IJEAS
International Journal of Energy and Applied Sciences

Finite Element Method (FEM) in Harmonic Reactor Design

Nazlı Demir[1], Atilla Dönük[2]*

[1] Institute of Science, Aydin Adnan Menderes University, Aydin, Turkiye; demirnazo@gmail.com
[2] Electrical and Electronics Engineering Department, Engineering Faculty, Aydin Adnan Menderes University, Aydin, Turkiye; adonuk@adu.edu.tr
*Correspondence: adonuk@adu.edu.tr

Received: 13 April 2026
Revised: 23 April 2026
Accepted: 25 April 2026
Published: 25 May 2026

https://doi.org/10.47526/2026-1/2505-3123.01

Abstract

The increasing integration of power electronic converters in modern electrical power systems has led to a significant rise in harmonic distortion, posing serious challenges to power quality, system stability, electromagnetic compatibility, and equipment lifetime. Harmonic filter reactors play a critical role in mitigating harmonic propagation and limiting resonance phenomena in electrical networks by providing controlled inductive impedance and stabilizing system behavior under distorted operating conditions.

In this study, the application of the Finite Element Method (FEM) in the design and analysis of harmonic filter reactors is comprehensively reviewed. Rather than proposing a new design methodology, the paper focuses on how FEM has been utilized in existing reactor designs to address the limitations of conventional analytical approaches. In particular, the capability of FEM to capture nonlinear magnetic behavior, leakage flux distribution, fringing effects, and core saturation under realistic loading and frequency-dependent conditions is examined.

The study highlights how FEM-based analyses improve inductance estimation accuracy, enable detailed electromagnetic field visualization, and support the evaluation of complex geometrical configurations that are difficult to handle analytically. In addition, the role of FEM in facilitating design validation, optimization processes, and performance assessment in compliance with IEEE 519 power quality requirements is discussed. The findings demonstrate that FEM has become an essential tool in modern harmonic filter reactor engineering, significantly enhancing design reliability and providing deeper insight into reactor performance under distorted operating conditions.

Keywords: Harmonic reactor design; FEM; ANSYS Maxwell; COMSOL; magnetic field analysis.

1. Introduction

With the increasing integration of power electronics into modern electrical systems, harmonic distortion has become a prevalent and critical issue. Nonlinear loads such as variable frequency drives (VFDs), rectifiers, inverters, and uninterruptible power supplies (UPS) generate harmonics—undesired frequency components that are integer multiples of the fundamental frequency (typically 50 or 60 Hz). These harmonics propagate throughout the network, leading to degraded power quality, increased thermal losses, malfunction of sensitive equipment, and reduced overall system efficiency [1].

To mitigate these effects, harmonic filter reactors are widely employed as inductive elements connected in series with capacitors to form tuned or detuned passive filter circuits. By introducing controlled impedance at specific frequencies, these reactors prevent resonance between system impedance and capacitive reactance, while also limiting the propagation and amplification of harmonic currents—particularly toward capacitor banks. As a result, they play a crucial role in improving system reliability, protecting equipment, and ensuring compliance with international standards such as IEEE 519 [2].

However, conventional design approaches for harmonic filter reactors, which are mainly based on analytical calculations and empirical assumptions, are often insufficient to accurately capture complex electromagnetic phenomena such as non-linear core behavior, leakage flux, and localized saturation effects. These limitations become more critical with increasing design constraints related to performance, compactness, and thermal limits.

In this context, the Finite Element Method (FEM) provides a powerful tool for detailed electromagnetic analysis, enabling accurate modeling of reactor behavior under realistic operating conditions. FEM allows the inclusion of complex geometries, nonlinear material properties, and field distributions that are not easily addressed using classical methods.

This paper focuses on the application of FEM in harmonic filter reactor design. The main contributions of this study are summarized as follows:

- A comprehensive overview of FEM-based modeling approaches used in harmonic filter reactor analysis and design.
- A review of key design parameters reported in the literature that influence inductance and electromagnetic performance.
- An assessment of how reactor performance is evaluated in terms of harmonic mitigation and electromagnetic behavior using FEM-based studies.
- A discussion on the advantages of FEM in improving analysis accuracy, supporting design validation, and facilitating optimization processes in existing reactor designs.

Harmonic Reactors

Neutral grounding reactors Harmonic filter reactors, also known as detuned reactors, are inductive components used in conjunction with capacitors to form filter circuits that mitigate the effects of harmonics. By introducing a specific impedance at certain frequencies, these reactors prevent resonance conditions and limit the flow of harmonic currents into sensitive components like capacitor banks. This not only protects the capacitors from potential damage but also enhances the overall power quality of the system.

The commonly used reactor types in power systems are listed as follows:

- Line reactors;
- Harmonic filter reactors;
- Motor starting reactors;
- Current-limiting reactors;
- Shunt reactors;
- Electric arc furnace reactors.

