Taj Al-Ma'rifa Journal مجلة تاج المعرفة
ISSN : 3104-8846, ISSN-L: 3104-8838

Performance Evaluation of Permanent Magnet Fault Current Limiter Compared with Current Limiting Reactor

* Asmaiel Ramadaan
Lecturers - The Higher Institute of Science and Technology, Tarhuna, Libya
asmailramadan@gmail.com

[2] Aimen Matoug
Lecturers - The Higher Institute of Science and Technology, Tarhuna, Libya
aymnaldwkaly896@gmail.com

[3] Khaled Elshibani
Lecturers - The Higher Institute of Science and Technology, Tarhuna, Libya
Kalshebane@gmail.com

[4] Sarah AlzarQani
Assistant Lecturer - The Higher Institute of Science and Technology, Tarhuna, Libya
frhhbefghv@gmail.com

*Corresponding Author: * Asmaiel Ramadaan

Keyword

Permanent Magnetic fault current limiter; FEM simulation; Limiting reactor.

Abstract

The electrical grid is close to exceeding safe levels of short-circuit current, which poses a serious threat to the stability, security, and continuity of the power grid. Hence, reducing the fault current levels has become an unavoidable task in the ongoing development of modern power infrastructure. This paper presented a comparative analysis of the fault current mitigation performance of a Permanent magnet fault current limiter (PMFCL) device and current limiting reactor. The modelling scheme has been performed on 1.2kV system voltage, which is primarily used for the industrial applications and mainly for the three phase 34.5/1.2 kV distribution transformers used in oil field production systems in Libya. The two methods of fault current moderation were modelled and compared by means of 3D FEM modelling tool. FEM modelling revealed fruitful results regarding the limiting capability of the permanent magnet fault current limiter versus current limiting reactor.

Received : 01/01/2026 Accepted : 15/03/2026

DOI: https://doi.org/10.64943/jkc.2026.040123

تقييم أداء محدِّد تيار القصر بالمغناطيس الدائم مقارنةً بمفاعل تحديد التيار

* إسماعيل رمضان
محاضر - المعهد العالي للعلوم والتتقنية ، ترهونة، ليبيا
asmailramadan@gmail.com

2 أيمن معتوق
محاضر - المعهد العالي للعلوم والتتقنية ، ترهونة، ليبيا
aymnaldwkaly896@gmail.com

3 خالد الشيباني
محاضر - المعهد العالي للعلوم والتتقنية ، ترهونة، ليبيا
Kalshebane@gmail.com

4 سارة الزرقاني
مساعد محاضر - المعهد العالي للعلوم والتتقنية ، ترهونة، ليبيا
frhhbefghv@gmail.com

*الباحث المرسل: * إسماعيل رمضان

الكلمة المفتاحية: محدد تيار الخطأ المغناطيسي الدائم؛ محاكاة FEM؛ المفاعل المحدد.

الملخص

تقترب الشبكة الكهربائية من تجاوز المستويات الآمنة لتيار القصر، مما يشكّل تهديدًا خطيرًا لاستقرار وأمن واستمرارية منظومة القدرة الكهربائية. لذلك، أصبح تقليل مستويات تيار العطل مهمة لا مفرّ منها في التطوير المستمر للبنية التحتية الحديثة للطاقة. قدّمت هذه الورقة تحليلًا مقارنًا لأداء الحد من تيار العطل لكلٍ من جهاز محدِّد تيار القصر بالمغناطيس الدائم (PMFCL) ومفاعل تحديد التيار. تم تنفيذ مخطط النمذجة على نظام جهد مقداره 1.2 كيلوفولت، والذي يُستخدم بشكل أساسي في التطبيقات الصناعية، ولا سيما في محولات التوزيع ثلاثية الطور بجهد 1.2/34.5 كيلوفولت المستخدمة في أنظمة إنتاج حقول النفط في ليبيا. وقد جرى نمذجة طريقتي الحد من تيار العطل ومقارنتهما باستخدام أداة النمذجة ثلاثية الأبعاد بطريقة العناصر المحدودة (FEM). وأظهرت نمذجة العناصر المحدودة نتائج مثمرة فيما يتعلق بقدرة محدِّد تيار القصر بالمغناطيس الدائم على تحديد تيار العطل مقارنةً بمفاعل تحديد التيار.

