Permanent magnet fault current limiter device performance improvement

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Abstract

The power system short-circuit current is at a critical level, which endangers the security, stability and reliability of the power system. Hence, how to restrict the short-circuit current has become an obligatory issue in the modernization of power grid system. This paper looks at the performance improvement of the Permanent magnet Fault Current Limiter (PMFCL) device. It presents the influence of AC coil span across the iron core on the performance enhancement of the PMFCL device. The modelling scheme has been performed on three PMFCL models of 0.033m, 0.066m and 0.099m AC coil span.

A prototype of 0.099m AC coil span has been built and tested. The 3DFEM simulation and Lab measured results for the prototype were adopted as standard results. These results were used as a baseline for a comparison with 0.033m and 0.066m AC coils span FEM models. The practical results ensured the validity of the FEM software simulation tool, test the concept of the PMFCL device and revealed the effect of AC coil span across the core on the performance of the PMFCL device working operation.

Key words-- AC coil; Experimental results; FEM modelling; Permanent magnetic fault current limiter; Performance.

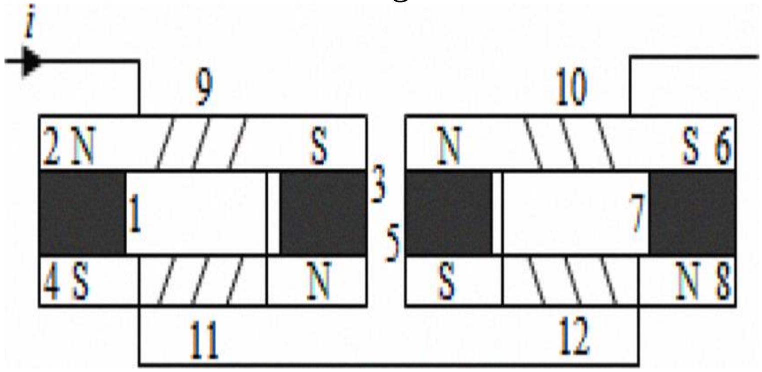
1- Introduction.

Short circuit is a serious fault in high-voltage power network. In the event of a fault, the short circuit current may surge to over eight times the normal load current. The high abnormal circuit current rapidly increases the high mechanical and thermal stress on the electrical devices and the whole electrical equipment [1]. Fault current reduction enables the interconnection of large networks without replacing the infrastructure, improves transient system stability, and reduces the cost of apparatus [2]. With recent developments in magnetic materials and a geometry design research, Fault Current Limiter based on permanent magnet biased Saturation (PMFCL) has recently been attracted by a lot of researchers and scientists [3]-[8]. During the power system normal operation, the device offers low impedance to the grid and during the fault state the scheme offers additional impedance that mitigates the high short circuit current [9]-[12]. The objective of this paper is to study the effect of AC coil span on the capability of the permeant magnet fault current limiter (PMFCL) device. The modelling scheme has been performed on three PMFCL models of 0.033m, 0.066m and 0.099m AC coil span. A prototype of 0.099m AC coil span has been built and tested. The computed and experimental lab measurement results for the PMFCL prototype were taken as a reference to study the modelling behaviour of the device with 0.033mm and 0.066 mm AC coils span. In this work the magneto static flux density based on the model magnetic circuit equations was systematically obtained and compared with the 3-D FEM calculated value to ensure the model is factual [13]. The steady state software simulation was performed on the 0.099m AC coil span model. Then a 0.099m

PMFCL prototype was built and tested. The practical and simulation results were compared to check the validity of the modelling design tool. Finally, the device FEM modelling results with 0.033m and 0.066m AC coil span were compared with the reference results of 0.099m.

2- The PMFCL device mode of operation.

The PMFCL consists of Permanent magnet, limiter coils and the iron-core as shown in Fig1.



1,3,5,7-permanent magnet; 2,4,6,8-iron-core; 9,1O,11,12-coil

Figure 1: Schematic diagram of the PMFCL topology [6, 7].