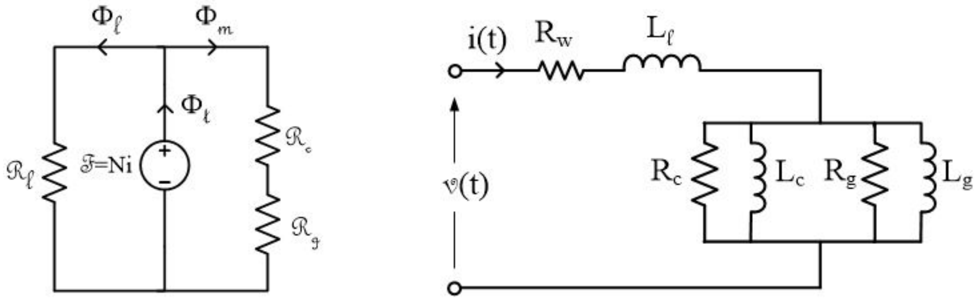

Figure 1. Magnetic and electric equivalent circuits of a single-phase iron-core shunt reactor [3]

Harmonic filters suppress or mitigate harmonic components and absorb harmonic currents within specific frequency ranges, removing this energy from the system. As a result, the circulation of harmonic components within the system, which could otherwise damage sensitive equipment or degrade power quality, is prevented. This process reduces Total Harmonic Distortion (THD), thereby improving system stability of the grid but also extending the lifespan of equipment, increasing system efficiency, and minimizing energy losses.

The most commonly used metric is the Total Harmonic Distortion (THD), defined as:

$$THD = \frac{\sqrt{\sum_{n=2}^{\infty} V_n^2}}{V_1} \; x \; 100\% \tag{1}$$

where,

Vn is the magnitude of the nth harmonic component.

V_1 is the magnitude of the fundamental component.

2. Materials and Methods

In harmonic filter reactor design, not only the accurate determination of inductance but also the evaluation of harmonic mitigation performance is essential. A key performance indicator in this context is the Total Harmonic Distortion (THD), which quantifies the distortion level of current or voltage waveforms in the system.

In practical power systems, THD limits are defined by international standards such as IEEE 519, which specifies acceptable harmonic levels at different voltage levels and system conditions [4]. Therefore, the design of harmonic filter reactors must ensure that the resulting system THD remains within these limits.

A conventional passive harmonic filter consists of a reactor (inductor) connected in series with a capacitor. This configuration is designed to exhibit low impedance at a particular harmonic frequency, thereby diverting harmonic currents away from the main system.

Series resonance circuits are utilized in the design of harmonic filters, aiming to provide minimum impedance at the target harmonic frequency. These circuits are formed by connecting an inductor (L) and a capacitor (C) in series. At resonance, the circuit presents a low-impedance path, allowing harmonic currents at the selected frequency to pass through the filter and be eliminated from the system.

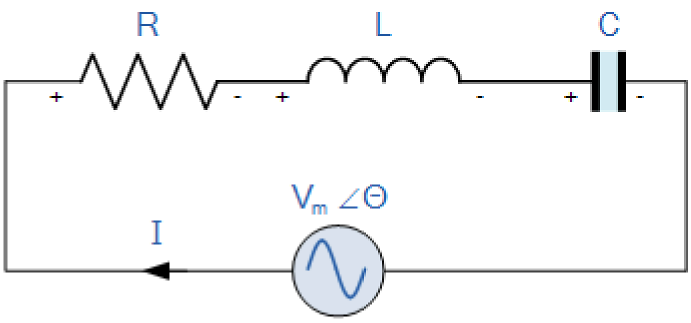

Figure 2. Series resonance circuit used in harmonic filters [5].

The tuning of harmonic filters is directly related to the reactor inductance and capacitor values. The resonance frequency fr of the filter is determined by the inductance (L) and capacitance (C) values (2,3):

$$Z = R + j\left(wL - \frac{1}{wC}\right) \tag{2}$$

$$wL = \frac{1}{wC} \quad \rightarrow f_r = \frac{1}{2\pi\sqrt{LC}} \tag{3}$$

Accurate control of this frequency is critical, as any deviation may lead to insufficient harmonic attenuation or amplification due to parallel resonance with the grid impedance. Improper tuning may result in a substantial degradation of THD performance, especially in systems with time-varying harmonic spectra. [6, 7].

Large-scale reactor manufacturers commonly utilize finite element analysis (FEA) software tools such as ANSYS Maxwell, MagNet, Opera, COMSOL, Flux and FEMM during both the design and production stages. In many modern applications, FEM-based design approaches have become standard practice to enhance accuracy and reliability in electromagnetic analysis.

In line with this trend, several recent studies have demonstrated the effectiveness of FEM in evaluating critical design parameters. For instance, in a study investigating the impact of the number of air gaps on core losses, a single-phase iron-core shunt reactor was analyzed using the FEM-based ANSYS Maxwell 3D environment. In this work, the reactor model was developed under magnetostatic conditions, and the number of air gaps per limb varied as 1, 5, 10, 16, 20, and 35.

