DIFFERENTIAL EVOLUTION ALGORITHM APPLIED TO 2D FINITE ELEMENT METHOD FOR AIR CORE REACTOR DESIGN WITH VOLUME MINIMIZATION

Jeylto Alves de Souza Cruvinel [1]; José Roberto Camacho [2]

[1] *Laboratório de Energias Renováveis e Proteção de Sistemas Elétricos (LEAPSE), Universidade Federal de Uberlândia (UFU), Uberlândia, Brazil, jeylto@ufu.br;*
[2] *Laboratório de Energias Renováveis e Proteção de Sistemas Elétricos (LEAPSE.), Universidade Federal de Uberlândia (UFU), Uberlândia, Brazil, jrcamacho@ufu.br;*

ABSTRACT

This article presents an approach to optimize the volume of air core reactors, specifically 2D electrical inductors, using the Differential Evolution (DE) technique in conjunction with the Finite Element Method (FEM). Minimizing the volume of these reactors is crucial for enhancing efficiency and reducing costs in the electric power industry. This study proposes an effective methodology that enables the optimization of reactor geometry while maintaining desired performance characteristics.

Keywords: Conductor volume reduction, Differential Evolution, Dry-type air core reactor, Finite Element Method, Optimization

Introduction

Air core reactors play a fundamental role in high-power electrical systems. They are used to limit short-circuit currents, stabilize voltages, and improve power supply quality. Minimizing the volume of these reactors is an important goal for the electric power industry, as smaller volumes mean space savings and material costs reduction. In this context, optimization becomes a valuable strategy.

Dry-type air core reactors are devices used in medium-voltage distribution and high-voltage transmission for various applications, such as fault current limitation, load flow control, reactive compensation (shunt reactors), and as the inductive part of tuned harmonic filters [1].

The Finite Element Method (FEM) is widely employed to analyze the performance of electrical equipment. However, optimizing the geometry of these devices is a complex challenge due to the large number of variables involved. Differential Evolution (DE) is a global optimization algorithm that has excelled in handling multidimensional and nonlinear problems, making it a suitable choice for air core reactor optimization.

Air core reactors outperform other reactor types in several areas, including efficiency, reduced energy loss, extended lifespan, corrosion resistance, and cost savings.

Proposed Methodology

In this article, the Finite Element Method (FEM) will be used in conjunction with Differential Evolution (DE) to optimize the volume of an air core reactor.

To perform the analysis of the air core reactor using the finite element method, axisymmetric cylindrical coordinates were employed [2]. This is a way to represent a three-dimensional design through a plane that is symmetrical to a vertical axis, such that this plane represents all planes symmetrically rotated around the central axis.

In this model, four independent variables will serve as input for the optimization process. These variables are the height (h), base (b) of the conductor's cross-sectional area, the average radius of each coil (R), and the number of turns (N). Meanwhile, Volume (V), Current Density (J), and Quality Factor (Q) will be output variables from the Finite Element Method (FEM).

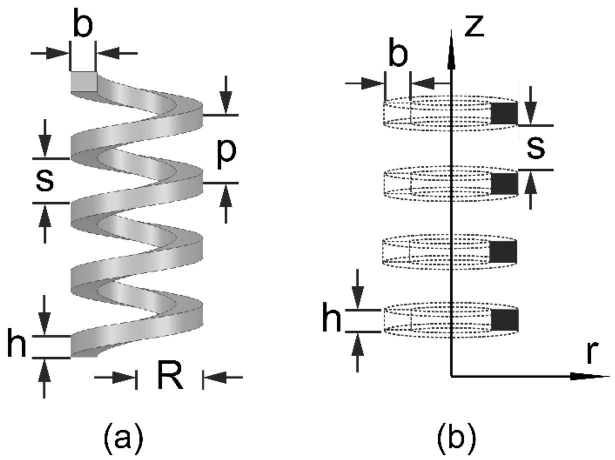

Figure 1: (a) Air Core Reactor Dimensions Scheme and (b) representation of a solid in an axisymmetric coordinate system.

A. Design Variable Bounds

In order for our model to achieve the desired parameters, it is crucial to apply certain design constraints, ensuring that the input variables (h, b, R, and N) fall within a range with maximum and minimum values.

B. Fitness function

The above-mentioned constraints assist the solution of the problem of finding a solution within specific parameters. In the studied model, the goal is to minimize the reactor's volume, subject to constraints as the inductance, current density, and quality factor. The penalty technique [3] is employed for volume reduction [4], as evidenced in Equation 2.

The objective function ϕ , in Equation 1, is composed of two parts: the volume of equation (2) and penalties associated with three criteria. The first penalty belongs to achieving the desired inductance, the second is related to the maximum current density, and the third concerns attaining the minimum quality factor.

$$\phi = V + r_p[\left(\left(L_{femm} - L_0\right)w\right)\left(\max\left(0, J_{femm} - J_{max}\right)\right)^2\left(\min\left(0, Q_{femm} - Q_{min}\right)^2\right)] \tag{1}$$

Being,

$$V = Nbh\sqrt{(2\pi R)^2 + (h+s)^2} \tag{2}$$

Where ϕ is the objective function to be minimized, V is the volume of the reactor coil given by Equation (2), r_p controls the impact of the penalty function on the objective function, L_{femm} is the simulated inductance in FEMM, L_0 is the desired inductance, w is a weighting factor, J_{femm} is the simulated current density, J_{max} is the maximum desired current density, Q_{femm} is the Quality Factor [5] obtained through the resistance and reactance simulated in FEMM, and Q_{min} is the minimum desired quality factor.