The two similar magnetic devices are connected in series with opposite magnetomotive forces to restrict the positive and negative half-wave currents respectively [6,7]. Under standard operating conditions of the device the AC magnetic field generated by coil is not enough to bring the iron-core into desaturation state, so the PMFCL acts like an existing in-service series reactor but with a significantly low inductance. While during the abnormal power system condition each of the cores comes out of saturation and thus naturally flashed to a high impedance state that mitigates the high short circuit current [3].

2- The model design framework.

The geometric design of the model is 3D axis symmetric. It contains of four Neodymium Iron Boron type N52, two iron cores of M4 class electrical steel cores and the device AC cupper coils. The FEM model design topology is depicted in figure 2. The 85V PMFCL model description parameters are stated in Table1

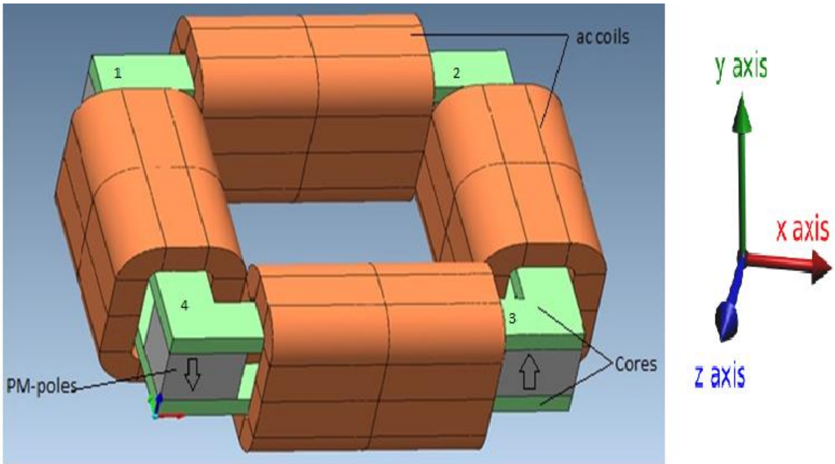


Figure 2: The FEM model design.

The four PMs are placed between the two M4 cores (C1 and C2) in such that each opposite magnets are magnetized in the same direction. The model specifications are as shown in table1.

Table 1: The PMFCL model parameters

Parameter	Type or value	Type or value
Iron core size	(0.189 x 0.027 x 0.004) m	Instantaneous
Magnet type	Neodymium N52	Single line to ground
Magnet dimensions	(0.03 x 0.03 x 0.03) m	37A

Parameter	Type or value	Type or value
Operating voltage	85V $_{RMS}$, 50 Hz	0.099 m
Source resistance	0.1 Ω	40 Ω
No of turns	212	3.17Apeak

3- The limiter core magneto static flux density.

An important task in the design of the PMFCL devices is the systematic approach. The magnetic field in the iron-core without the contribution of the AC current was calculated using PMFCL equivalent circuit. The series magnetic circuit consists of a neodymium magnet, which is the magnetic field source that consistently supplies the core. The leakage flux in the circuit was neglected due to the consideration of the iron core's saturation depth ratio." [12].

The symbols m and e express for the magnet and the iron core respectively. The subscript H is the magnetic field intensity. The coercivity H_c is an essential element when selecting the permanent magnet. H_c is the coercivity of the neodymium magnet (N52), $H_c = 8.68 \times 10^5$ A/m .

