. The weight considered for each set of coils is equal to total weight of copper coil and retaining structure.

The performance of proposed FCL is evaluated in three subsections that is discussed as the following.

A. VOLTAGE DROP AND POWER LOSS

In normal condition, the network includes line impedance, FCL impedance and load resistance. The reactors are aligned with maximum negative mutual inductance, and consequently minimum resultant inductance. Therefore, when FCL is connected to the network (Fig. 3), the voltage profile of the network remains approximately intact as confirmed by the simulation results of Fig. 4. In this simulation, the maximum load power is 10 MW with power factor of 0.8 lag and to obtain the voltage profile, the load power varies from 0 to maximum value. As seen in Fig. 4, the addition of the proposed FCL to the network has not any tangible effect on the network's voltage profile.

Since the proposed design does not require DC power circuit, iron core and permanent magnet the power loss is only related to the resistance of the coils as expressed by:

$$P_{loss} = 3 \times R_{FCL} \times i^2 \tag{2}$$

The impedance value of proposed FCL is very low at the normal condition, and thus, the related power loss is not significant. Based on the resistance value and the nominal current listed in Table 2, three phase power loss is calculated as 2.3kW, which is negligible within the scale of the power in the power network.

B. SHORT CIRCUIT FAULT CONDITION

The response of the FCL at faulty condition can be modeled by the following analytical representation.

$$V = Ri + \frac{d\lambda(x,i)}{dt} \tag{3}$$

$$\lambda = L(x).i \tag{4}$$

$$\begin{aligned} V &= Ri + \frac{d(L(x).i)}{dt} = Ri + L(x)\frac{di}{dt} + \frac{dx}{dt}\frac{dL(x)}{dx}.i \\ &= Ri + L(x)\frac{di}{dt} + \nu\frac{dL(x)}{dx}.i \end{aligned} \tag{5}$$

$$R = R_{Line} + R_{FCL} \tag{6}$$

$$L(x) = L_{Line} + L_{FCL}(x) \tag{7}$$

$$e(x,i) = \nu\frac{dL(x)}{dx}.i \tag{8}$$

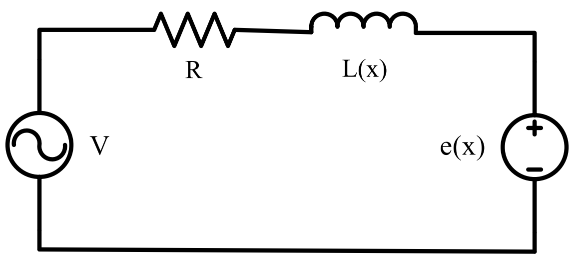


FIGURE 5. Equivalent circuit of the distribution system during fault.

The equivalent circuit of the distribution network is obtained from (5) and shown in Fig. 5. The equivalent circuit implies that the fault current is limited not only due to the rise of the inductance $L(x)$ but the moving induced voltage $e(x, i)$ induced by the axial motion of the reactors. The moving induced voltage is proportional to speed as expressed in (8).

When a fault occurs, a surge of a short circuit current passes through the FCL that includes both the ac and dc components as follows:

$$\begin{aligned} |V_m|\sin(\omega t + \alpha) &= Ri + L(x)\frac{di}{dt} + e(x,i) \\ &= Ri + L(x)\frac{di}{dt} + \nu\frac{dL(x)}{dx}i \\ &= (R + \nu\frac{dL(x)}{dx})i + L(x)\frac{di}{dt} \\ &= (R + e(x))i + L(x)\frac{di}{dt} \end{aligned} \tag{9}$$

Solving (9), the short circuit current of the system takes the form:

$$I_{SC} = \frac{|V_m|}{|Z|}\left[\sin(\omega t + \alpha - \theta) - e^{-(R+e(x))t/L(x)}\sin(\alpha - \theta)\right] \quad (10)$$

$$|Z| = \sqrt{(R + e(x))^2 + (\omega L(x))^2} \quad (11)$$

$$\theta = \tan^{-1}\frac{\omega L(x)}{(R + e(x))} \quad (12)$$

The repulsive force caused by the high short circuit current amplitude pushes the two reactors away to an unaligned position. At unaligned position the mutual inductance is low, and thus, the total inductance rises up to a level that limits the fault current. In addition, the moving induced voltage also contributes in limiting the fault current as expressed in relations (9) and (10). According to these relations, the induced voltage and the current passing through coils are in-phase, and thus, limits the fault current similar to a resistance.