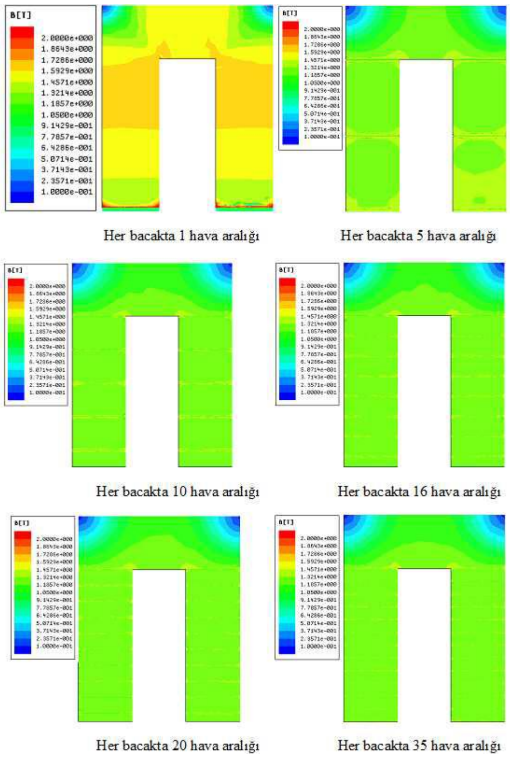

Figure 3. Distribution of magnetic flux density along the reactor limb for varying numbers of distributed air gaps [8].

The simulation results provided detailed insights into the electromagnetic behavior of the reactor, particularly the distribution of magnetic flux density along the core structure. As illustrated in Fig. 3, the magnetic field distribution obtained from the simulations clearly shows the influence of varying air-gap configurations on flux uniformity and core saturation levels. These findings highlight the significant role of air-gap design in controlling core losses and improving overall reactor performance [8].

Geometry Definition and Parametric Modeling

The reactor geometry is defined in a two-dimensional axisymmetric configuration, which is widely adopted in electromagnetic finite element analysis to significantly reduce computational cost while preserving solution accuracy for rotationally symmetric structures [9, 10]. This modeling assumption is particularly suitable for reactor and inductor-type devices, where the circumferential field variation is negligible compared to radial and axial field components.

The computational domain typically consists of three main regions: the coil (winding) region, the surrounding air domain, and the magnetic core region. Each region is explicitly represented in the finite element model to ensure accurate coupling of electromagnetic field interactions and energy storage mechanisms. In air-core reactor designs, the absence of a magnetic core eliminates nonlinear saturation effects, while in iron-core configurations, nonlinear permeability must be incorporated through experimentally derived B–H characteristics [9], [11].

All geometrical parameters, including inner and outer coil radius, winding thickness, axial height, and conductor cross-sectional area, are defined in a parametric form. This parametric modeling approach enables systematic design space exploration and supports automated optimization procedures when coupled with numerical solvers such as FEM-based iterative algorithms or evolutionary optimization methods [10], [12]. Furthermore, parametric definition is essential for sensitivity analysis, allowing the evaluation of how small geometric variations influence inductance, flux distribution, and loss mechanisms.

Material Modeling

The first step is to clearly define the technical requirements of the system in which the reactor will operate. An example table illustrating the parameters to be determined is provided in Table 1.

Table 1. Design Data for Set of Iterations with 13.8kV Operating Voltage and 80K Temperature Rise [13].

Feature	**1.**	**2.**	**3.**	**4.**	**5.**
Temparature Rise	80	80	80	80	80
# gap	40	40	40	40	40
kVAR	250	250	250	250	250
Voltage (l-l) kV	13,8	13,8	13,8	13,8	13,8
Current Amps	31,4	31,4	31,4	62,8	62,8
L (mH)	808	808	808	404	404

Inductance (L) depends on the reactor core material, air gap, number of turns and magnetic circuit parameters. The basic inductance value of the reactor is calculated by the following formula:

$$L = \frac{N^2 \cdot \ \mu_0 \ \cdot \ \mu_{eff} \cdot \ A_c}{l_m} \tag{5}$$

Here:

μ_0: Air gap permeability,

μ_0: Core material permeability,

N: turns of winding,

A_c: magnetic cross-sectional area,

l_m: magnetic path length.

If the core contains an air gap (g), the total magnetic circuit length is:

$$l_m = l_{core} + g \tag{6}$$

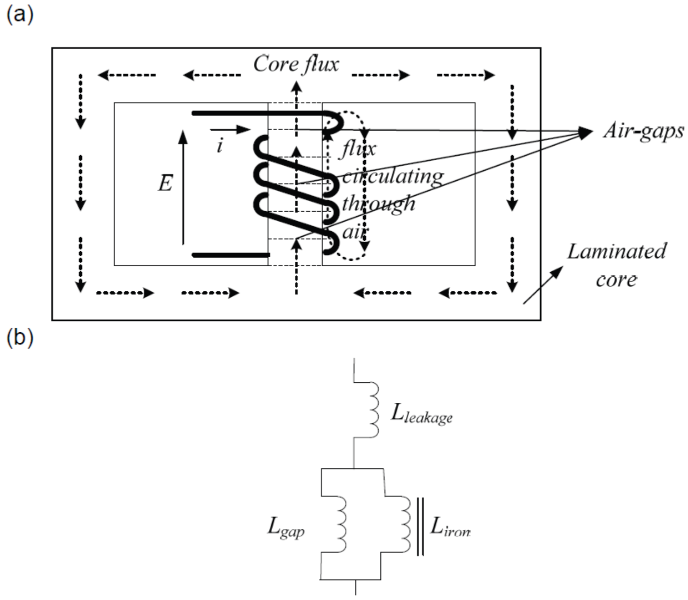

Figure 4. Simplified definition of flux paths (a); the most popular equivalent circuit (b) [14, 15]

