

ASOG-SP-Based Design Optimization of a Permanent-Magnet-Biased Fault Current Limiter Using Nonlinear FEM and Experimental Validation

Tirtha Sankar Daphadar^{1*}, Tapan Santra², Amalendu Bikash Choudhury³

¹Department of Electrical Engineering, College of Engineering & Management, Kolaghat, West Bengal-721171, India,

*tirthadafadar@cemk.ac.in

²Department of Electrical Engineering, Alipurduar Government Engineering and Management College, Alipurduar, West Bengal, India, tapan.santra@kgec.edu.in

³Department of Electrical Engineering, Indian Institute of Engineering Science and Technology, Shibpur, West Bengal, India, ab_choudhury@yahoo.com

Abstract: This paper presents the design and optimization of a single-phase permanent-magnet-biased fault current limiter (PMFCL) using nonlinear finite-element modelling (FEM), an Adaptive Single-Objective Gradient Single-Point (ASOG-SP) optimization method, and experimental validation. The proposed PMFCL employs permanent-magnet biasing to establish a controlled magnetic operating point during normal operation and increase the effective impedance during fault conditions. The initial design has a core area of 180 mm², magnetic-path length of 68 mm, air gap of 1.5 mm, permanent-magnet thickness of 2 mm, and 200 winding turns. Following ASOG-SP optimization, these parameters are adjusted to 195 mm², 65 mm, 1.2 mm, 3 mm, and 220 turns, respectively. Under the specified simulation conditions, the peak fault current decreases from 1.72 A to 1.27 A, corresponding to a 26.2% reduction. Experimental testing further demonstrates a reduction in peak fault current from 5.5 A without the PMFCL to 3.1 A with the optimized device, corresponding to a 43.6% reduction. The optimized design is also evaluated in terms of magnetic flux distribution, voltage characteristics, and harmonic behavior. The results demonstrate that coordinated optimization of magnetic geometry and winding turns enhances fault-current-limiting performance while maintaining suitable normal-state operation. The proposed nonlinear FEM-based framework provides a practical approach for PMFCL design, optimization, and experimental assessment.

Keywords: Permanent-magnet-biased fault current limiter; Nonlinear FEM; Magnetic saturation; Fault-current limitation; ASOG-SP optimization

1. INTRODUCTION

The continuous growth of electrical demand, expansion of interconnected power networks, increasing penetration of distributed generation, and integration of additional generation and load have contributed to increasing prospective short-circuit current levels in modern power systems. When the available fault current approaches or exceeds the interrupting capability of existing circuit breakers and other protection equipment, utilities may need to consider higher-rated switchgear, network reconfiguration, increased system impedance, or dedicated fault-current-limiting devices. Fault current limiters (FCLs) provide an alternative or complementary approach by reducing the magnitude of short-circuit current while maintaining comparatively low impedance during normal operation [1], [2].



FCL technologies include superconducting, inductive, resistive, solid-state, and hybrid configurations. Superconducting fault current limiters can provide substantial fault-current reduction, but their implementation may require superconducting materials, cryogenic systems, and associated infrastructure [3]. Non-superconducting magnetic FCLs provide an alternative approach by exploiting the nonlinear magnetization characteristics of ferromagnetic cores to obtain a substantial change in impedance between normal and fault conditions [4]- [6].

Among non-superconducting magnetic technologies, permanent-magnet-biased fault current limiters (PMFCLs) are attractive because a permanent magnet can establish the required magnetic bias without a continuously energized dc excitation winding. A permanent-magnet saturated-core FCL can therefore provide a passive operating principle while avoiding continuous excitation losses associated with conventional dc-biased saturated-core configurations [7]- [8]. Linden et al. investigated the design optimization of a permanent-magnet saturated-core fault current limiter, while Eladawy and Metwally investigated compact permanent-magnet-biased FCL configurations and their electromagnetic and transient characteristics [9].

The operating principle of a PMFCL is based on controlling the magnetic operating point of the ferromagnetic core. During normal operation, the permanent-magnet bias drives the core toward saturation, resulting in relatively low incremental permeability and consequently low inductive impedance. During a short-circuit fault, the alternating magnetomotive force generated by the line winding opposes the permanent-magnet bias and shifts the magnetic operating point toward a higher-permeability region. The resulting increase in effective inductance produces a higher series impedance and limits the fault current [10], [11]. The effectiveness of a PMFCL therefore depends on establishing an appropriate balance between the normal-state saturated condition and the desired magnetic response during a fault.

The magnetic operating point is strongly influenced by the physical and electromagnetic parameters of the limiter. Core cross-sectional area, magnetic-path length, air-gap length, permanent-magnet dimensions, magnet position, magnetic properties, and winding turns can significantly affect flux distribution, saturation level, normal-state voltage drop, and fault-current limitation. Previous PMFCL investigations have demonstrated that appropriate selection of core and permanent-magnet parameters is important for obtaining the required fault-limiting characteristics while maintaining acceptable normal-state performance [12]- [15]. The performance of PMFCL structures is therefore closely associated with their electromagnetic geometry and magnetic operating point.

A further challenge arises from the nonlinear magnetic behavior of the core. The permeability of a ferromagnetic material varies substantially with magnetic-field intensity, and consequently the inductance of a PMFCL cannot generally be represented by a single constant value over the complete operating range. Hysteresis, saturation, and transient magnetic-field redistribution can influence the current and voltage waveforms during prefault, fault, and post-fault conditions. Previous passive magnetic FCL studies have demonstrated the importance of hysteresis modelling for representing the transient magnetic response of saturated-core devices [16]. The Jiles–Atherton model has also been investigated and validated for representing static hysteresis characteristics of magnetic materials [17].

Finite-element analysis (FEA) is consequently an important tool for PMFCL design because it can represent the spatial distribution of magnetic flux density, local saturation, leakage flux, air-gap effects, and interaction between the permanent-magnet field and the ac winding field. Nonlinear FEM also enables the influence of geometric parameters to be investigated before prototype fabrication. Previous studies have demonstrated the usefulness of electromagnetic modelling and optimization for determining suitable PMFCL configurations [18]- [21]. However, incorporating nonlinear FEM into an optimization loop can become computationally demanding because each candidate design may require a new electromagnetic solution and subsequent performance evaluation.