The response time of the FCL device is another important performance metric. When the fault occurs, the limiter must operate rapidly and limit the fault current within a short time frame. The response time of the moving reactor can be obtained by the following mechanical relations:

$$F \pm Fgravity - Fspring = ma \quad (13)$$

$$Fgravity = mg \quad (14)$$

$$Fspring = k\,.\,\Delta x \quad (15)$$

$$v = at + v_0 \quad (16)$$

$$x = \frac{1}{2}at^2 + v_0 t + x_0 \quad (17)$$

In relation (13) the positive sign refers to the outer reactor (moving downward, the same direction as gravitational force) and the negative sign refers to the inner reactor (moving upward opposite to gravitational force).

Given that the inner and outer rectors have different masses, the positional change for each coil is calculated separately as expressed in (18) and (19). Therefore, the overall distance between the reactors is equal to the sum of the positions of the moving reactors according to equation (20):

$$x_1 = \frac{1}{2}a_1 t^2 + v_{0_1} t + x_{0_1} \quad (18)$$

$$x_2 = \frac{1}{2}a_2 t^2 + v_{0_2} t + x_{0_2} \quad (19)$$

$$x_{Total} = x_1 + x_2 \quad (20)$$

where x_1, x_2 and x_{Toatl} are position of the inner coil, position of the outer coil and distance between the two coils respectively. It is noted that the acceleration, initial speed and initial position of each reactor in each step time is calculated separately.

With the continuous positional displacement of the reactors at faulty conditions, the FCL parameters such as inductance, instantaneous value of the current, force and distance between the coils continuously change. Utilizing the presented relations the instantaneous current, and the distance between the coils are calculated in each time step. Meanwhile, the inductance and the repulsive force between the coils in each time step is obtained via FE and presented in Table 4. These results are captured per time step of one millisecond within 1-cycle from the moment when the fault occurs (i.e., 0 to 20 ms).

Table 4 implies that at 13 ms after the fault, the reactors reach at the desired distance of 700 mm (Fig. 6), with the total inductance of the FCL increases up to 5 times the normal value and thus, the device can successfully limit the short circuit current. The profile of the short circuit current waveforms with and without the proposed FCL is shown in Fig. 7.

As depicted in Fig. 7, when the fault occurs, the current value is equal to the short circuit current, but the FCL operates rapidly and limits the fault current. The values and the percentage limit of the short circuit current at different fault periods are listed in Table 5. As seen in Table 5, the current decreases from 35 kA peak to 28.52 kA peak at the first period, and declines even further at later periods. Another important take away from the data presented in Table 5 is that the proposed FCL begins to curb the short circuit current at the very first moment when the fault occurs, and continues limiting the current until the fault current declines to the permissible level. In another words, the FCL starts limiting the fault current from the very beginning and does not wait until the reactors arrive at the final position.

It is observed that the current waveform with the proposed fault current limiter has slightly more harmonics than that of without a current limiter. This is attributed to the rapid change of the effective inductance and the moving induced voltage of the FCL.

Figs. 8 and 9 present the positional displacement of the moving coils and the repulsive force between the coils within the first fault cycle (i.e., 0 to 20 ms). As seen, the repulsive force is initially small due to a relatively low current

TABLE 4. Parameters of the FCL-ACVSR operation at different times.

Time (ms)	Distance (mm)	Inductance (mH)	Current (kA)	Force (kN)
0	100	0.27697	0	0
1	100	0.27697	0.9122	1.554
2	100.124	0.2772	3.5437	23.448
3	100.981	0.279	7.6126	108.207
4	104.178	0.28406	12.68	304.526
5	112.722	0.29887	18.18	633.868
6	131.052	0.33845	23.337	1.0807×10^3
7	164.627	0.4115	27.024	1.5886×10^3
8	218.54	0.5431	28.52	1.9709×10^3
9	294.67	0.7524	26.753	1.9179×10^3
10	389.5	1.003	22.219	1.3523×10^3
11	496.12	1.18	17.748	715.699
12	608.823	1.305	16.394	351.461
13	700	1.38	14.165	172.896
14	700	1.38	11.857	98.478
15	700	1.38	9.4714	88.669
16	700	1.38	7.0263	34.582
17	700	1.38	3.2446	7.374
18	700	1.38	0.2652	0.0493
19	700	1.38	-1.6304	1.862
20	700	1.38	-2.267	3.600

amplitude in the first few milliseconds. However, the repulsive force rises rapidly (proportional to the current amplitude) and separates the two coils away within a short time frame. According to Newton's third law the two coils exert a force of equal magnitude on each other but the displacement of the inner coil is more significant due to the lighter weight. The rate of change of the FCL inductance for the same period is plotted in Fig. 10. As seen, the inductance of the reactor rises from 0.27697 mH to 1.38 mH within 13 ms, which is less than one cycle (The period of power network is 20 ms, Frequency=50 Hz).

