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## Permanent magnet fault current limiter for the power grid

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### Abstract

With several significant advantages such as compactness, reliability, zero reset time, safe operation and fail safe, the permanent magnet fault current limiter (PMFCL) is a preferable solution to mitigate the fault current in power grids these years.

In this paper, the substation voltage level PMFCL device, aims to extend the capacity of the power grid, is presented. The dry type PMFCL that does not require DC excitation coils is designed and simulated by 3D FEM. The 3D FEM magneto static solver has been used as time saving approach to predict the device fault current limitation in case of a fault. The peak transient currents simulation results were in agreement with the RMS values obtained using the magneto static inductance-current profile. The effect of the PMFCL on the fault current mitigation has been compared with an air-cored of similar specifications and a useful reduction in the fault current has been achieved.

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*Keywords:* PMFCL, power grid, modelling results.

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### 1. Introduction

As the application of renewable sources of electrical energy is fast growing, the power grid keeps expanding. Hence the ever increasing short circuit current is persistently becoming more severe, which endangers the reliability and stability of the power system operation [1]. Many means of limiting fault currents have been suggested in the past including upgrading fast circuit breakers, system reconfiguration, installing transformers with higher impedance, current limiting fuses, air-core reactors, etc. [2 ]-[5]. However, those methods were not satisfactory due to high estimated costs, lack of system security and reliability. A fault current limiter (FCL) is a changeable impedance device connected in series with a circuit breaker and has insignificant influence on the power system under normal conditions, but can limit the current within a predefined value during a transient condition.

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There are up to date approaches to limit the fault current such as the introduction of superconductors fault current limiters and solid state fault current limiters but they still fall behind in addressing one or more of the following concerns such as the running cost, installation cost, maintenance cost and reliability. Thus, it is very necessary to develop a preferable current limiting device to reduce the rating of each element required, to lower the capital cost, thereby improving protection coordination [6]. With the recent advance in magnetic materials as well as geometry design research, permanent magnet fault current limiter (PMFCL) has recently attracted the interests of many researcher and scientists [2]-[5]. In this paper, a square shape topology, 11KV substation dry type PMFCL model is designed and simulated by 3DMagNet FEM. The modelling of the whole model is not suitable for engineering applications as it takes a long period of time to obtain the required results. As the model is quite large, only a quarter of it was simulated using 3D FEM magneto static and time-step solvers.

The device can be installed at the high voltage side of a 10MVA, step down transformer or at the low voltage side of any step up transformer of the same size such as 11/66 kV or 11/220 kV,...etc.

<b>Nomenclature</b>	
A	<i>Magnetic vector potential</i>
B	<i>Magnetic flux density (Tesla (T))</i>
e	<i>core</i>
H	<i>Magnetic field intensity (Amper/meter (A/m))</i>
J	<i>Current density (Amper/meter (A/m))</i>
L	<i>Inductance (Henry).</i>
M	<i>Magnetization vector</i>
m	<i>Magnet</i>
N	<i>No of turns</i>
n	<i>No of turns per unit length</i>
R	<i>Magnetic Reluctance (Ampere/weber(A Wb<sup>-1</sup>))</i>
AC	<i>Alternating current</i>
A <sub>e</sub>	<i>Core cross sectional area (m<sup>2</sup>)</i>
A <sub>m</sub>	<i>Magnet cross sectional area (m<sup>2</sup>)</i>
B <sub>r</sub>	<i>Remanence (Tesla (T))</i>
H <sub>c</sub>	<i>Coercivity (Ampere/meter (A/m))</i>
DC	<i>Direct current</i>
kV	<i>Kilovolt</i>
vc	<i>Coil volume (m<sup>3</sup>)</i>
FEM	<i>Finite Element Method</i>
mmf	<i>Magneto motive force (Ampere turn(AT))</i>
IF	<i>Fault current (Ampere (A))</i>
PMFCL	<i>Permanent magnet fault current limiter</i>
RMS	<i>Root mean square</i>
S <sub>c</sub>	<i>Coil cross sectional area (m<sup>2</sup>)</i>
λ	<i>Flux linkage (Weber).</i>
Ø	<i>Magnetic flux (Weber)</i>
μ <sub>m</sub>	<i>Magnet permeability (Wb/(A m))</i>
ω	<i>Angular frequency (Rad/sec)</i>