Reactors usually target a particular harmonic order (h).

$$f_h = h \cdot f_{temel} \tag{7}$$

$$Z_h = j2\pi h\, f_{temel} \cdot L \tag{8}$$

Magnetic flux density (B) is important to determine whether there is saturation in the reactor core.

$$B = \frac{\mu_0 . \mu_r \, . \, N \, . \, I}{l_m} \tag{9}$$

The following equation is used for the thermal model of the reactor.

$$\Delta T = \frac{P_{loss}}{A_{cooling} \cdot h} \tag{10}$$

Loss Calculations

Harmonic reactors are fundamental passive components used in energy systems to suppress unwanted harmonic components. However, during the design process of these reactors, both electromagnetic and electrical losses must be carefully analyzed. Depending on the reactor's structure, the materials used, and the operating conditions, various types of losses may arise. Accurate calculation of these losses is critical for ensuring the efficient operation of the reactor and maintaining its thermal stability.

1. **Copper Losses (Joule Losses)**

Copper losses refer to the energy losses converted into heat due to the current flowing through the reactor windings. These losses can be calculated using the following formula:

$$P_{Cu} = I_{rms}^2 \cdot R_{ac} \tag{11}$$

Here, Irms represents the total root-mean-square (RMS) current flowing through the reactor, while Rac denotes the AC resistance of the winding. The AC resistance is not limited to the direct current (DC) component; it significantly increases due to the skin effect and proximity effect at harmonic frequencies. In systems where high-frequency harmonic components are prevalent, these effects can substantially elevate copper losses. Therefore, in high-frequency applications, it is recommended to either increase the conductor cross-sectional area or employ stranded conductors (such as Litz wire) to mitigate these losses.

2. Core Losses (Iron Losses)

In harmonic reactors utilizing a magnetic core, two primary types of losses occur within the core material due to the alternating magnetic field: hysteresis loss and eddy current loss.

a) Hysteresis Losses:

Hysteresis loss refers to the energy dissipated during each cycle of magnetization and demagnetization of the material. According to the Steinmetz model, it can be expressed as follows:

$$P_h = k_h \cdot f \cdot B_{max}^n \cdot V \tag{12}$$

- Here, f represents the frequency,
- Bmax denotes the maximum magnetic flux density,
- V is the core volume,
- kh is the material-specific constant, and
- n is a constant defining the hysteresis characteristic (typically ranging from 1.6 to 2).

Although this model does not directly account for the effects of harmonic frequencies, it can be used to estimate the total losses.

b) Eddy Current Losses:

Eddy current losses occur as a result of circulating currents induced within the core due to the changing magnetic field:

$$P_e = k_e \cdot f^2 \cdot B_{max}^2 \cdot t^2 \cdot V \tag{13}$$

In this formula,

- t represents the lamination thickness,
- ke is the material constant.

Since the eddy current losses are proportional to the square of the frequency, the presence of harmonic components significantly increases these losses. Therefore, thin laminations are preferred in harmonic reactors, and the use of air gaps is employed to prevent local saturation.

3. Additional Source Losses

In addition to the above, other losses that may occur during the reactor design include:

- Contact resistances at connection points,
- Damped vibration losses caused by mechanical oscillations,
- Increased thermal conduction losses due to insufficient cooling systems.

These losses are generally not formulated directly but are considered in thermal analysis simulations.

4. Total Loss and Efficiency

When all these components are combined, the total reactor loss is expressed as follows:

$$P_{total} = P_{cu} + P_h + P_e + P_{extra} \quad (14)$$

Here, P_{extra} represents the additional losses arising from connection points, mechanical damping, and environmental effects.

These total losses directly affect the efficiency of the reactor:

$$\eta = \frac{P_{output}}{P_{input}} = 1 - \frac{P_{total}}{P_{input}} \quad (15)$$

3. Results and Discussion

Table 2 illustrates the analytical calculation. The calculations were conducted five iterations based on the data presented in Table 1.

Table 2. Analytical Calculation Results for Set of Iterations with 13.8kV Operating Voltage and 80K Temperature Rise [13].