Finite Element Method

The authors implemented the finite element method in the FEMM software, using the 2D axisymmetric model. Axisymmetric analysis involves electromagnetic analysis through the rotation of a surface around the z-coordinate, as shown in Figure 1(b). The drawing implementation was carried out through automation in the Python language using the pyFEMM library [6].

Differential Evolution

Using the Differential Evolution algorithm [7] applied to the Finite Element Method utility, the flowchart depicted in Figure 2 can be applied. The authors implemented the Differential Evolution code using Python and established a connection and automation with FEMM, a Finite Element Method software, through the Python library pyFEMM.

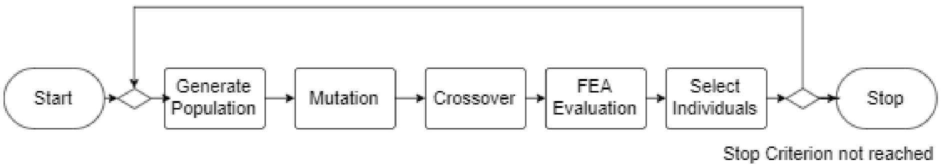

Figure 2: Flowchart of the differential evolution algorithm.

The first step in the flowchart of figure 2 is to define the necessary initial values for the algorithm. Next, the reactor's design parameters are input into the algorithm, and random values within the boundaries established by the design limits are generated from them. To find the best values, an iterative process is required.

Following that, the mutation, crossover, and selection operations described in [8] were applied. Based on performance evaluations, solutions to be retained and used in the next iteration are chosen. Iterations continue until the stopping criteria are met, and the best-found solution is returned as the optimization result. The Python programming language was used to implement the DE algorithm.

In this paper, we analyze a single-phase air-core dry-type reactor, with specific parameters listed in Table 1.

Optimization parameters and criteria

To demonstrate the method, a reactor with an inductance of 100μH will be constructed using the differential evolution method. In this model, the distance between the conductors (spacing) is set at 5 mm, increasing the quality factor, and decreasing current density to reduce losses. For this simulation, the following parameter values from Table 1 were used in the differential evolution code.

Table 1: Design parameter limitations

Parameter	**Minimum value**	**Maximum value**	**Parameter**	**Minimum value**	**Maximum Value**
h	1 mm	40 mm	N	10	200
b	1 mm	40 mm	J	–	6 A/mm^2
R	100 mm	500 mm	Q	15	–

DOI: 10.55592/ISE.2023.2713954

Findings and discussion

By simulating the reactor with the established parameters in DE, including a scale factor of 0.8, a crossover rate of 0.9, a population size of 100, r_p of 100, and a total of 50 generations, we obtained the graphs shown in Figure 3 and the data summarized in Table 2.

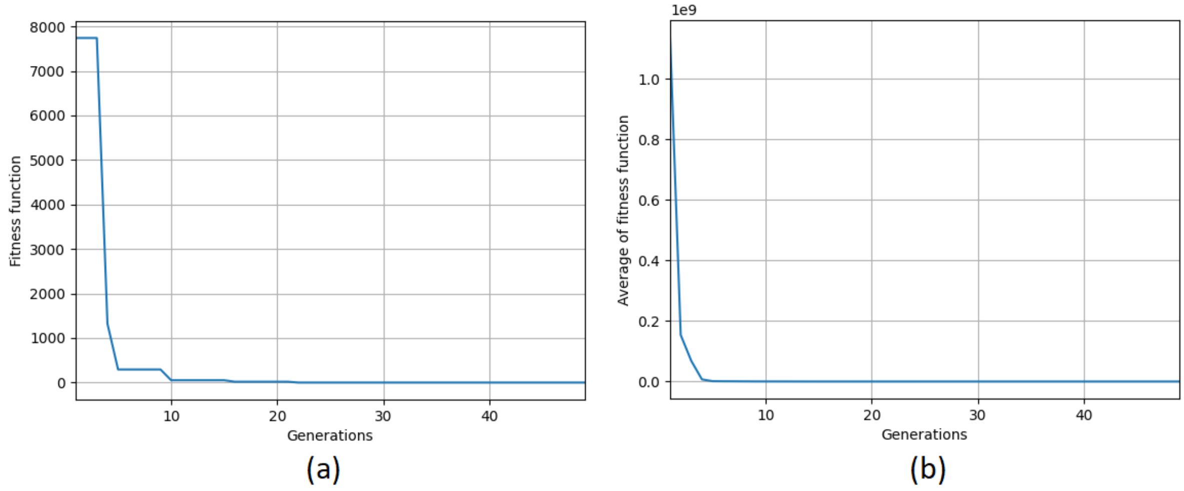

Figure 3: Graphs of the fitness function (a) and the average of the fitness function (b).