The flux density in Tesla and magnetic flux in Weber are expressed by B and Ø respectively. The reluctance is represented by the subscript R. The cross-section area in square meter is denoted by S. The length is expressed by l, The permeability of the permanent magnet μ_m and μ_s is the permeability of the iron core. $\mu_m = 1.4 \times 10^{-6}\ H/m$, $\mu_s = 2.1 \times 10^{-5}\ H/m$ [5,6]

The series magnetic circuit flux equation is given by.

$$H_m l_m = \Phi_m R_m - H_c l_m \qquad (1.1)$$

When the power is off and no AC current flows, the summation of the amber turns of the iron core and the magnet is zero.

$$H_e l_e + H_m l_m = ni = 0 \qquad (1.2)$$

$$H_e\, l_e = H_c l_m - \Phi_m R_m \qquad (1.3)$$

$$\Phi_e\, R_e = H_c\, l_m - \Phi_m\, R_m \qquad (1.4)$$

$$B_e\, S_e \left[\frac{l_e}{\mu_s S_e} + \frac{l_m}{\mu_m A_m}\right] = H_c l_m \qquad (1.5)$$

The magnetic field in the core has been systematically calculated using the above equation. The magnetic field in the core was 2.05T. The device core saturation extent was checked with the absence of the ac current. The 3-D FEM flux density in the iron core was performed on the one-fourth of the model. The FEM calculated flux density was 2.04T. The FEM computed static magnetic field ensures that the device was in full saturation. This means that the device is unseen by the grid in normal working condition and thereby has no effect on the normal power system operation.

Figure 3 illustrates that the main section of the iron core enclosed by the coils was in complete saturation. The flux density at the centre of the core is 2.03 Tesla.

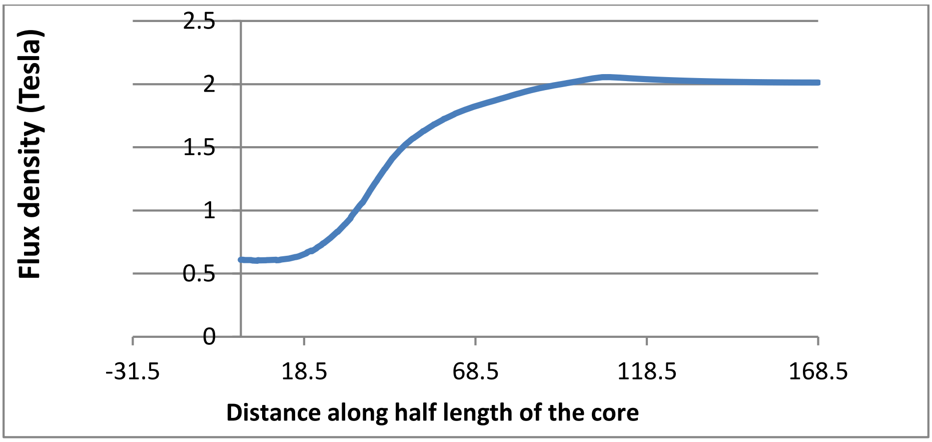


Figure 3: Core flux measurement in 3-D

4-The 0.099m AC coil span normal state experimental and FEM modelling results

The device was simulated using FEM Magnet to explore the properties of the PMFCL and to envisage the fault current restraint at which the device activates at the fault occurrence. The PMFCL device with 0.099m AC coil span was designed, built and tested to compare the computed and actual results and to gain a deeper insight in regard to the concept of the working operation. The coils of the limiter device resistance and inductance were measured by the LCR meter at 50 HZ, as displayed in figure 4. The four coils total resistance and inductance were 1.17Ω and 9.6mH and the total resistance and inductance for a current limiting reactor of comparable dimensions as the PMFCL was 1.5 Ω and 3.97 mH.