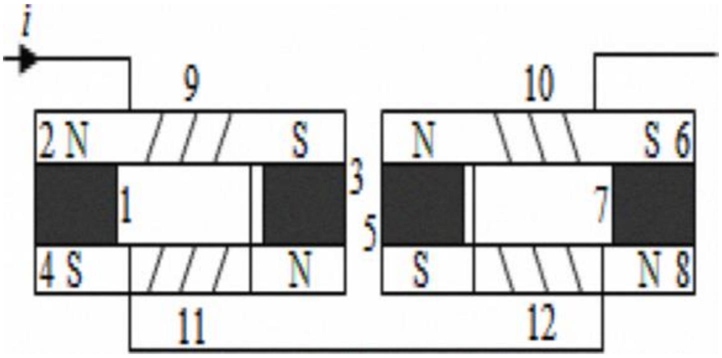
تاريخ الإستقبال: 2026/01/01 تاريخ القبول: 2026/03/15
DOI: https://doi.org/10.64943/jkc.2026.040123

INTRODUCTION

A short circuit is a severe problem in high-voltage power networks. In the event of a fault, the abnormal current surpasses the regular load current by more than eight times. High fault circuit current initiates a rapid rise in mechanical and thermal stress on all electrical components and devices.[1]. By reducing fault currents, large networks can be interconnected without the need for new oversized equipment, improving the system transient stability and reducing the costs of the equipment [2]. Hence, mitigating short-circuit current should be a top priority, as the electrical grid is approaching its maximum safe limits [3]. With the current innovations in magnetic materials and geometry design study, permanent magnet fault current limiter (PMFCL) has drawn significant interest by many researchers and scientists in recent times [4]-[8]. In regular power system operation, the device offers minimal impedance to the grid and during the fault state the scheme offers an additional impedance that mitigates the high fault current [9]-[12]. The work presented in this paper is to study and investigate the performance of PMFCL versus the traditional current limiting reactors by means of 3D Magnet FEM simulation tool [13]. The design simulation has been performed on 1.2 kV system voltage, which is primarily used for the industrial applications and mainly for the three phase 34.5/1.2 kV distribution transformers. The 1.2 kV level represents the secondary (low voltage) side of the 34.5/1.2 kV distribution transformer used in oil field production systems in Libya. This voltage level is used to supply power for oil and gas extraction operations [14]. While the 1.2 kV side serves as the secondary of the distribution transformer, faults on this side can propagate back to the primary 34.5 kV medium-voltage system due to transformer coupling. This study aims to evaluate the performance of fault current limiters in comparison with conventional current-limiting reactors. In this analysis, the magneto-static flux density was determined systematically from the model magnetic circuit equations and compared with the 3-D magneto static computed value to ensure the model is factual. Then, the steady state 3-D current/ inductance curve is plotted to study the inductance steady state behavior with increased load current. Finally, this work will deal with the transient condition in 3-D modelling.

The PMFCL working Principle

The device is designed to substitute for the existing current limiting reactor and thereby is inserted between the power source and the circuit breaker. The PMFCL consists of the magnets, limiter coils and the iron-cores 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 identical magnetic devices are connected in series arrangement and their magnetomotive forces act in opposite in direction to limit the positive and negative half-cycles currents respectively [6,7]. During standard operation, the magnetic field produced by the AC coils is not strong enough to force the iron core out of saturation, so the machine acts like the existing in use current limiting reactor but with a minimal inductance. While during transient conditions, one of the cores exits saturation and rapidly flashes to a high impedance state, thereby instantly limiting the high fault current [12].