The design of a PMFCL is therefore a coupled optimization problem rather than an independent selection of individual parameters. Increasing the core cross-sectional area can reduce local saturation but may increase the volume and mass of magnetic material. Increasing the number of winding turns can enhance the inductive response but may also increase the normal-state voltage drop and copper requirement. Increasing permanent-magnet dimensions

can strengthen the bias field but can also modify the magnetic operating point and affect the transition between normal and fault conditions. Similarly, the air gap influences magnetic reluctance, flux density, and the operating point. These interactions create competing design requirements that need to be considered simultaneously [22]- [24]. Optimization techniques can provide a systematic approach for resolving these coupled design requirements. Conventional population-based optimization methods can require the evaluation of numerous candidate solutions, which may become computationally expensive when nonlinear FEM is used for every candidate. Biogeography-based optimization, for example, is a population-based evolutionary optimization method introduced by Simon [25]. For nonlinear electromagnetic design problems, reducing the number of FEM evaluations can be important because each evaluation involves the solution of a computationally intensive field problem.

To address this computational issue, this study employs an Adaptive Single-Objective Gradient Single-Point (ASOG-SP) optimization strategy based on a single evolving feasible design point. At each iteration, local numerical sensitivity information is used to determine the search direction, while an adaptive step size controls the magnitude of the design update. A trial design is evaluated using the nonlinear electromagnetic model, and the search is continued until the prescribed convergence condition is satisfied. Unlike population-based approaches, the proposed procedure does not maintain multiple candidate solutions simultaneously. The computational benefit of this strategy is assessed through the resulting optimization process and FEM evaluations rather than through an unsupported claim of universal superiority over other optimization algorithms. Nonlinear magnetic behavior can also affect the waveform characteristics of magnetic FCLs. However, harmonic performance should be quantified using appropriate FFT or THD measures under clearly specified operating conditions. Therefore, harmonic characteristics in the present study are treated as a supporting performance parameter rather than the primary contribution. The principal assessment focuses on fault-current limitation, magnetic flux distribution, normal-state voltage behavior, and the influence of the principal geometric and winding parameters.

Accordingly, this paper develops a nonlinear FEM-based design and optimization framework for a permanent-magnet-biased fault current limiter using the Adaptive Single-Objective Gradient Single-Point (ASOG-SP) method. The primary objective is to minimize the peak fault current subject to prescribed design and electromagnetic constraints. A parametric sensitivity analysis is first employed to identify the principal design variables, followed by ASOG-SP optimization of the selected variables. The optimized design is subsequently evaluated using nonlinear FEM and MATLAB/Simulink, followed by experimental testing of a laboratory prototype. The main contribution of this work is the formulation and application of the ASOG-SP single-point optimization procedure to the PMFCL design problem and its validation through both numerical and experimental results.

The main contributions of this work are as follows

1. A permanent-magnet-biased magnetic fault current limiter is developed to obtain low effective impedance during normal operation and increased impedance during fault conditions.
2. A nonlinear FEM model is established to represent the magnetic-field distribution, core saturation, permanent-magnet bias, and transient fault response.
3. The effects of the principal geometric and electromagnetic parameters on fault-current limitation and normal-state performance are systematically quantified.
4. ASOG-SP optimization: An adaptive single-objective gradient single-point optimization strategy is developed to minimize peak fault current subject to prescribed electromagnetic and design constraints.
5. Harmonic performance analysis: The optimized PMFCL is assessed in both the time and frequency domains to quantify waveform distortion and the principal harmonic components under normal and fault conditions.
6. Integrated design assessment: Electromagnetic performance, fault-current limitation, normal-state operation, and harmonic behavior are considered within a common design and evaluation framework.

2. Mathematical Modelling

The proposed permanent-magnet-biased fault current limiter (PMFCL) is mathematically modelled by relating the magnetic geometry, permanent-magnet bias, nonlinear core characteristics, electrical response, fault current, harmonic distortion, and optimization variables. Because the PMFCL operates through a transition between saturated and less-saturated magnetic states, a nonlinear electromagnetic model is adopted.

The PMFCL consists of an iron core, an AC winding, and NdFeB permanent magnets arranged to provide DC magnetic bias to Core-1 and Core-2, as shown in Fig. 1. Under normal operation, the DC bias flux Φ_{dc} drives the cores into deep saturation, reducing the effective permeability μ , inductance L_{ss} , and steady-state impedance $Z_{ss} \approx \omega L_{ss}$.

During a fault, the large AC fault current produces an additional flux Φ_{ac} , giving the total flux as

$$\Phi_{total} = \Phi_{dc} + \Phi_{ac}. \quad (1)$$

The opposing component of Φ_{ac} temporarily drives the core toward the unsaturated region, increasing the effective permeability μ_{lim} and transient inductance L_{lim} . The complete model incorporates the magnetic circuit, permanent-magnet bias, nonlinear core behaviour, electrical circuit, fault-current response, harmonic analysis, and constrained optimization. The design parameters used for the single-phase PMFCL prototype are listed in Table 1.

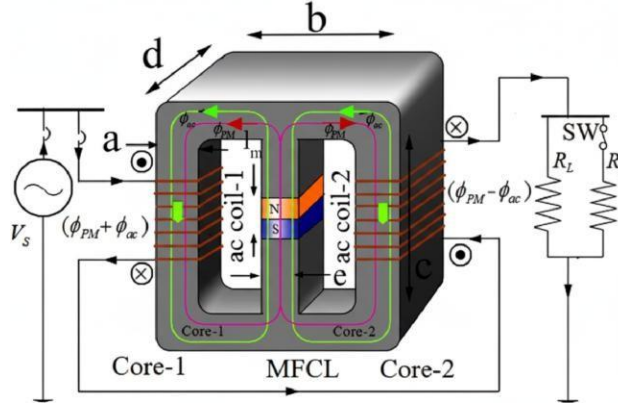


Fig. 1. Schematic model circuit of the PMFCL.