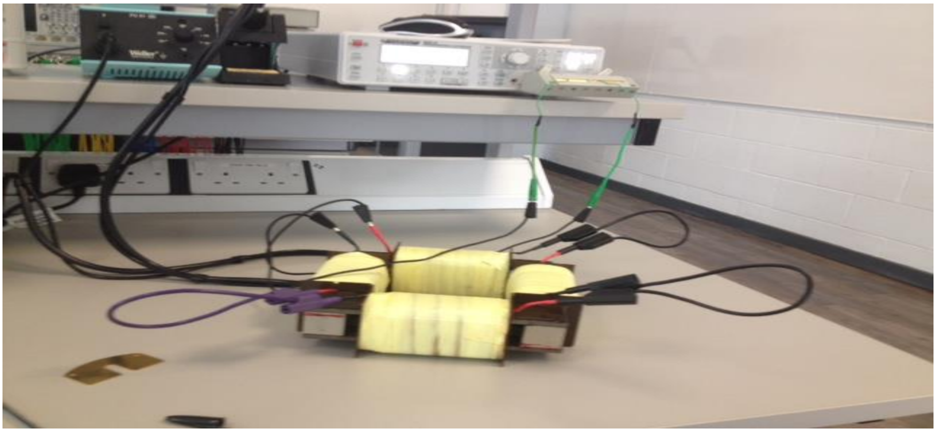


Figure 4: Prototype PMFCL device

The experimental circuit diagram, as shown in Figure 5, consists of the autotransformer, 3300VA, which is powered by 230V, 50 Hz, connected to the PMFCL and a stray resistance of 0.04 kΩ in parallel with an isolator switch.

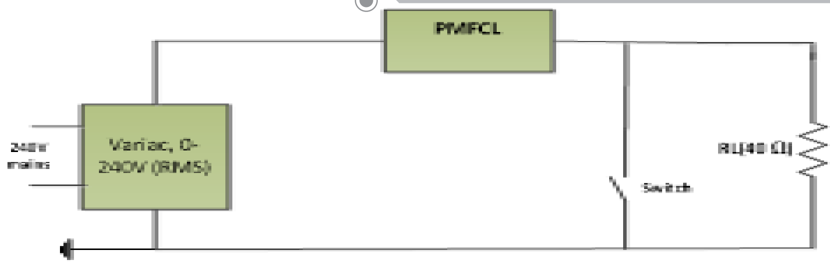


Figure 5: A practical circuit connection

The following points were considered during the performed work on the prototype:

- Make certain that the device iron cores are in complete saturation, which is above 2.0 Tesla without the contribution of the AC current
- Ensure that N52 magnet has a capability to endure the high fault current without experiencing any damage.
- Perform FEM simulation to assess the limiter normal and abnormal working operation to evaluate the normal load current and the determined short circuit current. the normal steady state current was evaluated to be 3.17 A, and the determined short circuit current was calculated to be 37 A.
- Ensure that the PMFCL device under test is placed and remained in a secure enclosure.
- Choose the proper cables in terms of current rating for connecting the equipment with the supply voltage.
- Ensure that the equipment is properly earthed.
- Check that the heat generated does not have a negative effect on the circuit components.
- Place the device close to an easily accessible emergency stop switch.
- Check the autotransformer to ensure to have the accurate off load voltage.

- Perform a No-load test on the PMFCL to verify the load measurement.
- Repeat the test occasionally several times to ensure that the device stay within permissible working operation temperature rise to obtain accurate results.
- Make certain that the instrument devices used for measurement are properly accurate to achieve fruitful results.

The PMFCL experimental and modelling steady state results are as shown in figure 6.