Results	1.	2.	3.	4.	5.
Lleak	0,05	0,1	0,2	0,05	0,1
Bm (T)	1,1	1,1	1,1	1,1	1,1
A (mm^2) (x103)	45	39,2	39,2	57,8	57,8
A_eff (mm^2) (x103)	44,1	38,4	38,4	56,6	56,6
foil thickness (mm)	0,15	0,15	0,15	0,25	0,25
J (A/mm^2)	1,4	1,3	1,4	1,1	1,2
height (mm)	729	717	705	865	837
N (turns)	730	730	680	550	490
l_gap (mm)	39,2	36,1	35,2	57,2	47,9
Winding width (mm)	329	329	306	303	270
window (mm)	474	474	451	448	415
a (mm)	150	140	140	170	170
b (mm)	300	280	280	340	340
Temp Rise (K)	82	81,5	81,7	82	81,7
wind-wind clear. (mm)	25	25	25	25	25

yoke clearance (mm)	120	120	120	120	120
tube (mm)	60	60	60	60	60
PVC (euro)	2518	2421	2191	3912	3745

FEM-Based Harmonic Reactor Design Approach

The application of the Finite Element Method (FEM) in harmonic filter reactor design follows a structured and physics-based workflow to ensure high accuracy in electromagnetic analysis. The simulations are generally conducted using ANSYS Maxwell, which is specifically developed for the analysis of low-frequency electromagnetic devices, including transformers and reactors. ANSYS Maxwell enables both 2D and 3D field analysis, incorporates nonlinear material modeling, and provides advanced post-processing capabilities for inductance, losses, and field visualization [16].

In addition to the primary simulation environment, FEM-based analysis can also be performed using COMSOL Multiphysics, which provides a flexible multiphysics platform for accurately modeling the electromagnetic and structural behavior of reactor systems [17].

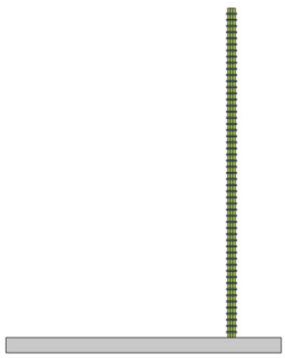

Figure 5. 2D axisymmetric finite element model of reactor in COMSOL software [17].

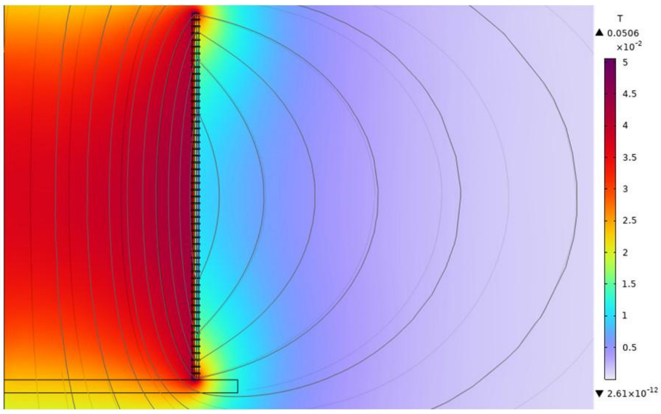

Figure 6. Distribution of magnetic flux density in COMSOL software [17].

ANSYS Maxwell provides a comprehensive set of boundary condition definitions that are essential for accurately formulating electromagnetic field problems. According to the Maxwell Theory Documentation [18], these boundary conditions are categorized into several types such as Dirichlet (essential) boundaries, Neumann (natural) boundaries, and symmetry or periodic boundaries, each serving a specific physical modeling purpose. Dirichlet boundary conditions are typically used to enforce fixed potential or field values on domain surfaces, while Neumann boundary conditions define the normal component of the field flux across boundaries. In addition, symmetry and periodic boundary conditions are widely applied to reduce computational domain size and improve simulation efficiency without compromising accuracy. These formulations are detailed in the boundary condition sections of the official ANSYS Maxwell Theory Guide [18], ensuring that the numerical model is consistent with fundamental electromagnetic field theory and real-world physical constraints.

Table 3. Boundary Conditions Used in ANSYS Maxwell [19].

Boundary Condition Type	**Mathematical Formulation**	**Physical Meaning**	**Typical Application in Maxw**
Dirichlet (Essential)	$\phi = constant$	Fixed potential / field valu imposed on boundary	Electric potential or magneti vector potential fixed surfaces
Neumann (Natural)	$\frac{\partial \emptyset}{\partial n}$	Zero normal flux across boundary	Magnetic insulation or oper boundary approximations
Symmetry Boundary	$\boldsymbol{n} \cdot \boldsymbol{B} = 0\ or$ $\boldsymbol{n} \times \boldsymbol{A} = 0$	Field symmetry condition reducing computational domai	Periodic or geometrically symmetric structures
Periodic Boundary	$\phi(x) = \phi(x + T)$	Repetition of field distributi in periodic structures	Rotating machines, repetitiv magnetic structures
Open Bounda (Infinite Element	$Far - field\ approxim$	Simulation of unbounded domain	External field radiation and leakage flux problems

1) Geometry Definition

The first step in FEM-based design is the creation of an accurate geometrical model of the harmonic filter reactor. Depending on the design type, this may include iron-core or air-core configurations. The model must represent all critical components, including the magnetic core, windings, insulation layers, and air-gap regions.

Geometry is typically constructed using parametric modeling tools in ANSYS Maxwell, allowing key dimensions such as core diameter, air-gap length, and winding spacing to be defined as variables. This parametric structure is essential for subsequent design optimization studies.