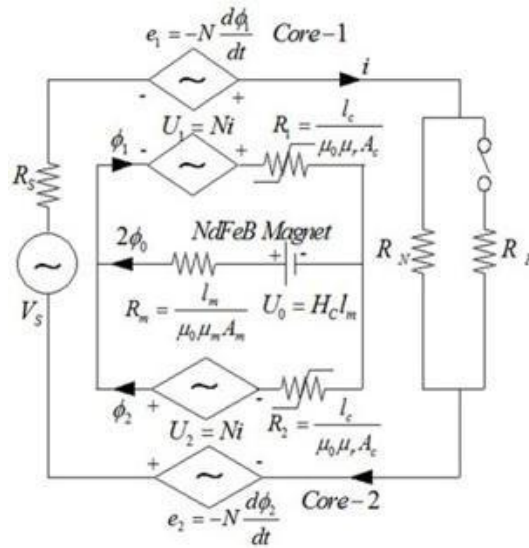


Fig. 2. Magnetic equivalent circuit of the PMFCL.

Table 1. Design Data for Steel-Core Single-Phase MFCL

Specification	Steel core
Dimension of the core	a = 7.5mm; b = 24 mm; d= 20mm; c = 48 mm
Dimensions of the magnet	e =15 mm; $l_m = 5mm$
Parameters of the Permanent Magnet	$H_c = 0.8 * 10^6$ A/m; $\mu_{ru} = 1.4 * 10^{-6}H/m$; Material NdFeB
Parameters of the core	$\mu_s = 5$; $\mu_u = 5000$; $B_k = 1.3$
Other Parameters	No. of turns $N = 200$ per limb; $V_s = 15V$ r.m.s; $f = 50Hz(ac)$; $R_L = 11\Omega$; $R_f = 1.7\Omega$

2.1 Magnetic Circuit

The magnetic circuit of the PMFCL consists of the ferromagnetic core, permanent-magnet sections, air gaps, and excitation winding as shown in Fig.2. The magnetic flux is established by the combined action of the permanent-magnet magnetomotive force (MMF) and the alternating MMF produced by the winding. The total magnetic MMF can therefore be expressed as

$$F_{tot}(t) = F_{PM} + F_{ac}(t) \quad (2)$$

where F_{PM} is the MMF produced by the permanent magnet and F_{ac} is the winding MMF.

For an N -turn winding carrying current $i(t)$,

$$F_{ac}(t) = Ni(t) \quad (3)$$

and the permanent-magnet MMF can approximately be represented as

$$F_{PM} = H_c l_m \quad (4)$$

where H_c is the coercive field of the permanent magnet and l_m is its effective magnet length along the magnetization direction.

The corresponding magnetic flux is

$$\Phi(t) = \frac{F_{tot}(t)}{R_{tot}} \quad (5)$$

where R_{tot} is the total reluctance of the magnetic path.

For a magnetic region j ,

$$R_j = \frac{l_j}{\mu_j A_j} \quad (6)$$

where l_j , A_j , and μ_j denote the effective magnetic-path length, cross-sectional area, and permeability, respectively.

Hence,

$$R_{tot} = \sum_j \frac{l_j}{\mu_j A_j} \quad (7)$$

For the air-gap region,

$$R_g = \frac{g}{\mu_0 A_g} \quad (8)$$

where g is the effective air-gap length, A_g is the effective gap area, and μ_0 is the permeability of free space.

The magnetic flux density is

$$B(t) = \frac{\Phi(t)}{A_c} \quad (9)$$

where A_c is the effective core cross-sectional area.

The magnetic-field intensity can be expressed as

$$H(t) = \frac{F_{tot}(t)}{l_{eff}} \quad (10)$$

where l_{eff} is the effective magnetic-path length.

Because the permeability of the ferromagnetic core varies with magnetic-field intensity, the magnetic reluctance is nonlinear. Therefore, (5)–(10) are used to establish the physical relationships and provide initial design estimates, whereas the final field solution is obtained from nonlinear FEM.

The magnetic circuit demonstrates the fundamental PMFCL operating mechanism. During normal operation, the permanent-magnet MMF establishes a bias point close to the saturated region. During a fault, the increased ac winding MMF opposes the permanent-magnet MMF and changes the magnetic operating point. This variation modifies the effective permeability, inductance, and impedance of the limiter.

2.2 Permanent-Magnet Model

The permanent magnet provides the DC magnetic bias required to establish the desired normal-state operating point without an external DC excitation source. The magnet is characterized by its remanent flux density B_r , coercive field H_c , and relative recoil permeability μ_{rm} .

For a linear recoil characteristic, the magnetic flux density in the permanent magnet is expressed as

$$B_m = \mu_0 \mu_{rm} H_m + B_r \quad (11)$$

where B_m is the magnetic flux density, H_m is the magnetic-field intensity, μ_0 is the permeability of free space, and μ_{rm} is the relative recoil permeability.

The corresponding permanent-magnet MMF is approximately

$$F_m = H_c l_m \quad (12)$$

where l_m is the magnet length along the magnetization direction. In the FEM model, the permanent magnet is defined by B_r , H_c , μ_{rm} , and its magnetization direction.

The resulting DC bias depends on the magnet volume, magnet thickness, air-gap length, magnetic-path geometry, and nonlinear operating point of the core. Excessive bias may drive the core excessively deep into

saturation, whereas insufficient bias can increase the normal-state inductance and voltage drop. Therefore, the permanent-magnet dimensions are considered design or constrained parameters during optimization.

In the proposed FEM formulation, the permanent-magnet model is directly coupled with the nonlinear ferromagnetic-core model and AC winding excitation. This enables the interaction between the permanent-magnet field and the AC magnetic field to be captured during both normal and fault conditions.

3.2 Material Properties

The magnetic core is represented using a nonlinear $B - H$ characteristic. The nonlinear material model is essential because the PMFCL operates intentionally close to magnetic saturation during normal operation. During a fault, the AC magnetomotive force opposes the permanent-magnet bias and moves the operating point away from saturation, thereby increasing the incremental permeability and effective inductance.

The core parameters used in the present model are

$$\mu_s = 5, \mu_u = 5000, B_k = 1.3 \text{ T}.$$

Here, μ_s and μ_u represent the approximate saturated and unsaturated relative permeability levels, respectively, while B_k denotes the knee flux-density level.