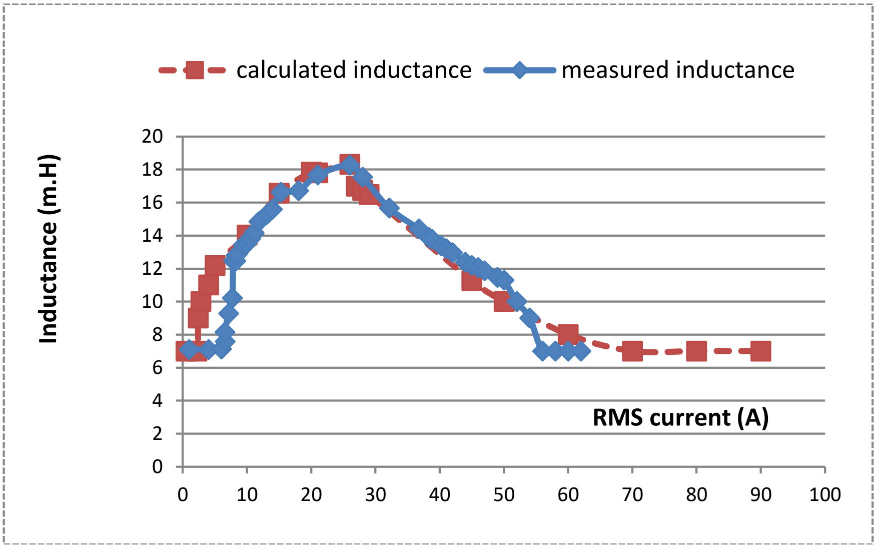


Figure 6: Steady state FEM modelling and experimental results

Figure 6 exhibits the steady state measured and calculated inductance with increased current, which are almost the same. The figure shows that the inclusion calculated and measured inductance is almost 7 mH, which is constrained by the air inductance. It can be seen from the figure that the greatest computed and measured inductance is 18.29 mH at a corresponding peak current of 37A. The 0.099mAC coil span

PMFCL model was simulated in transient condition using 3D FEM Magnet.

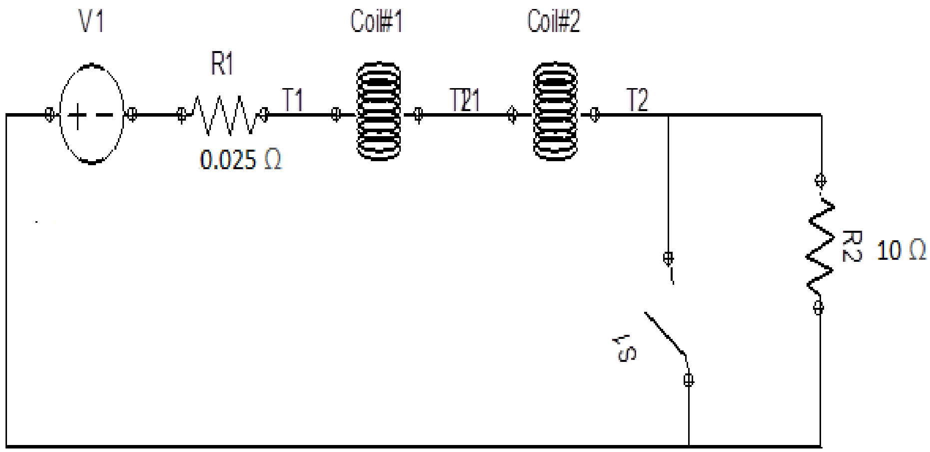


Figure 7: FEM single line to ground fault simulation for one-fourth of the model

The one-fourth of the PMFCL model and the current limiting reactor were simulated using FEM simulation tool. The circuit was powered by V1, which was adjusted by the autotransformer voltage source. The source voltage was $(85\sqrt{2})/4$Vpeak. The system input and stray load resistances were as shown on figure 7. The fault circuit was activated by closing the switch at 0.04S and the simulation continued for four complete cycles. The oscilloscope was connected to capture the fault current waveform. The circuit input voltage was increased via the autotransformer till it reached 85V where the peak normal load current through the stray resistance (R2) was 3.17A. The oscilloscope stored the current waveforms for four complete cycles. Then the data was uploaded to the computer for comparison with the FEM simulation results. The assessed results were finally compared with the current limiting reactor to evaluate the limiter device fault current mitigation capability.