A conventional approach to defining the equivalent inductances of a reactor typically relies on analogies with transformer models, where inductance components are associated with distinct magnetic flux paths. However, unlike transformers, reactors consist of a single winding, and therefore the separation between main flux and leakage flux cannot be rigorously defined based on mutual coupling. This ambiguity becomes even more pronounced in gapped iron core reactors, where magnetic flux lines partially leave the core, traverse the air region, and re-enter the core structure [20].

Consequently, the identification of discrete flux tubes corresponding to "main" and "leakage" inductances becomes highly approximate and physically inconsistent [20].

FEM-based approaches have been widely used for the calculation of inductance and winding losses in dry-type detuned reactors. In previous studies, inductance values obtained using COMSOL Multiphysics were validated with experimental results, showing that models including the core and air-gap configuration provide high accuracy, whereas air-core simplifications lead to significant errors due to the strong dependence on air-gap geometry [21].

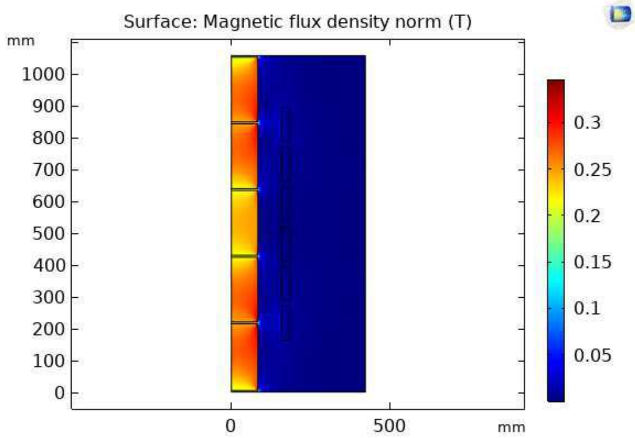

Figure 7. Magnetic flux density distribution in configurations of the core window COMSOL software [21].

Similarly, winding loss calculations performed using both detailed and simplified modeling approaches yield comparable results, indicating that model selection can be based on the trade-off between computational cost and accuracy [21].

To overcome these limitations, traditional analytical models introduce simplified magnetic flux paths, as illustrated in Fig. 8a, leading to equivalent inductance circuits composed of series and/or parallel elements (Fig. 8b) [14], [15]. In such representations, the inductance associated with the iron core is often neglected due to its relatively small contribution in series models or its dominance in parallel models under unsaturated conditions. However, these simplifications rely heavily on assumed flux distributions and typically require empirical correction coefficients to account for fringing effects, leakage flux, and nonlinear material behavior.

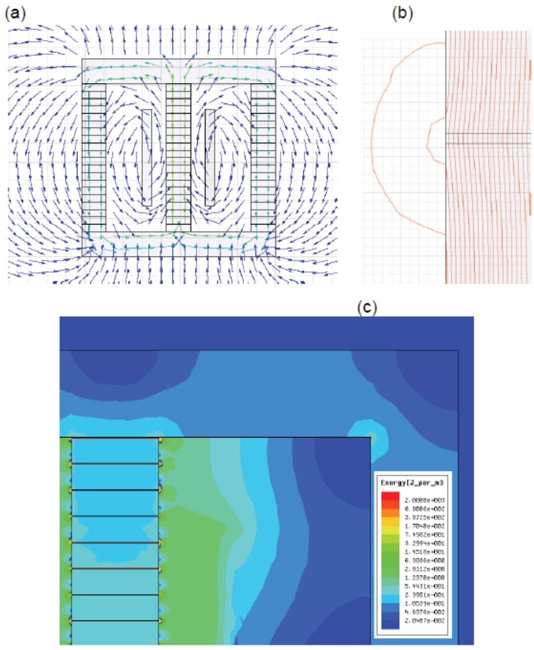

Figure 8. Magnetic flux pattern in a three-limb reactor (a); a detail showing fringing (b); energy distribution (c) [20].

In contrast, a Finite Element Method (FEM)-based approach eliminates the need for predefined flux paths by directly solving Maxwell's equations over the reactor geometry. The magnetic field distribution is obtained numerically, allowing all flux components—including core flux, leakage flux, and fringing fields—to be inherently captured without artificial separation.

Accurate geometry definition is particularly important because electromagnetic field distribution—especially leakage flux and fringing effects—is highly sensitive to physical dimensions. Studies in 2024 confirm that simplified geometrical assumptions can lead to significant errors in inductance estimation and loss prediction [9], [23].

2) Material Modelng

Material definition is a critical step in FEM simulations. In harmonic filter reactors, nonlinear magnetic materials are commonly used in iron-core designs. Therefore, accurate representation of the B–H curve is required.

Nonlinear material properties can be directly defined in ANSYS Maxwell, enabling accurate representation of magnetic saturation effects. The relationship between magnetic field intensity H and flux density B is inherently nonlinear and is typically defined based on experimental measurements or manufacturer-provided data.

Additionally, electrical conductivity of winding materials (typically copper or aluminum) is defined to account for eddy current losses. Frequency-dependent effects such as skin and proximity effects become significant at harmonic frequencies and must be considered for accurate loss estimation [9].