Table 2: Parameters obtained using the differential evolution algorithm.

Input parameters	Found result	Output parameters	Found result
h	28.06 mm	L_{femm}	99.98 μH
b	18.18 mm	J_{femm}	0.39 A/mm²
R	434.21 mm	Q_{femm}	19.26
N	10	Volume (V)	$13.91\times 10^{-3} m^3$

The graphs in Figure 3 show that the initial volume of the reactor was significantly reduced using the differential evolution algorithm applied to the FEM until the desired criteria were met. It is possible to verify that the algorithm achieved the best values for obtaining a better volume with less than 50 iterations. The average of the values evaluated by the objective function reached considerably high values. The axisymmetric model of the inductive reactor is shown in Figure 4.

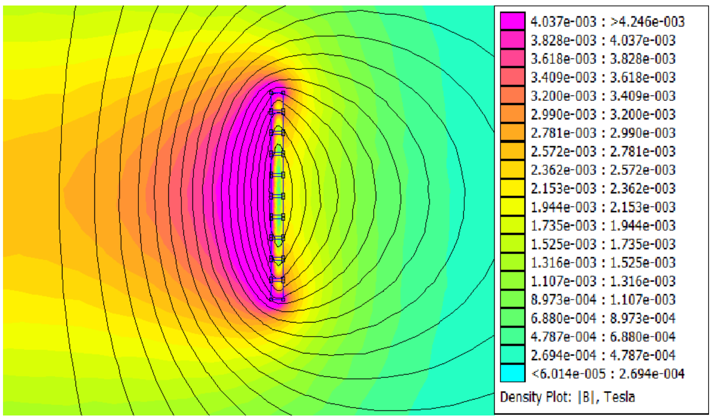

Figure 4: Reactor built using the parameters found by the differential evolution algorithm.

DOI: 10.55592/ISE.2023.2713954

Conclusion

Therefore, it was possible to conclude, through this article, that the differential evolution algorithm can significantly contribute to electrical machine design. By reducing the volume of the used material, it is possible to cut expenses and operational costs, thus making the design more sustainable. Moreover, it becomes a highly practical tool, especially when combined with FEM, as it offers great precision in modeling physical problems. This allows for the definition of desired parameters such as quality factor, inductance, and current density. Consequently, it can be stated that the application of the differential evolution algorithm to FEM can significantly enhance the efficiency of air-core reactor production and other equipment that can be modeled with FEM. The study findings have broader implications for the electrical equipment industry, as they can be used to enhance the efficiency of electrical component production.

Acknowledgement

Our thanks to Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) and Fundação de Amparo à Pesquisa do Estado de Minas Gerais (FAPEMIG) for financial support in the preparation of this research; the colleagues in the research group at the Laboratory of Alternative Energies and Electric Systems Protection (LEAPSE), and the Postgraduation at the School of Electrical Engineering (FEELT) at Universidade Federal de Uberlândia (UFU) for the physical installations used and the resources offered in its premises.

References

[1] Caverly et al., “Air core reactors: Magnetic clearances, electrical connection, and grounding of their supports”, in Minnesota Power Systems Conference, vol. 1, Minneapolis, Apr. 2017, pp. 1–24.

[2] L. Hu and A. Palazzolo, “An enhanced axisymmetric solid element for rotor dynamic model improvement”, *Journal of Vibration and Acoustics*, vol. 141, no. 5, p. 051 002, 2019.

[3] “A survey of penalty techniques in genetic algorithms”, in *Proceedings of IEEE international Conference on Evolutionary Computation*, May 1996. DOI: 10.1109/ICEC.1996.542704.

[4] Z. Zhang, *Antenna Design for Mobile Devices*, 2nd ed. Wiley-IEEE Press, 2017, ISBN: 978-1-119-13232-5.

[5] Kajfez and E. Hwan, “Q-factor measurement with network analyzer”, IEEE Transactions on Microwave Theory and Techniques, vol. 32, no. 7, pp. 666–670, 1984. DOI: 10.1109/TMTT. 1984.1132751.

[6] D. Meeker, “Finite element method magnetics: pyFEMM 0.1.3 user’s manual,” 2021. [Online]. Available: https://www.femm.info/wiki/pyFEMM. (Accessed: 17/10/2023).

[7] Jagodziński and J. Arabas, “A differential evolution strategy”, in 2017 IEEE Congress on Evolutionary Computation (CEC), 2017, pp. 1872–1876. DOI: 10.1109/CEC.2017.7969529.

[8] J. Brest, S. Greiner, B. Boskovic, M. Mernik, and V. Zumer, “Self-adapting control parameters in differential evolution: A comparative study on numerical benchmark problems”, *IEEE Transactions on Evolutionary Computation*, vol. 10, no. 6, pp. 646–657, 2006. DOI: 10.1109/TEVC. 2006.872133.