## 2. Topology and operating principle

The 3.3m square shape model design, as shown in Fig. 1, incorporated four L shaped Neodymium Iron Boron magnets (PM), two grain oriented M4 electrical steel cores placed between the magnets, and copper coils wound around the two cores. The magnets are positioned in the corner between the two cores and they are placed in alternate polarity such that each two opposite magnets are magnetized in the same direction. The model parameters

specifications are as shown in table1. At rated or below the maximum steady state current, the permanent magnets bias the cores and keep them in full saturation state with low inductance and hence the PMFCL behaves like an air-cored reactor. The cores must be saturated during normal operation of the system and driven out of saturation in the case of a fault. Thus the core inherently rushed to a high impedance state that immediately limits the high short circuit current. During normal regime, the saturation must be deep enough so that the maximum expected normal current cannot drive the core out of saturation. The PMFCL should appear invisible to the system under normal operating conditions and should have zero effect on other components in the system. Also, the power losses should be limited to zero in any operation mode. However, once a fault occurs, a fast and high impedance needs to be placed into the system to limit the magnitude of the fault current in a range where relays can distinguish between a fault and normal operation. This allows the protective relays to send the control signal reliably to the circuit breakers to interrupt the fault once the distinction has been made.

Table 1 PMFCL prototype specifications.

Component	Material	Length (m) or Turns	Cross section (m <sup>2</sup> )
Iron core	M <sub>4</sub>	3.3	0.3 x 0.008
Permanent magnet	N <sub>d</sub> -F <sub>e</sub> -B (N52)	1.1	1.1 x 1.1
Coil	Copper	100	1.050 x 0.31

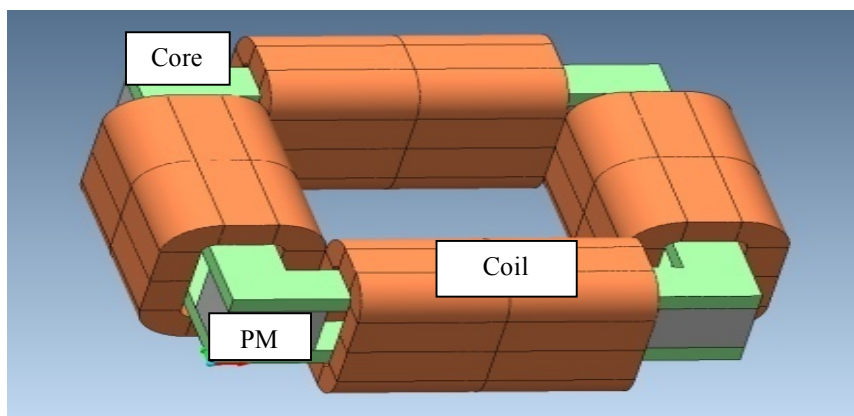


Fig. 1 PMFCL model topology

The approximate core inductance is given by [7]:-

$$L = \frac{\mu A_e N^2}{l_{core}} \quad (1)$$

The value of inductance is dependent greatly on the a.c coils number of turns (N). Upon fault inception, the rising mmf N\* IF desaturates the core and increases the PMFCL inductance considerably.