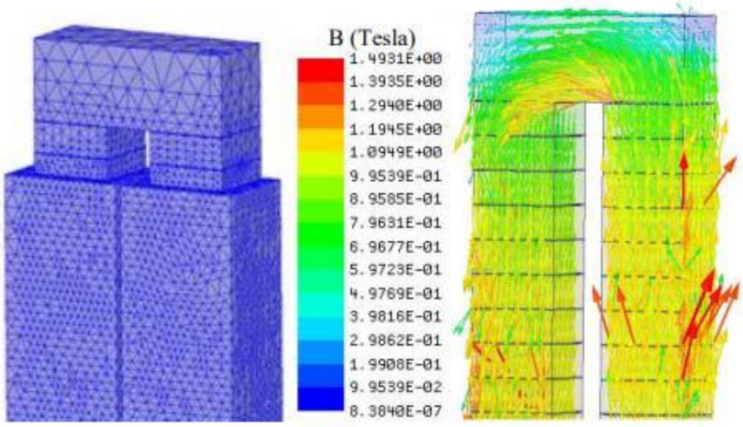

Figure 9. 3D model mesh distribution and magnetic flux density for single-phase model [3].

Recent literature searches highlights that improper material modeling can result in underestimation of core losses and incorrect prediction of saturation regions, directly affecting reactor performance [7], [23].

3) Meshing Strategy

The computational domain is discretized into finite elements through a meshing process. Mesh quality plays a crucial role in the accuracy and convergence of FEM simulations.

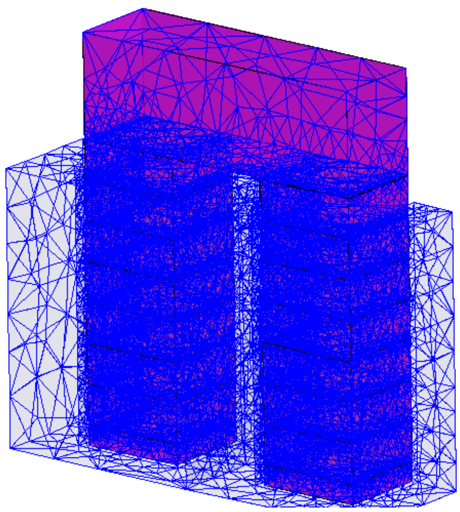

Figure 10. Mesh distribution of the Maxwell 3D magnetostatic analysis [8].

Adaptive meshing techniques are employed, where the mesh is automatically refined in regions with high field gradients, such as air gaps and near conductor surfaces in FEM based tools. A finer mesh improves accuracy but increases computational cost, requiring a balance between precision and efficiency.

Additionally, adaptive meshing algorithms are employed to ensure an optimal balance between numerical accuracy and computational efficiency. The solver initially generates a coarse mesh and progressively refines it based on error estimation criteria derived from field energy variation and magnetic flux density gradients. Regions exhibiting high field concentration, such as air gaps, core edges, and winding proximity zones, are automatically refined to capture leakage flux, fringing effects, and saturation phenomena with higher resolution.

In practical implementations, different meshing strategies can be applied depending on the complexity of the geometry and the desired level of accuracy. Within ANSYS Maxwell, both automatic and user-defined mesh operations are available. These include length-based mesh controls, surface approximation settings, and local mesh refinement operations applied to specific regions such as core edges, air gaps, and winding conductors. Length-based meshing, in particular, allows direct control of element size and is especially useful for resolving regions with high electromagnetic field gradients.

To improve solution robustness, a mesh convergence study is performed by systematically refining the mesh until variations in key output parameters, such as inductance and core losses, remain within an acceptable tolerance range. This ensures that the obtained results are independent of mesh density and numerically stable.

Mesh sensitivity analysis has been widely recognized as a critical step to ensure the reliability and numerical robustness of finite element simulation results, particularly in electromagnetic designs characterized by strong leakage flux paths and localized saturation effects [9, 23, 24].