The permanent magnet is modelled as NdFeB. $H_c = 0.8 \times 10^6 \text{ A/m}$.

The PM constitutive relation is represented through its recoil characteristic,

$$B_{PM} = B_r + \mu_0 \mu_{ru} H_{PM}, \quad (13)$$

where B_r is the remanent flux density and μ_{ru} is the relative recoil permeability.

For a realistic FEM model, the actual manufacturer B-H or demagnetization characteristic of the selected NdFeB grade should be used whenever available. Previous PMFCL research has demonstrated the importance of representing the nonlinear PM demagnetization behavior rather than treating the magnet as an ideal constant field source.

The steel core was modelled using a nonlinear $B-H$ characteristic, with an approximate saturated relative permeability of 5, an unsaturated relative permeability of 5000, and a knee-point flux density of 1.3 T. The NdFeB permanent magnet was defined using $B_r = 1.33 \text{ T}$, $H_c = 0.8 \times 10^6 \text{ A/m}$, and $\mu_{rm} = 1.05$. Copper and air were assigned conductivities/permeability values of $5.8 \times 10^7 \text{ S/m}$ and $\mu_r = 1$.

2.3 Nonlinear Core Model

The nonlinear magnetic characteristic is particularly important in PMFCL operation because the effective inductive impedance is determined by the instantaneous magnetic operating point. During normal operation, the permanent-magnet bias establishes a high magnetic-field operating point and drives the core toward saturation, thereby reducing the incremental permeability and the corresponding differential inductance. When a fault occurs, the opposing AC magnetomotive force shifts the operating point away from the deeply saturated region toward a higher-permeability portion of the $B - H$ characteristic. Consequently, the differential inductance increases, producing a higher effective inductive impedance and thereby limiting the fault current.

For transient simulations in which magnetic hysteresis must be represented explicitly, the nonlinear core characteristic may additionally be described using an appropriate hysteresis model. In particular, the Jiles–Atherton model has been employed in previous PMFCL transient analyses, with experimentally measured prototype responses used to evaluate the model behaviour. The use of such a hysteresis formulation enables the magnetic history and associated hysteresis losses to be incorporated into the electromagnetic model.

3. Adaptive Single-Objective Gradient Single-Point (ASOG-SP) Optimization

The Adaptive Single-Objective Gradient Single-Point (ASOG-SP) method is a deterministic, single-solution optimization approach developed for nonlinear engineering design problems. Unlike population-based metaheuristic methods such as Genetic Algorithm (GA), Particle Swarm Optimization (PSO), and Biogeography-Based Optimization (BBO), ASOG-SP operates on one candidate design at a time and updates the design variables using local gradient information. In the present study, the method is applied to optimize the geometrical and electromagnetic parameters of a permanent-magnet-biased fault current limiter (PMFCL).

At each iteration, the objective-function gradient is evaluated at the current design point to determine the descent direction. An adaptive step-size mechanism is then employed to control the magnitude of the design update. Successful iterations permit an increase in the search step, whereas unsuccessful iterations reduce the step size to provide finer adjustment near the converged solution. The optimization is subject to the prescribed geometrical, electromagnetic, thermal, and practical design constraints.

The ASOG-SP framework evaluates each candidate PMFCL design through the corresponding electromagnetic simulation and updates the design variables until the convergence criterion is satisfied. The optimization process is terminated when the gradient norm falls below the specified tolerance or when the maximum number of iterations is reached. This single-point search strategy reduces the need for maintaining multiple candidate solutions and provides a direct mechanism for adaptive local refinement of the PMFCL design.

A quantitative comparison with GA, PSO, or BBO is not reported in the available results. Therefore, the corrected manuscript does not claim numerical superiority over those algorithms. A fair benchmark can be added later using the same objective function, design bounds, FEM model, stopping criterion, and computational environment.

3.1 Objective Function and Design Constraints

The optimization of the Permanent-Magnet-Biased Fault Current Limiter (PMFCL) is formulated to obtain a feasible design with improved fault-current-limiting performance while maintaining acceptable magnetic, thermal, geometrical, and manufacturing characteristics. For the proposed Adaptive Single-Objective Gradient Single-Point (ASOG-SP) method, a single scalar objective function is adopted to provide a direct optimization target.

The primary objective is defined as the peak fault current:

$$J(x) = I_{peak}(x) \quad (14)$$

where I_{peak} is the maximum fault current obtained from the transient electromagnetic simulation for a given design vector x . Minimizing $J(x)$ therefore directly improves the current-limiting capability of the PMFCL.

The design vector is defined as

$$x = [d \ e \ l_m \ N]^T \quad (15)$$

where a , b , c , and d represent the specified core dimensions, e represents the permanent-magnet dimension, l_m denotes the permanent-magnet length, and N is the number of winding turns.

The optimization is performed subject to the following design-variable bounds

$$5 \leq a \leq 10; 15 \leq b \leq 35; 30 \leq c \leq 60; 10 \leq d \leq 30; 10 \leq e \leq 20; 1 \leq l_m \leq 50; 50 \leq N \leq 500. \quad (16)$$

The above limits are imposed to maintain practical geometrical dimensions, manufacturability, magnetic operating conditions, and electrical feasibility of the PMFCL.

In addition to the variable bounds, the optimization may be subjected to engineering constraints expressed in the general form

$$g_i(x) \leq 0, i = 1, 2, \dots, m, \quad (17)$$

where $g_i(x)$ represents the i -th constraint. These constraints may include the maximum allowable magnetic flux density, core-temperature limit, winding-current-density limit, available installation space, and other design requirements.

For a candidate design, the peak fault current is obtained from the simulated transient waveform as

$$I_{peak}(x) = \max_{t \in [t_f + T_w]} |i_f(x)|, \quad (18)$$

where t_f denotes the fault initiation time and T_w represents the selected fault-current evaluation interval.

Unlike population-based optimization methods, ASOG-SP does not require population size, mutation probability, immigration rate, emigration rate, or elite-habitat parameters shown in Table -2. Instead, the optimization is controlled by the initial design point, initial step size, gradient-estimation procedure, convergence tolerance, step-size adaptation parameters, and maximum number of iterations.