### 3. Analysis of the Equivalent magnetic circuit in the PMFCL device

The permanent magnet standard equation [7] is expressed as:-

$$H_m l_m = \Phi_m R_m - H_c l_m \quad (2)$$

$$R_m = \frac{l_m}{\mu_m^* A_m} \quad (3)$$

$$\mu_m = \frac{B_r}{H_c} \quad (4)$$

By ignoring the leakage flux, the influence of the angular frequency  $\omega$  in the time varying field, the hysteresis effect and the eddy current loss, the equivalent magnetic circuit of the permanent magnet, the core and the ac coils is as follows [1]: -

$$F_1 + H_1 l + Ni = 0 \quad (5)$$

$$F_2 + H_2 l - Ni = 0 \quad (6)$$

$$F_1 = \Phi_{m1} R_{m1} - H_c l_m \quad (7)$$

$$F_2 = \Phi_{m2} R_{m2} - H_c l_m \quad (8)$$

The magneto motive forces of the four ac coils are added up, equations 5 and 6 can be written as:-

$$2F_1 + H_1 l + 4Ni = 0 \quad (9)$$

$$2F_2 + H_2 l - 4Ni = 0 \quad (10)$$

The cores magneto motive forces becomes,

$$H_1 l = -2(F_1 + 2Ni) \quad (11)$$

$$H_2 l = -2(F_2 - 2Ni) \quad (12)$$

Hence, the magnetic flux in the cores is: -

$$\phi_{e1} = -2(F_1 + 2Ni)/R_{e1} \quad (13)$$

$$\phi_{e2} = -2(F_2 - 2Ni)/R_{e2} \quad (14)$$

The initial design specification of the model was based on the above equations and by considering the core is fully saturated without the contribution of the ac current. However, due to the core material relative permeability, which is varied from unsaturated to saturated state, the analytical approach is not appropriate in calculating the magnetic flux and hence the FEM is used in the model final design stage.

#### 4. FEM Magneto static solver

The magneto static solver was used to calculate the absolute inductance vs current profile. The magnetic field in this particular geometry is dependent on the into-the-page depth; thereby making the use of 2D FEM to be impossible. The 3D FEM is used to model each excitation current using magneto static solver.

The magnetic flux density is given by the following equation.

$$B = \mu_0 (H + M) \quad (15)$$

This modifies the standard equation from which the finite element formulation is derived to the following [8]: -

$$\nabla \times \frac{1}{\mu_0} \nabla A = J + \nabla \times M \quad (16)$$

The model symmetry factor is 4. As the model requires long computation time and lots of memory to obtain the required results, only a quarter of it was analyzed to reduce the solution time. In the quarter of the model, the normal flux boundary condition and the tangential boundary conditions were used.

The PMFCL cores were checked for adequate saturation without the contribution of the ac current. Figure 2 shows a complete model at full saturation. The figure shows the flux density distribution along the cores where the opposite magnets have the same polarity. The magneto static full saturation extent ensures that the device is invisible to the grid in normal case and thereby has no influence on the power system during normal steady state operation.

The inductance calculations using FEM approach could be evaluated using either the energy method or the flux linkage method. In this case where have multiple coils, the flux linkage method is the more appropriate one. In this context the flux linkage  $\lambda$  and the inductance L is defined as following:-

$$\lambda = LI + \lambda_o \quad (17)$$

Where L is the absolute inductance and  $\lambda_o$  corresponds to a constant flux linkage through the coil, caused by the presence of permanent magnet. The flux linkage for each coil in the model was evaluated from the FEM solution by calculating the average flux linkage over the coil cross sectional area  $S_c$ . as following [9].

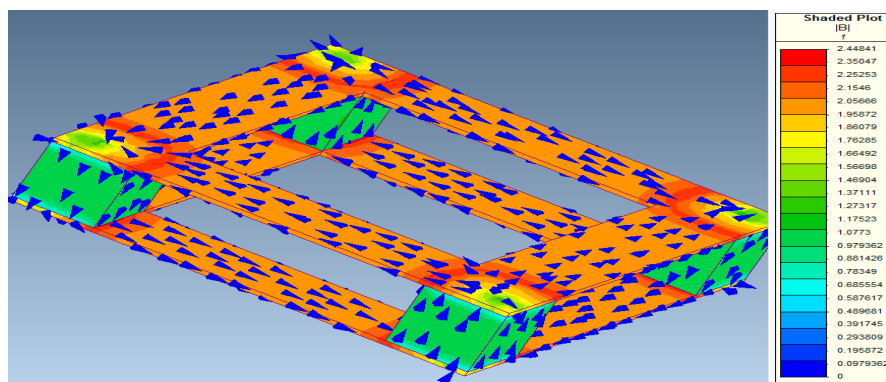


Fig. 2 Flux distribution in the core due to PM excitation only.