As mentioned earlier, in addition to decreasing the fault current due to the increase of reactor inductance $L(x)$, the current also decreases due to the moving induced voltage of $e(x, i)$. Fig. 11 shows the moving induced voltage in the reactor from the moment when the fault occurs (when the coils start to move). As seen in this figure the induced voltage reaches to approximately 4650 volt within 11 ms. Comparing this voltage with the network voltage (28000 volt peak) shows that the moving induced voltage is significant and could limit the short circuit current by approximately 17% at within 11 ms.

To further investigate the effectiveness of the proposed design, the performance characteristic of the presented FCL is compared against the existing structures (e.g., superconducting FCLs, power electronics based FCLs, and CLiP FCLs), as summarized below:

- Unlike superconducting FCLs, the proposed design does not require compartments with very low temperature. However, the operating speed is slightly less than that in superconducting FCLs, which typically operate within few milliseconds [40]–[42]. Although the proposed structure starts limiting the fault current from the very beginning, it takes 13 ms for the given structure to

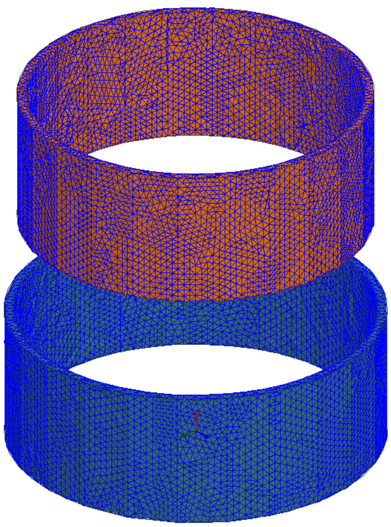


FIGURE 6. Positional displacement between the inner and outer reactor.

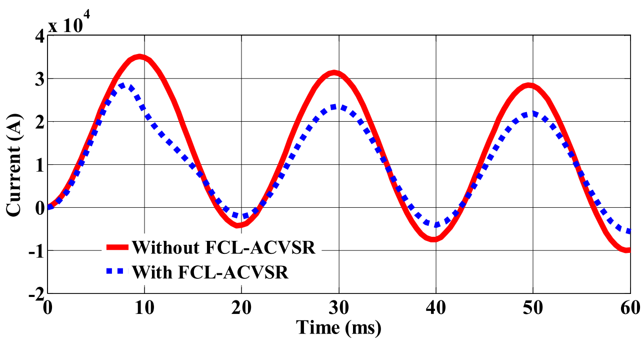


FIGURE 7. Short circuit current waveform.

TABLE 5. Simulation results of proposed FCL when the fault occurs.

Time Interval	Max. Short Circuit Current (kA)	Max. Limited Current (kA)	Limited Percentage (%)
First Period	35.035	28.520	18.6
Second Period	31.303	23.518	24.9
Third Period	28.421	21.802	23.3

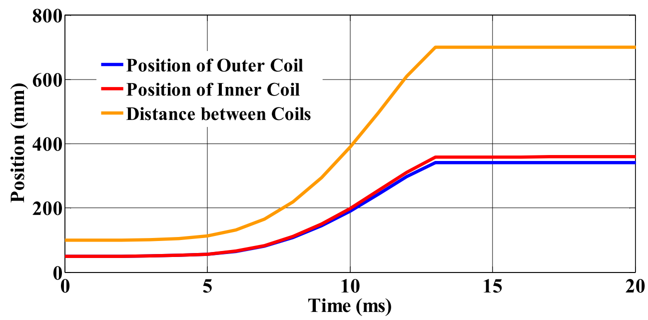


FIGURE 8. The positional displacement between the reactors.