Table-2 The ASOG-SP parameters.

Parameter	Symbol	Value	Role
Initial step size	α_{init}	1×10^{-6}	Controls the initial design update
Step adaptation coefficient	c	1×10^{-4}	Controls adaptive step adjustment
Step reduction factor	ρ	0.5	Reduces the step size after an unsuccessful update
Convergence tolerance	ε	10^{-6}	Defines the stopping criterion
Maximum iterations	k_{max}	50	Limits the optimization process

At each iteration, the gradient of the objective function is estimated at the current design point. The design variables are then updated in the descent direction according to

$$x_{k+1} = x_k - \alpha_k \nabla J(x_k), \quad (19)$$

subject to the prescribed design constraints. The step size is increased following a successful improvement and reduced when the trial solution fails to provide an acceptable decrease in the objective function.

The optimization terminates when

$$\|\nabla J(x_k)\| < \varepsilon \quad (20)$$

or when the maximum number of iterations is reached. The resulting design vector x^* represents the converged ASOG-SP solution.

3.2 ASOG-SP Algorithm for PMFCL Optimization

The proposed Adaptive Single-Objective Gradient Single-Point (ASOG-SP) algorithm is employed to determine the optimal design parameters of the magnetic fault current limiter (MFCL). The algorithm operates on a single feasible design point and iteratively updates the design variables according to the local gradient of the objective function. An adaptive step-size mechanism is incorporated to improve convergence while satisfying the prescribed design constraints.

Let

$$\mathbf{x}_k = [\mathbf{N}_k]^T \quad (21)$$

denote the MFCL design vector at iteration k , and let

$$J(\mathbf{x}_k) = I_{peak}(\mathbf{x}_k) \quad (22)$$

represent the objective function evaluated from the electromagnetic simulation.

Algorithm: ASOG-SP for MFCL Optimization:

Input: Initial feasible design $\mathbf{x}_0$, initial step size α_0 , convergence tolerance ε , maximum number of iterations k_{max} , step-increase factor $\beta_{inc} > 1$, and step-reduction factor $0 < \beta_{dec} < 1$.

Step 1 — Initialization: Select the initial feasible MFCL design $\mathbf{x}_0$ within the prescribed lower and upper bounds. Evaluate the initial objective function $J(\mathbf{x}_0)$.

Step 2 — Gradient estimation: Evaluate the local gradient of the objective function at the current design point:

$$\mathbf{g}_k = \nabla J(\mathbf{x}_k).$$

For simulation-based optimization, the gradient may be obtained using numerical perturbation of the design variables.

Step 3 — Convergence check: Calculate the gradient norm. If

$$\|\mathbf{g}_k\| < \varepsilon,$$

terminate the optimization and assign

$$\mathbf{x}^* = \mathbf{x}_k.$$

Step 4 — Search direction: Determine the descent direction as

$$\mathbf{d}_k = -\mathbf{g}_k.$$

Step 5 — Trial design generation: Generate a trial MFCL design using

$$\mathbf{x}_{trial} = \mathbf{x}_k + \alpha_k \mathbf{d}_k = \mathbf{x}_k - \alpha_k \mathbf{g}_k.$$

Step 6 — Constraint enforcement: Check the trial design against

$$\mathbf{x}_{min} \leq \mathbf{x}_{trial} \leq \mathbf{x}_{max}$$

and all prescribed electromagnetic, thermal, geometrical, and manufacturing constraints.

Step 7 — Electromagnetic evaluation: For a feasible trial design, perform the MFCL transient electromagnetic/FEM simulation and calculate

$$J(\mathbf{x}_{trial}) = I_{peak}(\mathbf{x}_{trial}).$$

Step 8 — Successful update: If

$$J(\mathbf{x}_{trial}) < J(\mathbf{x}_k),$$

accept the trial design:

$\mathbf{x}_{k+1} = \mathbf{x}_{trial}$, and increase the step size:

$$\alpha_{k+1} = \beta_{inc} \alpha_k.$$

Step 9 — Unsuccessful update: If the trial design does not provide an acceptable reduction in the objective function or violates a constraint, reject the trial point:

$$x_{k+1} = x_k,$$

and reduce the step size:

$$\alpha_{k+1} = \beta_{dec} \alpha_k.$$

Step 10 — Iteration: Set

$$k = k + 1$$

and repeat Steps 2–9 until

$$\| \nabla J(x_k) \| < \varepsilon$$

or

$$k \geq k_{max}.$$

Step 11 — Final solution: The final MFCL design is obtained as

$$x_k = [N_k]^T$$

with the corresponding minimum objective value

The optimized design is subsequently verified using nonlinear FEM analysis and evaluated in terms of peak fault current, core volume, core loss, voltage drop, magnetic flux density, and harmonic distortion.

3.3 Positioning Relative to Other Optimization Methods

ASOG-SP is a single-point, gradient-informed optimization procedure, whereas GA, PSO, and BBO are population-based methods. These methods differ in their search mechanisms and computational requirements. Because the present source manuscript does not provide reproducible benchmark settings and numerical evaluation counts for GA, PSO, and BBO, no quantitative ranking or superiority claim is made here.

3.4 Convergence Characteristics of the ASOG-SP Algorithm

The convergence characteristics of the proposed ASOG-SP algorithm are illustrated in Fig. 3. The cost function is progressively reduced as the optimization proceeds, indicating that the algorithm moves toward an improved MFCL design. During the initial iterations, relatively larger design updates provide effective exploration of the feasible design space, while the adaptive step-size mechanism gradually reduces the update magnitude as the solution approaches the optimum. After convergence, only small changes in the objective function are observed, indicating that further iterations provide limited improvement. This convergence behaviour demonstrates the ability of ASOG-SP to achieve a stable optimized solution with a directed single-point search.