The model design topology

The model geometry is 3D axis symmetric. It comprises of four neodymium magnets with L-shaped configuration, two cores of M4 electrical steel and AC cupper coils. The model schematic diagram is as shown in figure 2. The 1.2 KV PMFCL model specifications parameters are specified in Table1

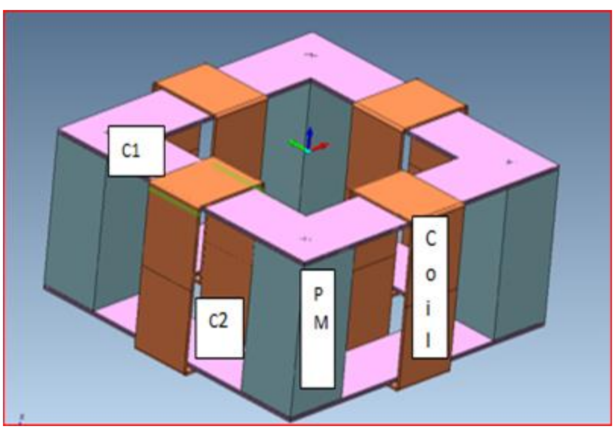


Figure 2: The model proposed design.

Two M4 cores (C1 and C2) have four L-shaped magnets positioned between them so that each pair of opposite magnets is aligned with the same magnetization direction. The model specifications are as shown in table1.

Table 1: The model specifications

Component	Material	Length or number of turns	Area
Core	Silicon electrical Steel	200 cm	200 x 15 cm^2
Magnet	Nd-Fe-B (N52)	30 cm	30* 15= 450 cm^2
Coil	Copper	40 turns	Ø3

The Limiter Core Magneto Static Field

An important task in the design of the PMFCL devices is the systematic approach. The magneto static flux density in the iron-core was determined by means of PMFCL equivalent magnetic circuit. The circuit magnetic field is supplied by the permanent magnet, which is capable enough to consistently saturate the cores without the contribution of the AC supply. The leakage flux in the circuit was not considered due to the consideration of the saturation depth ratio of the iron core [12]. The subscripts e and m denote for the core and magnet respectively. The notation H refers to magnetic field intensity. The coercivity H_c is an important factor when selecting the permanent magnet. The coercivity of the Neodymium Iron Boron, $H_c = 8.68 \times 10^5$ A/m . The flux density in Tesla and magnetic flux in Weber are represented 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. $\mu_m = 1.4 \times 10^{-6}\, H/m$ and $\mu_s = 2.1 \times 10^{-5}\, H/m$

The common permanent magnet equation is as follows.

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

At zero AC current, the summation of the magnetomotive forces of the core and the magnet (ni) is zero.

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

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

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

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

Equation 1.5 was used to determine the magnetic flux density within the core without the contribution of the AC supply. By substituting the values in the equation, the flux density in the core was 2.04 T. The core is considered to have adequate saturation when the flux density is 2 tesla or more. However, the model still needs to be verified by FEM simulation tool to ensure the adequacy of flux density in the core. The magnetostatic flux density in the centre of the core was attained by FEM as shown in Figure 3. The FEM simulation indicated that the core flux density in the centre of the core reached the required limit of saturation. The flux density in the centre of the ore is 2.02 Tesla.