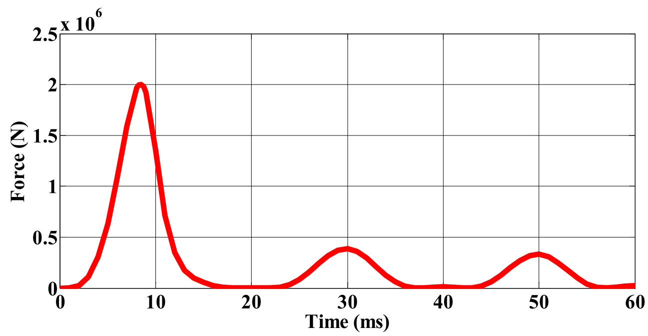


FIGURE 9. The repulsive force between the reactors (when the fault occurs).

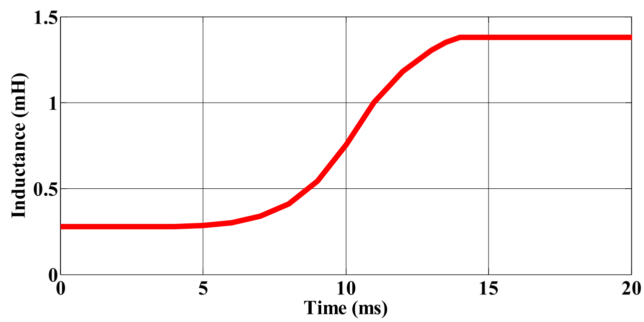


FIGURE 10. The rate of change of FCL inductance.

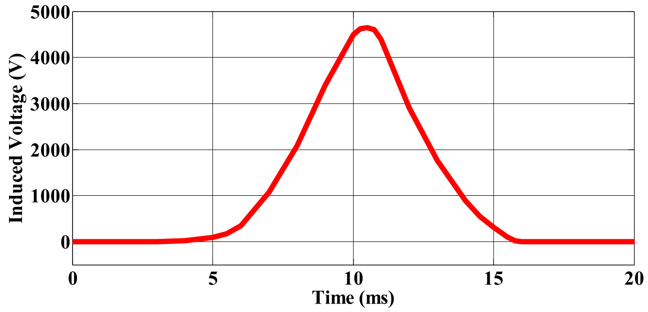


FIGURE 11. The moving induced voltage during the fault.

TABLE 6. Simulation results of proposed FCL when the fault occurs.

Parameters	Value	Unit
Initial distance Between Rectors	100	mm
Self Inductance of Outer Coil	0.8762	mH
Self Inductance of Inner Coil	0.778	mH
Mutual Inductance	0.6886	mH
Total Inductance	0.277	mH

TABLE 7. Simulation results of proposed FCL after operation of the FCL.

Parameters	Value	Unit
Distance Between Rectors	700	mm
Self Inductance of Outer Coil	0.8762	mH
Self Inductance of Inner Coil	0.778	mH
Mutual Inductance	0.1371	mH
Total Inductance	1.38	mH
Operation Time	13	ms

complete its action (reactors arrive at the final position after 13 ms). It should be noted that the structure presented in this article has a basic design (it is not optimized). Future research includes optimizing the design to maximize the operating speed.

- Power electronics based FCLs typically have a complex topology. The presented design has a simple topology, does not have voltage and current limitations, and their voltage and/or current waveforms are less distorted. However, the operating speed is slightly less than that in power electronics based FCLs.
- In the proposed structure, the reactors automatically return to the initial position after the fault is cleared meaning that the operation is reversible without any cost and/or difficulty. However, In CLiP's FCL, the fuse must be replaced after every operation [43].

Tables 6 and 7 present the simulated parameters of the proposed FCL during and after the operation.

IV. CONCLUSION

A novel coreless series FCL was introduced for limiting the fault current. The proposed FCL features simplicity with a fast response, negligible power losses, high operational reliability, and effective performance. Unlike most existing structures, the proposed design does not require DC power circuit, iron core, and permanent magnet. At the normal operating condition the device exhibits a low inductance with negligible voltage drop and power loss in the network. At faulty condition the two reactors are pushed away from each other, and thus, the inductance rapidly (i.e., less than one cycle, 13 ms) rises up to a level (i.e., from 0.27697 mH to 1.38 mH) to limit the fault current. It is noted that the proposed structure limits the short circuit current not only by the rise of inductance but also via the moving induced voltage. Another important feature of the presented design is that it starts limiting the fault current from the very beginning and does not wait until the reactors arrive at the final position.