$$\lambda = \int_{S_c} \oint_C A \cdot dl \quad (18)$$

In 3D tool the  $\lambda$  for a single coil is calculated as following:-

$$\lambda = \frac{1}{l} \int_{V_c} A \cdot J_o \quad (19)$$

The magneto static solver calculates the flux linkage at each current or a problem from low and gradually to high current values during which the fault current limitation is predicted. Figure 3a showed that one of the cores became out of saturation at RMS current of almost 1500A.

An important method to evaluate the PMFCL device is the inductance-current profile method. The inductance-current profile is illustrated by Fig.3b. As it can be seen from the figure that the inductance increases initially until it reaches its maximum value of 15.75 millihenry, which is corresponding to the maximum RMS current of 1500A. Then the inductance decreases as the core returns to its normal saturation state at high current values. The obtained RMS current is the predicted limited fault current during abnormal condition. The calculated limited transient current will be obtained by the 3D FEM time step solver, which is predicted to be almost equal to  $1500 \cdot \sqrt{2}$  A.

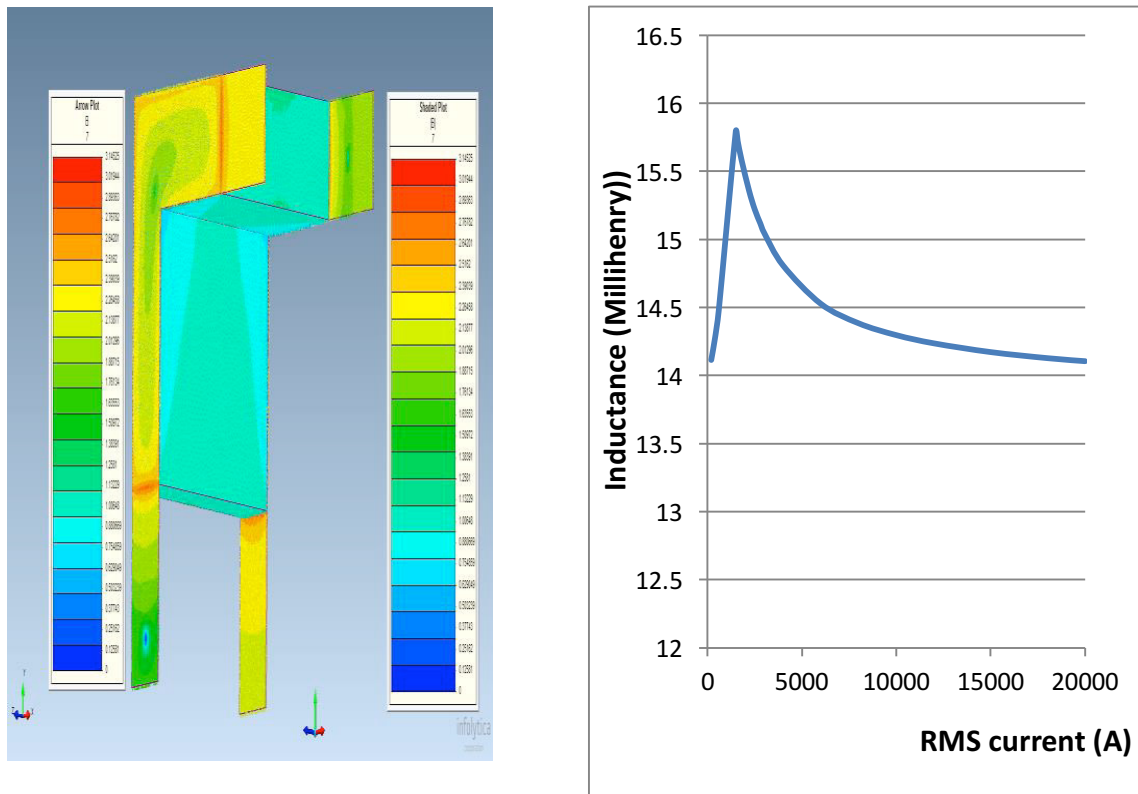


Fig. 3 (a) 3DFEM flux density distributions at predicted fault current; (b) 3D FEM inductance-current profile.