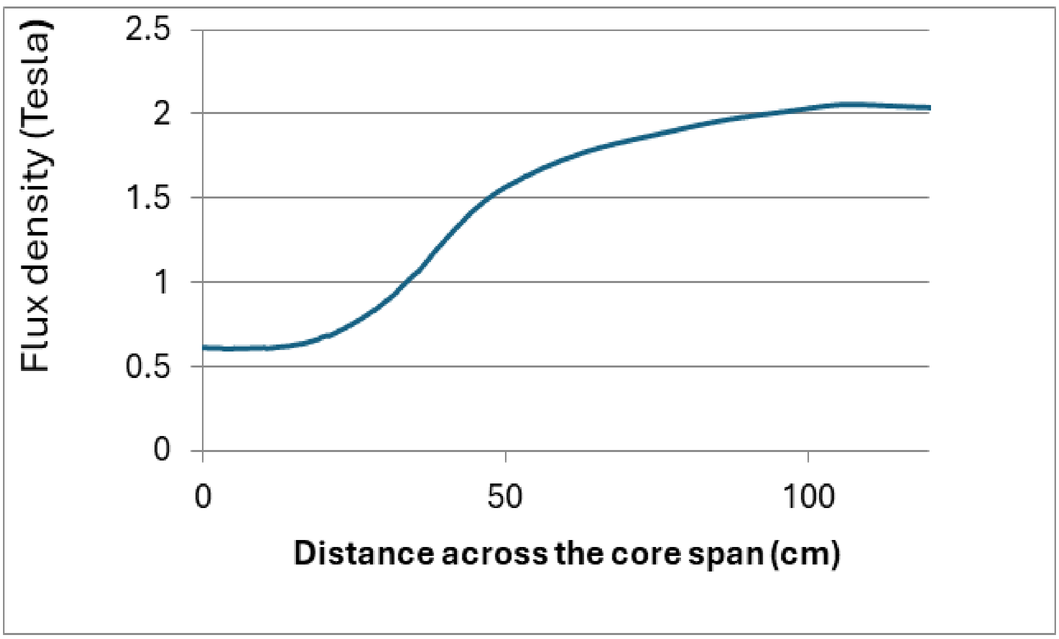


Figure 3: FEM core flux density.

Achieving full saturation for the core ensures that the machine remains invisible to the grid in normal case and thereby it does not affect the power system stability in normal steady-state operation

Steady State Modelling

The normal state working operation modelling aimed to explore the features of the PMFCL machine and assesses the potential for fault current control at which the unit is energized when an abnormal condition exists. The current- inductance curve was obtained by 3D (FEM) magneto static solver. Figure 4 shows the variation of inductance with increased current at steady state condition in 3-D modelling. The machine current-inductance curve shows that the steady state inductance increases initially to its highest value to limit the current and then sharply decreases and finally becomes steady as the current increases. The highest inductance of 0.0032 H occurs at a maximum steady state current of 700A. The effective current measured in steady-state condition modelling represents the expected fault current constraint during abnormal situations. The traditional current limiting reactor has a single value of 0.002 H, which is installed in the system all the time and contributes to the consistent system voltage drop and energy losses.

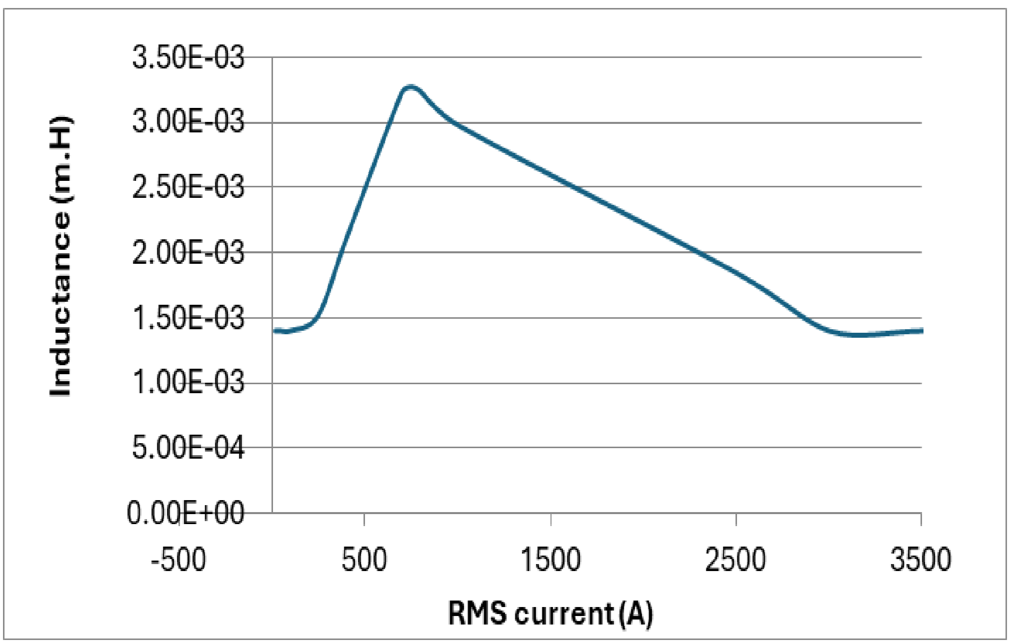


Figure 4: FEM inductance-current curve

PMFCL Transient Condition Modelling

In 3-D transient modelling, as the model was large only one-quarter of the unit was simulated. In one-fourth of the model, the normal flux boundary condition and the tangential boundary conditions were used. The circuit peak single-phase voltage for the quarter of the model was 245V.