The proposed FCL was described analytically and analyzed via FE. Simulation results confirmed the effective performance of the proposed design with a fast operational speed. Based on the FE simulation results, it is concluded that the presented model can effectively react and respond to the fault current with an acceptable speed, while featuring structural simplicity.

The proposed FCL can be a good replacement for the FCL equipment that are currently used in the power network. The related/future research work on this topic includes detailed mechanical design, optimal electromagnetic design with improved operational features, and dynamic analysis.

REFERENCES

[1] J. Gezan, J. E. Beehler, W. Khauer, and H. King. (1978). *Application and Development of a Fault Current Limiting Device*. [Online]. Available: https://e-cigre.org/publication/23-05_1978-application-and-development-of-a-fault-current-limiting-device

[2] F. H. Kierstead and H. O. Stephens, "Current-limiting reactors their design, installation and operation," in *Transactions of the American Institute of Electrical Engineers*, vol. 43, Jan./Dec. 1924, pp. 902–913, doi: 10.1109/T-AIEE.1924.5061047.

[3] V. A. Akpeh, T. C. Madueme, O. A. Ezechukwu, V. C. Ogboh, and V. C. Echedom, "A methodology for implementing fault current limiting reactors (CLRs) on feeders with minimal constant power losses," *Global J. Eng. Design Technol.*, vol. 4, no. 5, pp. 1–7, 2015.

[4] J. Amon, P. C. Fernandez, E. H. Rose, A. D'Ajuz, and A. Castanheira, "Brazilian successful experience in the usage of current limiting reactors for short- circuit limitation," in *Proc. Int. Conf. Power. Syst. Trans. (IPST)*, Montreal, QC, USA, Jun. 2005, pp. 215–220.

[5] O. Mendrock, "Short-circuit current limitation by series reactors," in *Transmission and Distribution*. Austria: Trench, Oct. 2009, pp. 45–49. [Online]. Available: https://www.ee.co.za/wp-content/uploads/legacy/Energize_Oct09/022_TT_Short-circuit.pdf

[6] CIGRE Working Group A3.10. (2003). *Fault Current Limiters in Electrical Medium and High Voltage Systems*. [Online]. Available: https://e-cigre.org/publication/239-fault-current-limiters-in-electrical-medium-andhigh-voltage-systems

[7] A. Abramovitz and K. M. Smedley, "Survey of solid-state fault current limiters," *IEEE Trans. Power Electron.*, vol. 27, no. 6, pp. 2770–2782, Jun. 2012.

[8] S. M. Blair, "The analysis and application of resistive superconducting fault current limiters in present and future power system," M.S. thesis, Strathclyde Univ., Glasgow, Scotland, 2013.

[9] Z. Guo, H. Sun, B. Bai, and X. Dong, "Experiment and simulation of PTC used in fault current limiter," in *Proc. Int. Conf. Electr. Dist.*, Nanjing, China, Sep. 2010, pp. 1–9.

[10] H. He, M. Rong, Y. Wu, F. Yang, Y. Lia, I. Man, J. Luo, and Q. Shi, "Experimental research and analysis of a novel liquid metal fault current limiter," *IEEE Trans. Power Del.*, vol. 28, no. 4, pp. 273–2566, 2013.

[11] M. T. Hagh and M. Abapour, "Nonsuperconducting fault current limiter with controlling the magnitudes of fault currents," *IEEE Trans. Power Electron.*, vol. 24, no. 3, pp. 613–619, Mar. 2009.

[12] D. K. Park, K. S. Chang, S. E. Yang, Y. J. Kim, M. C. Ahn, Y. S. Yoon, H. M. Kim, J. W. Park, and T. K. Ko, "Analytical and experimental studies on the hybrid fault current limiter employing asymmetric non-inductive coil and fast switch," *IEEE Trans. Appl. Supercond.*, vol. 19, no. 3, pp. 1896–1899, Jun. 2009.