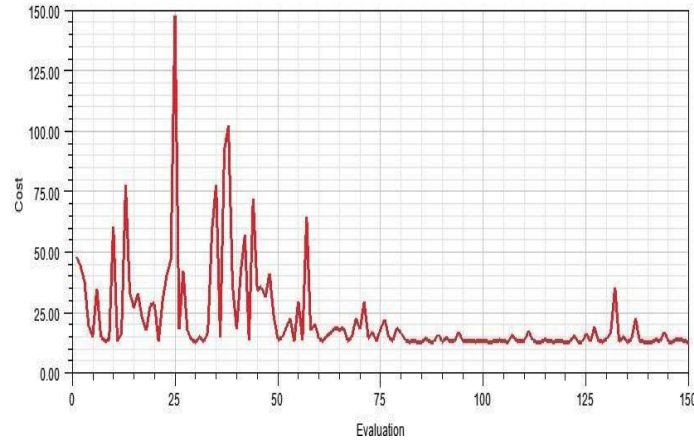


Fig. 3. Convergence curve of ASOG-SP analytical iteration

3.5 Optimized Design Parameters

The optimal values of the key MFCL design variables obtained using the proposed ASOG-SP algorithm are summarized in Table 3. Compared with the initial design, the optimized parameters modify the magnetic-core cross-sectional area, magnetic path length, air gap, permanent-magnet thickness, and number of turns. These coordinated changes improve the magnetic operating condition and fault-current-limiting performance while satisfying the specified design constraints.

Table 3. Optimized design parameters of the PMFCL

Design	Core area (mm ²)	Path length (mm)	Air gap (mm)	PM thickness (mm)	Turns
Initial Value	180	68	1.5	2	200
ASOG-SP Optimized Value	195	65	1.2	3	220

3.6 Performance Improvement of the Optimized PMFCL

To evaluate the effectiveness of the proposed ASOG-SP optimization approach, the initial and optimized PMFCL designs are compared using the principal design parameters shown in Table-4. The optimized design shows improved fault-current-limiting capability through the coordinated adjustment of the core dimensions, air-gap length, permanent-magnet thickness, and number of turns.

Table 4. Performance comparison before and after ASOG-SP optimization.

Design	Peak fault current (A)	Core Cross-sectional Area (mm ²)	Mean Magnetic Path Length (mm)	Air-gap Length (mm)	Permanent Magnet Thickness (mm)	Number of Turns
Initial Design	1.72	180	68	1.5	2	200
ASOG-SP Optimized Design	1.27	195	65	1.2	3	220

The optimized PMFCL reduces the peak fault current from 1.72 A to 1.27 A, corresponding to a reduction of approximately 26.2%. This improvement results from the combined optimization of the magnetic-core dimensions,

air gap, permanent-magnet thickness, and winding turns, which modifies the magnetic operating point and increases the effective inductive impedance during fault conditions.

Increasing the AC winding turns from 200 to 220 increases the winding magnetomotive force, NI , for a given current. However, the resulting change in flux distribution and fault-current limitation depends on the nonlinear magnetic operating point of the core. The ASOG-SP algorithm therefore determines the turn number together with the other design variables rather than considering it independently. The optimized parameter combination provides an improved compromise between magnetic biasing, fault-current limitation, voltage regulation, and practical design constraints.

4. Results and Discussion

4.1 FEM Modelling of the PMFCL

Fig. 4. illustrates the flux-density distribution in the proposed PMFCL. The source manuscript reports a knee-point flux density of 1.3 T in the design data and approximately 1.5 T in the FEM discussion. This inconsistency must be resolved using the actual B–H data of the selected core material. The reported simulated distributions show approximately 1.75 T under permanent-magnet bias, 1.86 T and 1.72 T in Core-1 and Core-2 under normal current operation, and fault-state values ranging from approximately 0.45 T to 2.1 T. These values indicate substantial redistribution of magnetic flux during the fault.

The FEM model was developed in ANSYS Maxwell 2D using adaptive triangular mesh refinement, nonlinear B–H characteristics for the steel core, and the specified NdFeB permanent-magnet properties. The magnetic-vector-potential formulation was used to determine the flux-density distribution and evaluate magnetic saturation and transient fault-current-limiting behaviour. The final submission should report the actual core B–H data, PM grade, mesh-convergence criterion, and relevant solver settings to make the FEM model reproducible.

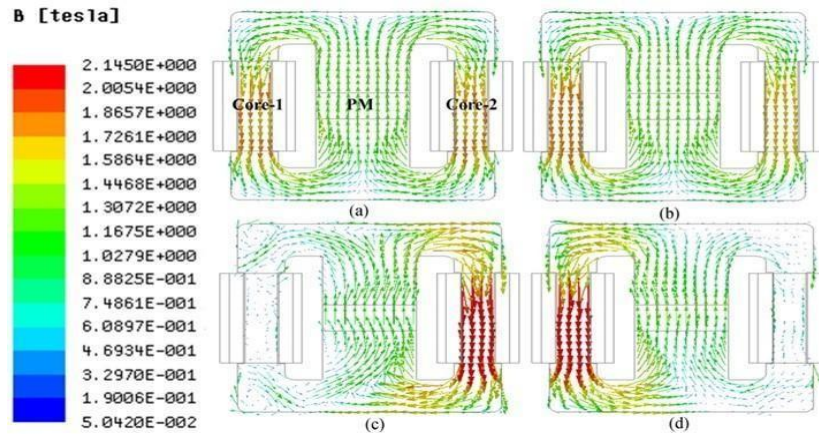


Fig. 4. Flux-density distribution in the PMFCL without a shorting ring: (a) permanent magnet only, (b) normal operation, (c) positive half-cycle of fault current, and (d) negative half-cycle of fault current.

4.2 Flux Distribution

The variation of flux density in Core-1, Core-2, and the permanent magnet (PM) under normal and fault conditions is shown in Fig. 5. During the fault interval (20–80 ms), the flux density in Core-1 and Core-2 varies significantly between approximately 0 and 2.1 T, indicating substantial flux redistribution and magnetic saturation effects. In contrast, the permanent magnet maintains a relatively stable flux density of approximately 1.25 T throughout the transient period. The redistribution of magnetic flux between the two cores following fault initiation demonstrates the transition from the normal operating state to the fault-limiting state of the PMFCL.