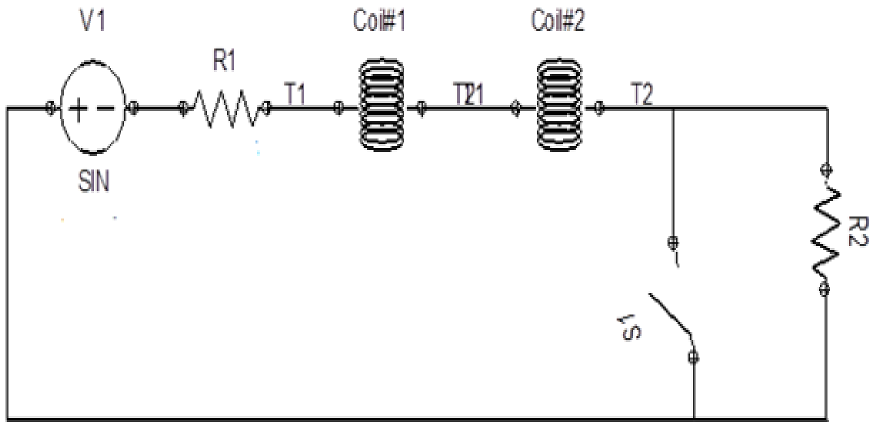


Figure 5: Transient circuit modelling

The source internal resistance for one-fourth of the model was 0.015 ohm, the load resistance was 1.25 ohms. The source voltage V1 was 245V, which was worked out as [1200(1.414)/ 1.731(4)]. Before the fault occurred, the steady state current was 200 A. The fault occurred at 0.04 seconds. The current limiting reactor of the matching size as the PMFCL was simulated to confirm the value of the fault current with and without the device. The actual maximum system fault current was 16.3 kA, which was obviously found by dividing the system input voltage by the source resistance (R1). The traditional existing in use current limiting reactor reduced the transient current to 1600A, however, the PMFCL device eased the fault current to 980A as it can be seen from figure 6. The high fault current caused one of the cores to desaturate and consequently its inductance rapidly increased. Hence, the fault current was reduced by the flashed impedance of the designed unit**.**