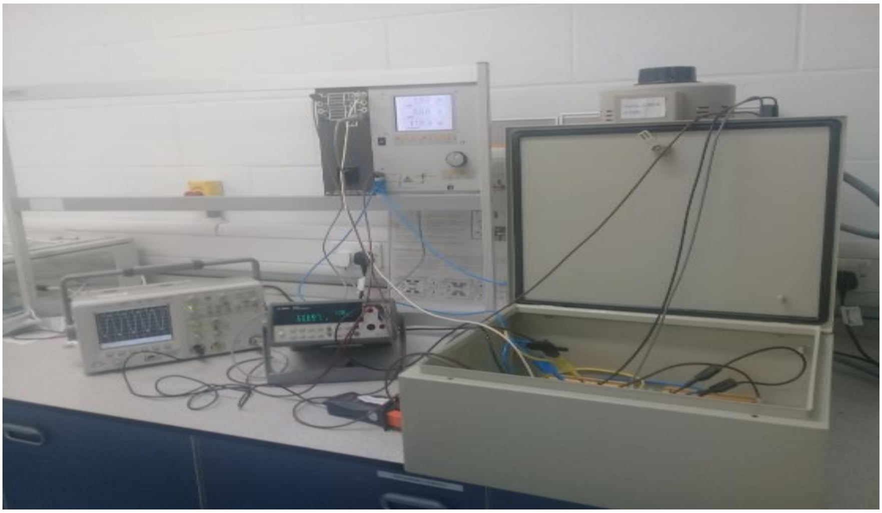


Figure 8: Experimental work

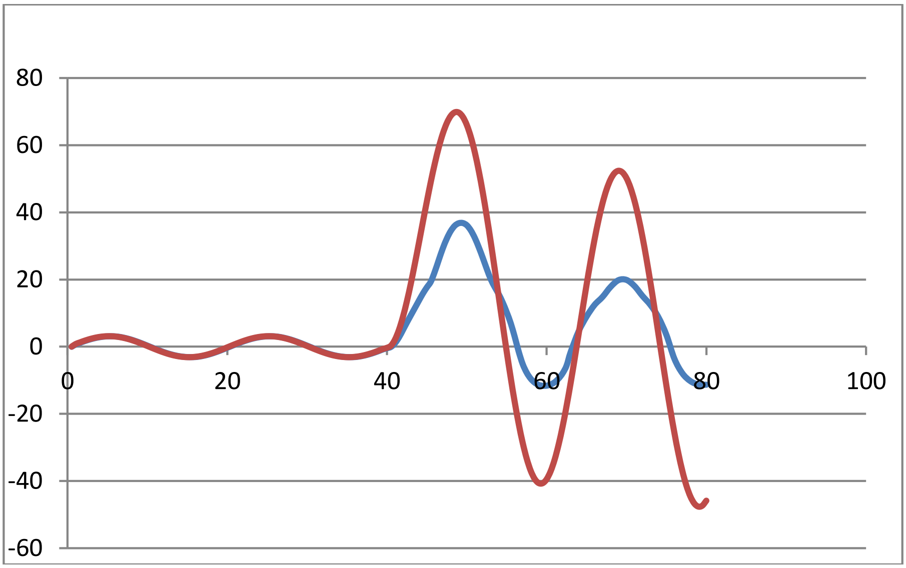


Figure 9: FEM calculated PMFCL and traditional reactor transient currents

The current limiting reactor of similar specifications as the PMFCL device was modelled. The mitigated current obtained by means of the existing in service current limiting reactor was then compared with the PMFCL device to evaluate the device fault current reduction. The first peak current moderated by the traditional current limiting reactor was 65A.

The PMFCL device with 0.099m AC coil span calculated and measured fault currents are plotted as shown in figure 10.