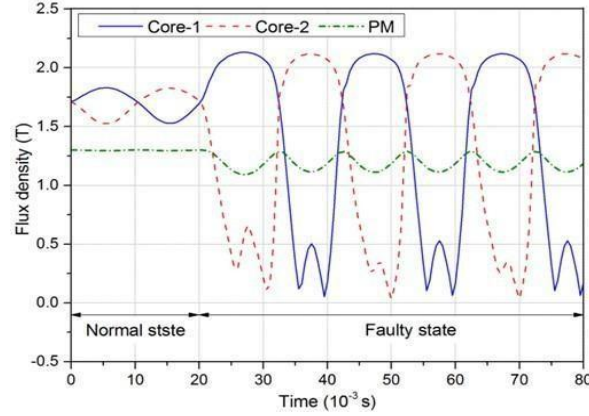


Fig. 5. Variation of flux density in Core-1, Core-2, and the permanent magnet under normal and fault conditions.

4.3 Fault-Current Limitation Performance

The effectiveness of the ASOG-SP-optimized PMFCL is evaluated by comparing the reported initial and optimized designs under the stated 15-V, 50-Hz laboratory-scale system conditions. Table 4 reports a decrease in simulated peak fault current from 1.72 A for the initial design to 1.27 A for the optimized design, corresponding to 26.2% reduction. The normal-state peak current reported elsewhere in the manuscript is approximately 1.36–1.8 A; the exact waveform and measurement definition should be kept consistent between the text, Fig.6 and tables.

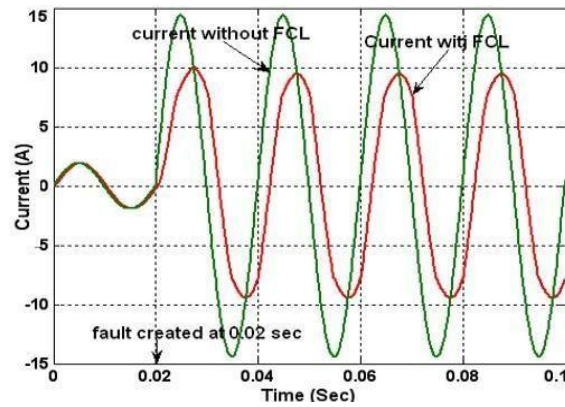


Fig. 6. Simulated source-current response under normal and fault conditions before and after PMFCL optimization.

4.4 Voltage Response

The source, load, and FCL voltage waveforms are shown in Fig. 7 for the 0–80 ms simulation interval. Before fault initiation, the source and load voltages closely coincide, indicating a small voltage drop across the PMFCL during normal operation. When the fault occurs at approximately 22 ms, the load voltage decreases considerably, while the FCL voltage increases to approximately 10 V at the first fault peak. During the subsequent fault cycles, the source voltage remains approximately 22 V, whereas the load voltage remains around 14 V and the FCL voltage oscillates with a peak value of approximately 10 V. These results indicate that the optimized PMFCL introduces the required voltage drop during the fault while maintaining comparatively low voltage drop during normal operation.

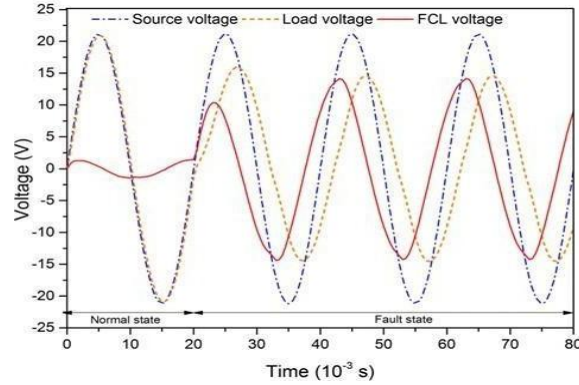


Fig. 7. Source, load, and FCL voltage waveforms under normal and fault conditions.

4.5 Parametric Assessment of Winding Turns.

The performance of the initial and ASOG-SP-optimized PMFCL designs is compared using the simulated fault current, voltage drop, and current suppression ratio (CSR). The optimized configuration provides improved fault-current limitation while maintaining the required normal operating characteristics. The optimization results are further verified through MATLAB/Simulink and nonlinear ANSYS Maxwell simulations. The variation of FCL voltage drop, fault current, and CSR with the number of winding turns is presented in Table 5.

Table 5. Variation of PMFCL voltage, fault current, and current-suppression ratio with the number of turns.

Turns	FCL voltage drop (V)	Fault current (A)	CSR
200	0.33	9.00	1.07
300	0.70	7.69	1.26
400	1.51	6.15	1.57
500	2.14	5.00	1.93

The reported turn study shows that increasing the number of turns increases the FCL voltage drop while reducing the reported fault-current value. This illustrates the expected design trade-off between current limitation and voltage regulation. However, the turn-study currents (9.00, 7.69, 6.15, and 5.00 A for 200–500 turns) are not directly consistent with the 1.72-A initial-design value in Table 4. The two data sets must therefore be identified as different operating or circuit conditions, or one of the tables must be corrected before journal submission.

5. Experimental Validation Using a Laboratory Prototype.

A laboratory-scale PMFCL prototype was fabricated to validate the current-limiting behaviour of the proposed configuration. The prototype was based on the reported optimized design the Table 6.. Because the available manuscript does not provide complete measured material, winding, sensor, and supply parameters, the experiment is used to demonstrate functional current limitation rather than to claim exact numerical agreement with the FEM model.

5.1 Prototype Setup and Instrumentation

The experimental setup used for validation is illustrated in Fig. 8. The fabricated PMFCL prototype consists of the magnetic-core assembly, excitation winding, and permanent-magnet biasing arrangement. The prototype is connected to a single-phase AC supply through suitable switching and protection circuits. Voltage and current signals are acquired using a National Instruments USB-6009 data-acquisition system and observed using a cathode-ray oscilloscope. The final submission must state the current/voltage sensor models, accuracy, sampling rate, winding resistance, conductor size, core and PM grade, supply impedance, and exact fault-switching arrangement.