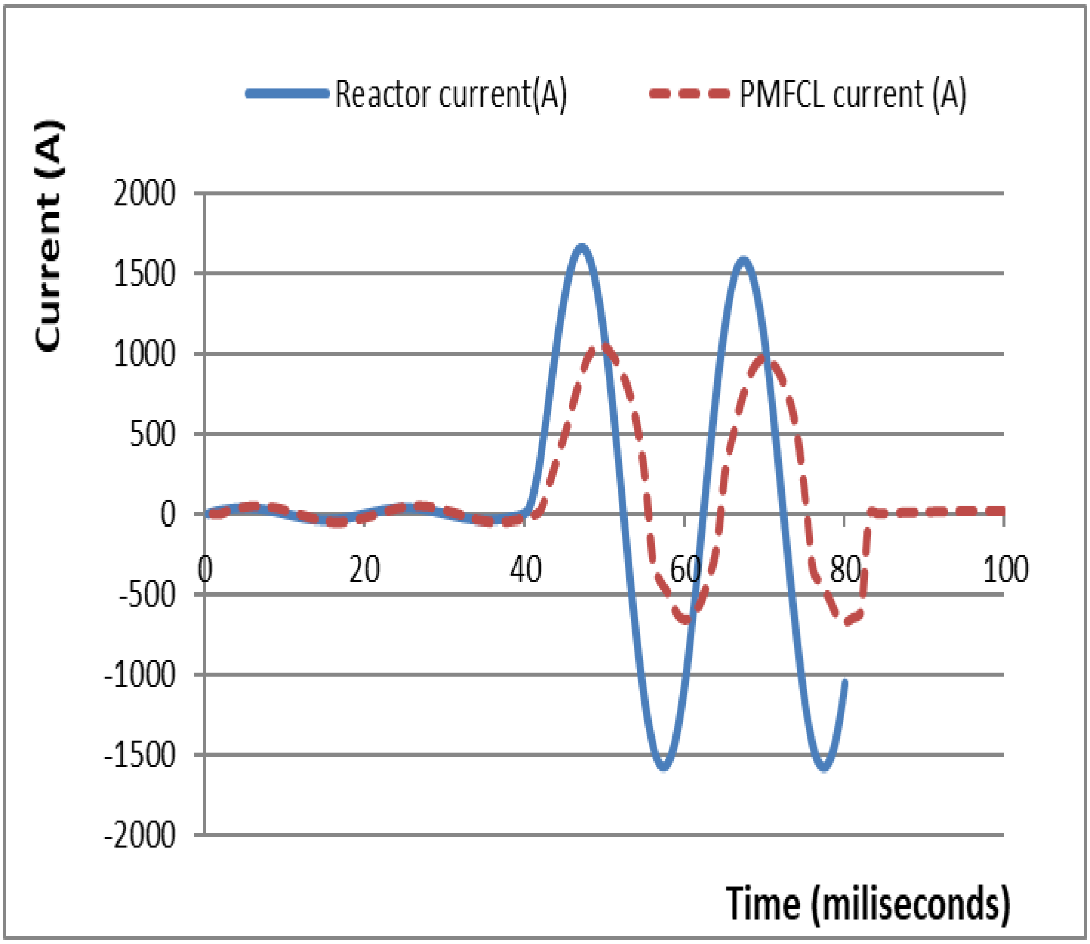


Figure 6: PMFCL and current limiting reactor transient current

Figure 7 shows the FEM simulation in a faulted condition. The figure shows a finite element analysis (FEA) generated by Infolytica Magnet, which is the simulation tool used in this work [13].