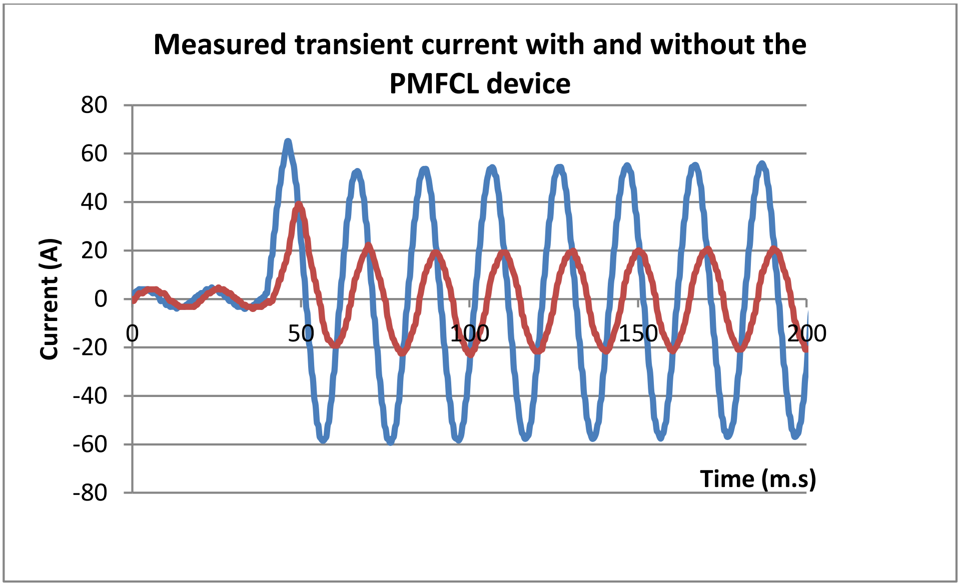


Figure 10: PMFCL device and series reactor measured transient currents

The first peak calculated, and experimental measured transient current is 37A.In comparison with the limiting reactor current of 65A, the device fault current limiting capability is 43 %.

5- The influence of AC coil length on the performance of PMFCL

The previous calculated and practical results for the PMFCL device were taken as a reference to evaluate the influence of the coil span on the performance of the fault current reduction. The steady state results for the device with 0.033m and 0.066m AC coil span were obtained using the FEM simulation tool and compared with the 0.099m AC coil span.

Table 2: inclusion and peak inductance for different coil length

PMFCL	initial inductance (mH)	Peak inductance (mH)	Steady/transient inductance ratio
0.039 m	17	24	1.41
0.069 m	13.98	20.3	1.45
0.099 m	7	18.3	2.61

The steady state modelling proves that the model with the shortest AC coil span across the core has the greatest normal and faulted inductance compared with the longer ones. This means that the shortest coil span has the weakest iron core flux saturation extent and hence its core can easily lose the required level of saturation. The figure also depicts that the 0.099 m coil span along the core shows a lower initial and peak fault inductance of 6.98 mH and 18.4mH respectively, compared with 0.039 m and 0.069 m, and hence it has an impedance ratio of 2.61.This suggests that the core has the greatest saturation level at 0.099 m coil span at which the magnetic flux causes the mutual inductance between the windings low and as a result the total inductance is diminished. The 0.099m AC coil span device has a low voltage drop in normal working condition as the device initial inductance is the lowest.

Table 3: Transient current for different coil span

PMFCL	PMFCL peak fault current (A)	Reactor transient current (A)	PMFCL capability
0.039 m	22	30	26%
0.069 m	27	41	34%
0.099 m	37	65	43%

The mitigated fault current is dependent on the coil span across the iron core as the longer coil along the core provides greater contribution to the fault current reduction. This is attributed to the strong magnetic field, which pushes the core out of saturation during the fault incident. The longer the AC coil span across the core the higher the device' performance.

6-Conclusion.

The 85v PMFCL was designed, built and tested.at both normal and faulted working conditions. The 0.099m AC coil span PMFCL FEM modelling simulations computed data were compared with the Lab experimental results for its replica. The experimental and theoretical matching results confirm the accuracy of the FEM modelling tool. The matching FEM and the Lab results for the constructed PMFCL device with 0.099 m coil span were taken as a reference. The simulated results attained by FEM for 0.039 m and 0.069m models, with fixed number of turns were compared with the reference results. The key findings show that the 0.099 m AC coil span is the more effective device as it offers greater percentage of fault current reduction and a low reactance in both the normal and faulted power system operations. The device with 0.099m has a lower insertion resistance compared with the 0.033m and 0.066m and hence the highest ac coils span device experiences the lowest voltage drop in the normal power grid operation. Therefore, the coil span along the core is a major factor to consider in the design of the PMFCL device. The designed prototype modelling and experimental results confirm the device principle of operation. According to the results, it has been observed that by increasing the AC coil span reduces the device normal inductive reactance and thereby reduces the voltage drop. The voltage drop reduction increases the efficiency of the device and reduces the power consumption in the power grid. Another benefit from the enlargement of the AC coil length is the device capability in mitigating the fault current. The PMFCL device with 0.099m AC coil span reduces the fault current to 37A whereas the 0.033m and 0.066m mitigated the fault current to 22A and 27A respectively. The consistently existing in service current limiting reactor mitigated the fault current with much lower capability compared to the PMFCL device. The PMFCLs must be incorporated into the Protection infrastructure design to ensure correct protective relays operation and to prevent any unintended tripping. The future power grid will have an economical PMFCL substitutes the traditional current limiting reactor. The new system improves the power system stability by incorporating the device from the early design stage The passive, dry type PMFCL mitigates the fault current in its first peak cycle and requires minimal servicing. It aims to enhance protection and extend the operational life of the undersized power system equipment such as the power transformers and circuit breakers.