[13] (2015). *Current Limiting Protector, G&W Catalog*. [Online]. Available: https://www.gwelectric.com/products/current-limiting-protection
[14] E. Calixte, Y. Yokomizu, H. Shimizu, T. Matsumura, and H. Fujita, ''Reduction of rating required for circuit breakers by employing series-connected fault current limiters,'' *IEE Proc. Gener., Transmiss. Distrib.*, vol. 151, no. 1, pp. 36–42, Jan. 2004.
[15] S. Sugimoto, J. Kida, H. Arita, C. Fukui, and T. Yamagiwa, ''Principle and characteristics of a fault current limiter with series compensation,'' *IEEE Trans. Power Del.*, vol. 11, no. 2, pp. 842–847, Apr. 1996.
[16] H. R. Baghaee, A. K. Kaviani, M. Mirsalim, and G. B. Gharehpetian, ''Short circuit level and loss reduction by allocating TCSC and UPFC using particle swarm optimization,'' in *Proc. 19th Iranian Conf. Electr. Eng.*, Tehran, Iran, May 2011, pp. 1–6.
[17] S. Kannan, S. Jayaram, and M. M. A. Salama, ''Real and reactive power coordination for a unified power flow control,'' *IEEE Trans. power syst.*, vol. 19, no. 3, pp. 1454–1461, Aug. 2004.
[18] H. Radmanesh, S. H. Fathi, G. B. Gharehpetian, and A. Heidary, ''A novel solid-state fault current-limiting circuit breaker for medium-voltage network applications,'' *IEEE Trans. Power Del.*, vol. 31, no. 1, pp. 236–244, Feb. 2016.
[19] H. Radmanesh, S. H. Fathi, G. B. Gharehpetian, and A. Heidary, ''Bridge-type solid-state fault current limiter based on AC/DC reactor,'' *IEEE Trans. Power Del.*, vol. 31, no. 1, pp. 200–209, Feb. 2016.
[20] M. Abdolkarimzadeh, M. Nazari-Heris, M. Abapour, and M. Sabahi, ''A bridge-type fault current limiter for energy management of AC/DC microgrids,'' *IEEE Trans. Power Electron.*, vol. 32, no. 12, pp. 9043–9050, Dec. 2017.
[21] D. Cvoric, S. W. H. de Haan, and J. A. Ferreira, ''New saturable-core fault current limiter topology with reduced core size,'' in *Proc. IEEE 6th Int. Power Electron. Motion Control Conf.*, Wuhan, China, May 2009, pp. 920–926.
[22] D. Cvoric, S. W. H. de Haan, and J. A. Ferreira, ''Improved configuration of the inductive core-saturation fault current limiter with the magnetic decoupling,'' *IEEE Ind. Appl. Soc. Annu. Meeting*, Edmonton, AB, Canada, Oct. 2008, pp. 1–7.
[23] D. Cvoric, S. W. H. de Haan, J. A. Ferreira, M. van Riet, and J. Bozelie, ''Design and testing of full-scale 10 kV prototype of inductive fault current limiter with a common core and trifilar windings,'' in *Proc. Int. Conf. Electr. Mach. Syst. (ICEMS)*, Incheon, South Korea, Oct. 2010, pp. 1879–1884.
[24] D. Cvoric, S. W. H. de Haan, and J. A. Ferreira, ''Guidelines for 2D/3D FE transient modeling of inductive saturable-core fault current limiters,'' in *Proc. Int. Conf. Electr. Power Energy Convers. Syst. (EPECS)*, Sharjah, United Arab Emirates, Nov. 2009, pp. 1–6.
[25] B. Xi and G. Chen, ''Influence of polymer matrix on the PTC properties of polyethylene/carbon black composites,'' in *Proc. IEEE 7th Int. Conf. Solid Dielectrics (ICSD)*, Eindhoven, The Netherlands, Jun. 2001, pp. 109–112.
[26] W. Song, X. Pei, J. Xi, and X. Zeng, ''A novel helical superconducting fault current limiter for electric propulsion aircraft,'' *IEEE Trans. Transport. Electrific.*, vol. 7, no. 1, pp. 276–286, Mar. 2021.
[27] V. Q. Dao, J. Lee, C.-S. Kim, and M. Park, ''Conceptual design of a saturated iron-core superconducting fault current limiter for a DC power system,'' *IEEE Trans. Appl. Supercond.*, vol. 30, no. 4, pp. 1–5, Jun. 2020.
[28] J. Lopez-Roldan, A. C. Price, F. De La Rosa, and F. Moriconi, ''Analysis of the effect of a saturable-core HTS fault current limiter on the circuit breaker transient recovery voltage,'' in *Proc. IEEE Power Energy Soc. Gen. Meeting*, Detroit, MI, USA, Jul. 2011, pp. 1–8.