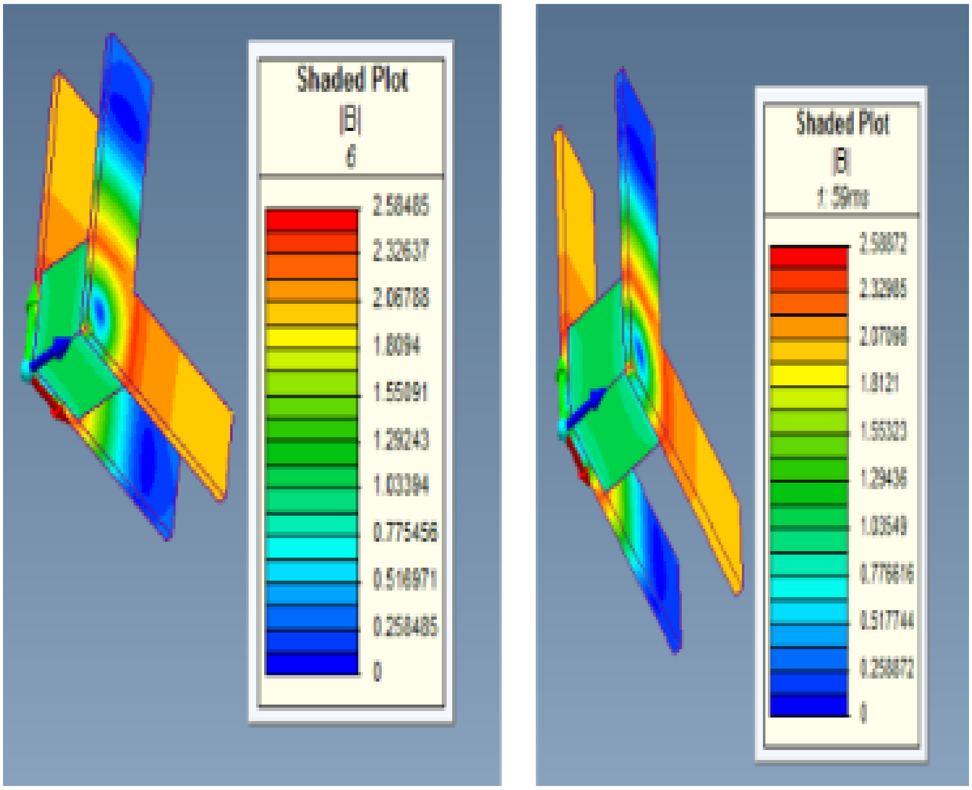


Figure 7: The unit energization at the moment of the fault occurrence

There are two legends on either side of figure 7. The arrow plot is shown on the left legend, and the shaded plot appears on the right. Both legends show a range of values for magnetic flux density B (in Tesla), at various regions of the device iron core. The magnitude of the flux density is color-coded from blue (low) to red (high). The figure clearly shows that a portion of the core becomes completely desaturated at the moment the fault occurs. This desaturation extent leads to a sudden increase in impedance, which effectively limits the fault current. The activation of the PMFCL during the first positive half-cycle results in a rapid suppression of the fault current, thereby protecting the power system equipment from potential damage.

Conclusion and future work

The model presented in this work is a superior power system unit used to moderate and reduce the extreme short-circuit currents to much more adaptable levels for the existing available switchgear equipment like circuit breakers (CBs) and power transformers. While sufficient fault current is necessary for effective fault detection and protection operation, excessive fault current does not improve system stability and can, in fact, threaten the safety and reliability of the grid. Reducing fault current enabling faster, more reliable fault clearing and reducing voltage severity. Hence**, it supports the power system's ability to remain stable after faults.**

The device operates independently without the need for any external power source. The main source of excitation is the neodymium magnet, which provides an acceptable magnetic field to saturate the core in the normal steady state operation.

The time-efficient inductance versus current curve for the simulated model was acquired to predict the limiter's behavior under fault conditions. The maximum current calculated using FEM inductance-current curve scheme aligned with the highest surge current obtained by the extensive calculation FEM time-based solver. The FEM inductance-current curve is obtained in much less simulation time compared with the transient simulation. The inductance current curve shows the highest effective current of 700A. This value is verified with the same simulation tool using the long-time transient analysis solver. The transient simulation in figure 6 shows the maximum fault current of 980A peak. Thus, the current-inductance curve is the viable time efficient tool used to estimate the maximum transient current at the fault occurrence. The designed unit exhibited exceptionally low inclusion impedance during standard operation and a magnificent fault impedance to deliberately enhance the fault current restriction capability at the fault occurrence. The current-limiting reactor of equal length to the proposed unit restricted the fault current to 1600 A. In comparison, the candidate unit reduced the fault current to 980 A, achieving a reduction of nearly 39%. Unlike the traditional current-limiting reactor, which remains permanently connected to the system and causes continuous voltage drop and power losses, the emerging unit offers a more efficient and responsive solution.

The PMFCL can be installed on the low-voltage side of industrial distribution transformers, typically used in Libya to supply power to oil plant for oil production. It protects the 1.2 kV low voltage side from excessive fault currents. Additionally, through transformer coupling, the limiter device also helps limit the impact of fault currents on the 34.5 kV primary side, thereby enhancing protection system across the distribution network.

The PMFCLs need to be coordinated with the protective relays to confirm the right operation for the switchgear equipment and to evade any unwanted system outages. In the present power network, the PMFCL should substitute the traditional current limiting reactor to improve the power grid working condition. The new unit provides a slump in the fault current and has a great benefit on the power system network as the switchgear equipment will work below the rated capacity. Furthermore, the fault current can easily be controlled without spreading to broader zones and causes more power outages and production downtime. The fault current reduction is crucial for maintaining the operational integrity, safety, and reliability of the power grid while also managing costs effectively.

The unit is commonly referred to as an install and ignore machine that confines the fault current in its first half cycle and requires trivial maintenance. It is guaranteed to protect and extend the life expectancy of power grid equipment such as circuit breakers and power transformers.

The future work will involve carrying out a cost-benefit analysis to assess the manufacturing and installation costs relative to the potential long-term economic advantages, such as increased equipment lifespan and reduced maintenance costs. Moreover, several limitations require further consideration, including the scalability of the design and the challenges involved in integrating the technology into existing power system infrastructure. Addressing these issues through further research will be crucial for facilitating extensive adoption and enhancing the overall effectiveness of the device in the existing power system network.

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