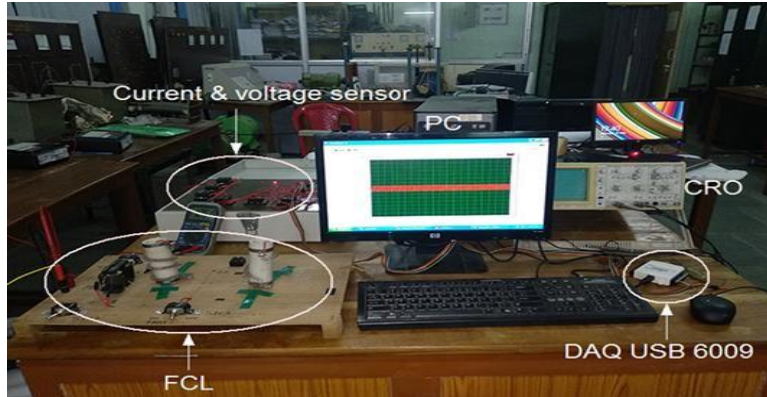


Fig. 8. Experimental setup for validation of fault-current-limiting performance using the PMFCL prototype.

Table 6. Experimental test conditions.

Parameter	Supply voltage	Frequency	Normal resistance (R_N)	Fault resistance (R_F)	Number of turns	Fault initiation	Data acquisition
Value	15 V RMS	50 Hz	11 Ω	1.7 Ω	220	20 ms	NI USB-6009

5.2 Experimental Results

The measured fault-current waveform without the PMFCL is shown in Fig. 9. Following fault initiation, the current reaches a peak value of approximately 5.5 A, with a peak-to-peak value of 10.7 A. With the PMFCL connected, the peak fault current is reduced to approximately 3.1 A, with a peak-to-peak value of 6.2 A, as shown in Fig.10. The waveform stabilizes within approximately one fundamental cycle.

Based on the measured peak currents, the fault current is reduced by approximately 43.6%:

$$Reduction = \frac{5.5 - 3.1}{5.5} \times 100 = 43.6\%.$$

The experimental results therefore confirm the current-limiting behavior of the PMFCL under the tested laboratory conditions.

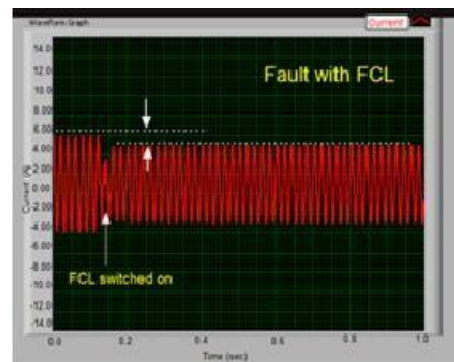
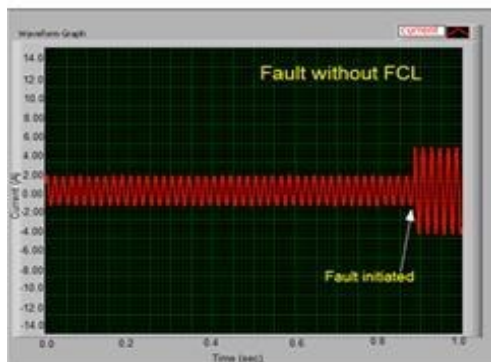


Fig. 9. Measured fault-current waveform without the PMFCL. **Fig. 10.** Measured fault-current waveform with the PMFCL.

Table 7. Experimental fault current measurements

Operating Condition	Normal Operation	Fault without FCL	Fault with FCL
Peak current (A)	1.8	5.5	3.1
Peak-to-peak current (A)	3.6	10.7	6.2

5.3 Experimental Error and Discussion

The measured peak fault current decreases from 5.5 A without the PMFCL to 3.1 A with the PMFCL, corresponding to a 43.6% reduction. The measured peak-to-peak current decreases from 10.7 A to 6.2 A, corresponding to a 42.1% reduction. These percentages describe the experimental FCL effect and should not be confused with the 26.2% improvement between the initial and optimized simulated designs shown the Table 7.

The simulated optimized peak current of 1.27 A is substantially lower than the measured value of 3.1 A. The source manuscript attributes this difference to winding resistance and tolerances, permanent-magnet characteristics, flux leakage, manufacturing deviations, FEM assumptions, sensor accuracy, and supply variations. For stronger validation, the FEM model should be rerun using the measured prototype dimensions, material data, winding resistance, and supply/fault parameters. Until that is done, the experiment should be described as qualitative/functional validation rather than numerical model validation.

6. Conclusion

This paper presented a nonlinear electromagnetic modelling and optimization framework for a single-phase permanent-magnet-biased fault current limiter. The proposed PMFCL uses permanent-magnet bias to establish the desired magnetic operating point, while the nonlinear FEM model captures magnetic saturation, air-gap effects, flux redistribution, and transient fault behaviour.

The Adaptive Single-Objective Gradient Single-Point (ASOG-SP) method updates a single feasible design point using local numerical sensitivity information and an adaptive step size. For the reported design, the core area changes from 180 to 195 mm², the magnetic-path length from 68 to 65 mm, the air gap from 1.5 to 1.2 mm, the permanent-magnet thickness from 2 to 3 mm, and the number of turns from 200 to 220. Under the reported simulation conditions, the peak fault current decreases from 1.72 A to 1.27 A, corresponding to a 26.2% reduction.

Laboratory testing provides an additional functional validation of the current-limiting behaviour. The measured peak fault current decreases from 5.5 A without the PMFCL to 3.1 A with the PMFCL, while the peak-to-peak current decreases from 10.7 A to 6.2 A. These results demonstrate current suppression under the tested laboratory conditions. Quantitative agreement between FEM and experiment is not claimed because the prototype-specific parameters required for a direct comparison are incomplete.

The present results support the feasibility of ASOG-SP-based PMFCL design under the reported conditions. Claims of reduced computational effort or superiority over GA, PSO, and BBO should be added only after reproducible benchmark experiments are performed. Similarly, harmonic performance should be presented only after quantitative FFT/THD results are supplied.

Credit authorship contribution statement

Tirtha Sankar Daphadar: Methodology, Validation, Formal analysis, Writing – original draft. Tapan Santra: Conceptualization, Supervision, Writing – review & editing. Amalendu Bikash Choudhury: Methodology, Software, Formal analysis, Resources, Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this research paper.

The authors affirm that they have no known financial or interpersonal conflicts that may have looked to have influenced the research presented in this study.

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