## 5. Dynamic modelling of the PMFCL

The transient FEM solver was used to model the dynamic response of the PMFCL. The PMFCL model and an air-cored of similar specifications were modelled to investigate the performance of the device. The system voltage was 11kV, 50 Hz and the normal load current in R2 was 525A. The model of the PMFCL is coupled to electrical

circuit model as shown in Fig.4 where the performance of the device was assessed. The fault was initiated by closing the switch S1 across the load resistance R2 at the time of 40 Milliseconds.

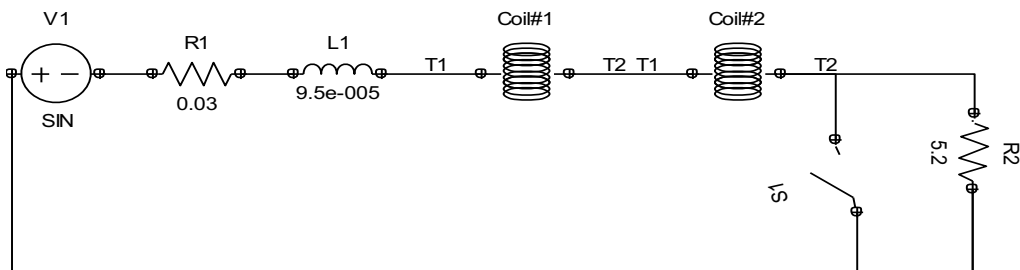


Fig. 4 Transient circuit modeling

Figure 5a indicates that the core lost its saturation in the half cycle of the fault current. When one of the cores completely desaturates due to the high fault current, its inductance increases and the fault current is reduced by the rushed impedance of the device. The Air-cored of similar specifications as the PMFCL device was modelled so as to compare the value of the fault current due to the presence of the device with the normal case, with no device in the circuit. The air-cored fault current was 3050A; however, the PMFCL reduced the fault current to 2130A after sub-transient period, as shown in Fig.5b. Thus, a reduction of 30% has been attained. Hence, the reduction to the fault has been achieved without using DC excitation coils.