[29] M. Nazari-Heris, H. Nourmohammadi, M. Abapour, and M. Sabahi, ''Multi-level nonsuperconducting fault current limiter: Analysis and practical feasibility,'' *IEEE Trans. Power Electron.*, vol. 32, no. 8, pp. 6059–6068, Oct. 2017.
[30] H. Nourmohamadi, M. Nazari-Heris, M. Sabahi, and M. Abapour, ''A novel structure for bridge-type fault current limiter: Capacitor-based nonsuperconducting FCL,'' *IEEE Trans. Power Electron.*, vol. 33, no. 4, pp. 3044–3051, Apr. 2018.
[31] F. Moriconi, F. De La Rosa, F. Darmann, A. Nelson, and L. Masur, ''Development and deployment of saturated-core fault current limiters in distribution and transmission substations,'' *IEEE Trans. Appl. Supercond.*, vol. 21, no. 3, pp. 1288–1293, Jun. 2011.
[32] F. Moriconi, F. De La Rosa, A. Singh, B. Chen, M. Levitskaya, and A. Nelson, ''An innovative compact saturable-core HTS fault current limiter–development, testing and application to transmission class networks,'' in *Proc. IEEE PES Gen. Meeting*, Minneapolis, MN, USA, Jul. 2010, pp. 1–8.
[33] D. Cvoric, S. W. H. de Haan, and J. A. Ferreira, ''Comparison of the four configurations of the inductive fault current limiter,'' in *Proc. IEEE Power Electron. Spec. Conf.*, Rhodes, Greece, Jun. 2008, pp. 3967–3973.
[34] D. Cvoric, S. W. H. de Haan, J. A. Ferreira, Z. Yuan, M. van Riet, and J. Bozelie, ''New three-phase inductive FCL with common core and trifilar windings,'' *IEEE Trans. Power Del.*, vol. 25, no. 4, pp. 2246–2254, Oct. 2010.
[35] A. D. Aliabad and S. H. Zarchi, ''Optimal design and analysis of a variable reactor fault current limiter,'' *IET Electr. Power Appl.*, vol. 11, no. 9, pp. 1–8, Nov. 2017.
[36] Y. Zhong, Y. Xie, Y. Liu, H. Ye, J. Yuan, H. Zhou, and L. Wei, ''A novel multi-function saturated-core fault current limiter,'' *IEEE Trans. Magn.*, vol. 55, no. 6, pp. 1–5, Jun. 2019.
[37] J. Yuan, Y. Zhong, S. Liao, L. Wei, Y. Gao, K. Muramatsu, J. Jia, B. chen, and L. Bai, ''A novel three-phase compact saturated-core fault current limiter,'' *IEEE Trans. Magn.*, vol. 53, no. 11, pp. 1–4, Nov. 2017.
[38] J. Yuan, P. Gan, Z. Zhang, H. Zhou, L. Wei, and K. Muramatsu, ''A novel six-leg three-phase fault current limiter,'' *IEEE Trans. Power Del.*, vol. 35, no. 4, pp. 1707–1715, Aug. 2020.
[39] M. Ahmadvand, S. Khanabdal, and M. T. Hagh, ''A novel three-phase saturable-core fault current limiter structure,'' *IEEE Trans. Power Del.*, vol. 34, no. 2, pp. 410–419, Apr. 2019.
[40] M. Moyzykh, D. Gorbunova, P. Ustyuzhanin, D. Sotnikov, K. Baburin, A. Maklakov, E. Magommedov, A. Shumkov, A. Telnova, V. Shcherbakov, and D. Kumarov, ''First Russian 220 kV superconducting fault current limiter (SFCL) for application in city grid,'' *IEEE Trans. Appl. Supercond.*, vol. 31, no. 5, pp. 1–7, Mar. 2021.
[41] L. Ye and A. M. Campbell, ''Case study of HTS resistive superconducting fault current limiter in electrical distribution systems,'' *Electr. Power Syst. Res.*, vol. 77, nos. 5–6, pp. 534–539, Apr. 2007.
[42] S. T. Lim, S. H. Lim, and T. H. Han, ''Analysis on operation characteristics and power burdens of the double quench trigger type SFCLs,'' *Prog. Supercond. Cryog.*, vol. 19, no. 2, pp. 33–37, 2017.
[43] (2014). *Current Limiting Protector*. G&W Catalog. [Online]. Available: https://www.gwelectric.com/products/current-limiting-system-protection/clip/

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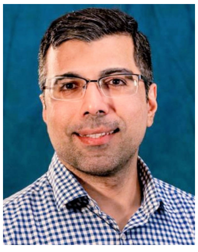

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