7-References

[1] GANG, C., et al. (2003). Simulation study of bridge type solid state fault current limiter. In: Power Engineering Society General Meeting, 2003, IEEE, 2526 Vol. 4.

[2] KARADY, G. G. (1992). Principles of fault current limitation by a resonant LC circuit. Generation, transmission and distribution, IEE proceedings C, 139 (1), 1-6

[3] RENZ, K., THUMM, G. and WEISS, S. (1995). Thyristor control for fault current limitation. In: Fault Current Limiters - A Look at Tomorrow, IEE Colloquium on, 3/1-3/4.

[4] HALL, J. and CHEER, A. (2013). Fault current limiter surge protection device for the power grid based upon zero power consumption ceramic ferrite permanent magnets. In: Electricity Distribution (CIRED 2013), 22nd International Conference and Exhibition on, 1-4.

[5] SANTRA, T., et al. (2009). Analysis of passive magnetic fault current limiter using wavelet transforms. In: Power Systems, 2009. ICPS '09.Internatio

[6] Liang Zou, et al. (2009). Study on the feasibility of developing high voltage and large capacity permanent-magnet-biased fault current limiter. In: Universities Power Engineering Conference (UPEC), 2009 Proceedings of the 44th International, 1-5.

[7] Li, Q., Xu, J., Zou, L., & Lou, J. (2012). Modelling methodology and experimental verification of the permanent-magnet-biased saturation-based fault current limiter. *Electric Power Applications*, *IET*, *6*(8), 504-512.

[8] Farzinfar, M., & Jazaeri, M. (2020). A novel methodology in optimal setting of directional fault current limiter and

protection of the MG. *International Journal of Electrical Power & Energy Systems, 116, 105564. doi: 10.1016/j.ijepes.2019.105564*

[9] J. Linden, Y. Nikulshin, A. Friedman, Y. Yeshurun and S. Wolfus, "Phase-Coupling Effects in Three-Phase Inductive Fault-Current Limiter Based on Permanent Magnets," in *IEEE Transactions on Magnetics*, vol. 56, no. 2, pp. 1-7, Feb. 2020, Art no. 8600107, doi: 10.1109/TMAG.2019.2956147.

[10] Rai, S., De, M. (2020). Optimal Placement of Resistive Superconducting Fault Current Limiters in Microgrid. In: Singh, S., Pandey, R., Panigrahi, B., Kothari, D. (eds) Advances in Power and Control Engineering. Lecture Notes in Electrical Engineering, vol 609. Springer, Singapore. https://doi.org/10.1007/978-981-15-0313-9_6

[11] Alam, M. S., Abido, M. A. Y., & El-Amin, I. (2018). Fault current limiters in power systems: A comprehensive review. *Energies*, *11*(5), Article 1025. https://doi.org/10.3390/en11051025

[12] Liang Zou, et al. (2008). Impact of saturation depth ratio of iron-core on the PMFCL. In: Electrical

[13] Machines and Systems, 2008. ICEMS 2008.International Conference on, 4338-43