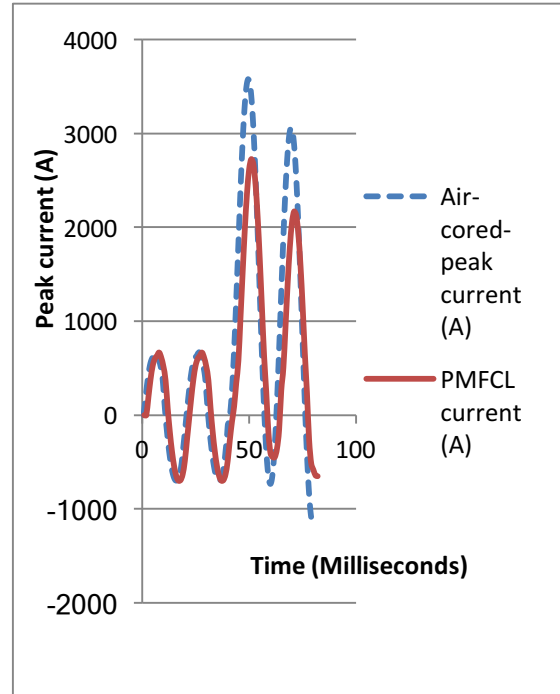
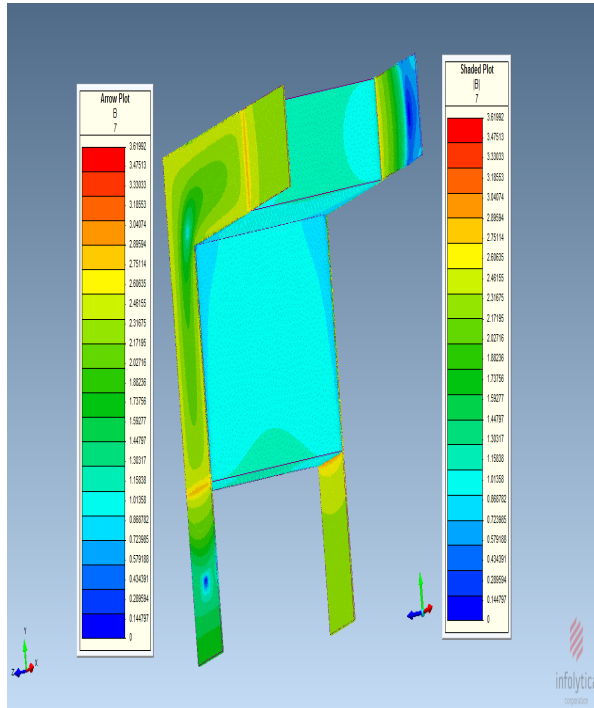




Fig. 5 (a) PMFCL at fault condition. ; (b) PMFCL and air-cored transient current simulation.

## 6. Conclusion

The substation voltage level PMFCL has been designed with M4 electrical steel core and NdFeB permanent magnet in order to find a new technological answer to the problem of higher level of short circuit current. The dry type PMFCL limits the fault current in its first peak cycle. This device requires minimum maintenance and does not need auxiliary power.

The current-inductance profile was obtained by 3D FEM magneto static solver to predict the behavior of the device in the abnormal condition. The calculated RMS current using the time saving inductance-current profile approach was in agreement with the peak transient currents obtained by the 3D FEM time-step solver. The convenient non-linear inductance-current profile is quite important and beneficial in the prediction of the PMFCL performance in fault conditions. The current limitation capability has been calculated in comparison with the air-cored of similar specifications as the PMFCL device and a useful reduction in the fault current has been achieved.

## References

- [1]- Analysis and simulation of the PMFCL based on coupled field circuit modelling methodology, Liang Zou.
- [2] -FARHOODNEA, M., MOHAMED, A. and SHAREEF, H. (2014). A comparative study on the performance of custom power devices for power quality improvement. In: Innovative Smart Grid Technologies - Asia (ISGT Asia), 2014 IEEE, 153-157.
- [3] -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.
- [4] -SANTRA, T., et al. (2009). Analysis of passive magnetic fault current limiter using wavelet transforms. In: Power Systems, 2009. ICPS '09. Internatio
- [5] 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.
- [6] MORICONI, F., et al. (2010). Modelling and test validation of a 15kV 24MVA superconducting fault current limiter. In: Transmission and Distribution Conference and Exposition, 2010 IEEE PES, 1-6.
- [7]- Liu, H., Li, Q., Zou, L., Zhang, L., & Siew, W. S. (2012). Comparative study on the static and dynamic characteristics of four types of PMFCLs for large capacity applications. International Journal of Electrical Power & Energy Systems, 34(1), 47-56.
- [8] -Design and Construction of a Magnetic Fault Current Limiter J-L. Rasolonjanahary, J.P. Sturgess\*, E.F.H. Chong, A.E. Baker, C.L. Sasse].
- [9]- Magnet user manual by Infolytica , [www.infolytica.com](http://www.infolytica.com)