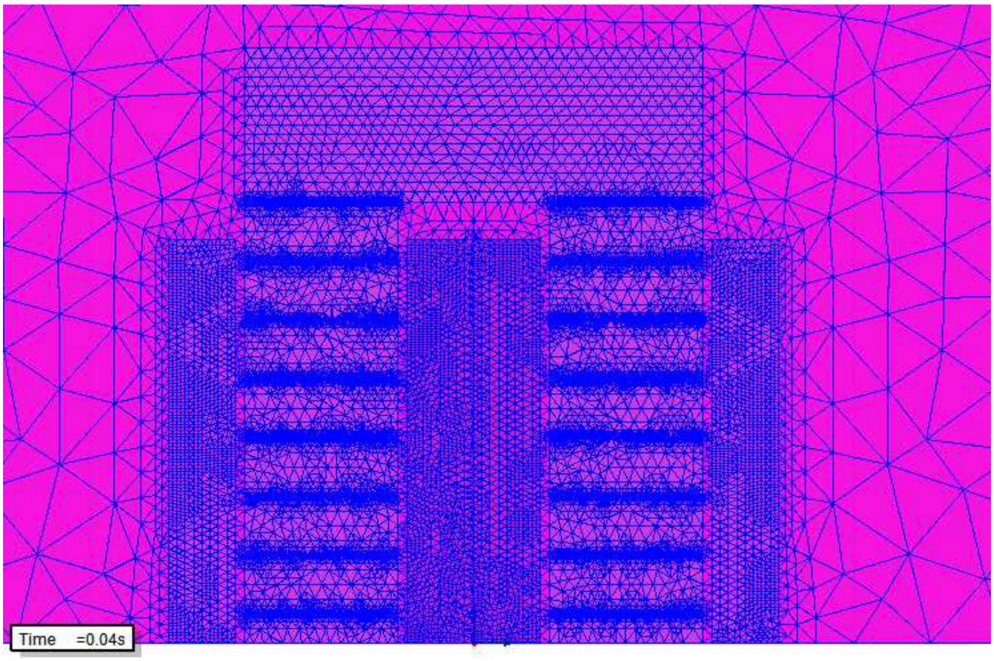

Figure 11. Core loss variations and mesh distributions of the single-phase shunt reactor (ANSYS Maxwell) [8].

Furthermore, special attention is given to the mesh quality near nonlinear magnetic materials, where the B–H curve introduces additional convergence sensitivity. In these regions, localized mesh refinement is applied to accurately resolve steep transitions in permeability. The final mesh configuration achieves a trade-off between computational cost and solution accuracy, ensuring reliable electromagnetic field representation while maintaining feasible simulation time.

Previous studies have demonstrated that adaptive meshing techniques significantly improve the accuracy of electromagnetic field simulations, particularly in regions with high field gradients and nonlinear material behavior [9], [24]. However, for high-accuracy applications, hybrid meshing strategies that combine automatic refinement with user-defined controls are often employed to ensure sufficient resolution of critical regions and to improve overall simulation accuracy.

Table 3. FEM Approach Simulation Results for Set of Iterations with 13.8kV Operating Voltage and 80K Temperature Rise [13].

Results	1.	2.	3.	4.	5.
L_total (mH)	944,8	892,7	789,8	470,4	434,3
L_gap (mH)	765,7	725	644,6	383,3	362,9
L_iron (mH)	1,69	1,82	1,55	0,62	0,68
L_leakage (mH)	177,5	165,9	143,6	86,5	70,7
Leakage %	18,8	18,6	18,2	18,4	16,3
Inductance decline %	16,85	10,39	2,34	16,33	7,40

According to the study presented in [13], a high level of agreement is achieved between the Finite Element Method (FEM) results and the corresponding analytical calculations. This consistency demonstrates that the FEM-based model accurately captures the electromagnetic behavior of the system, with numerical results closely matching the analytical predictions in terms of both trend and magnitude.

The power, The Finite Element Method (FEM)-based electromagnetic simulations were conducted to evaluate the performance of the harmonic filter reactor under realistic operating conditions, considering nonlinear magnetic behavior, complex geometry, and frequency-dependent effects. The numerical analysis performed using ANSYS Maxwell and COMSOL provides detailed insight into inductance variation, flux density distribution, and saturation phenomena, which are not fully captured by classical analytical approaches [9], [23].

The results indicate that the magnetic flux distribution is highly sensitive to geometric configuration, particularly air-gap length, core structure, and winding arrangement. Significant flux concentration and fringing effects are observed in air-gap regions, leading to localized increases in magnetic field intensity. These phenomena directly affect the effective inductance of the reactor and introduce deviations from ideal analytical predictions based on simplified flux path assumptions [14], [15]. Moreover, nonlinear B–H characteristics of the core material result in localized saturation under higher excitation levels, which further impacts inductance stability and increases core losses [7], [23].

The mesh refinement study demonstrates that solution accuracy is strongly dependent on mesh density, especially in regions with steep field gradients such as air gaps and conductor edges. Adaptive meshing in general ANSYS Maxwell and COMSOL tools improves the resolution of localized electromagnetic effects by iteratively refining elements based on field energy variation criteria. It is observed that inductance values converge within an acceptable tolerance range as mesh density increases, confirming the numerical stability and reliability of the FEM model [8], [23].

Furthermore, comparison with classical analytical models highlights that FEM based results provide significantly improved accuracy in predicting inductance and electromagnetic field behavior. Analytical approaches tend to underestimate leakage flux and fringing effects due to idealized assumptions on flux distribution, whereas FEM inherently captures these effects through direct numerical solution of Maxwell's equations [14], [15]. This discrepancy becomes more pronounced in gapped core structures, where magnetic flux paths are highly non-uniform and strongly influenced by geometric discontinuities.

4. Conclusion

The use of the Finite Element Method (FEM) has become increasingly important in the analysis and design of harmonic filter reactors, particularly with the growing complexity of modern power systems and the widespread presence of nonlinear loads. As discussed throughout this study, FEM enables a significantly enhanced predictive capability by providing a detailed representation of electromagnetic behavior that cannot be achieved through conventional analytical methods alone.

FEM-based analyses allow accurate modeling of complex geometries, nonlinear magnetic material properties, leakage flux paths, and fringing effects, all of which play a critical role in determining reactor performance. In this context, proper definition of geometry, material characteristics, and mesh quality is essential to obtain reliable and physically meaningful simulation results. These capabilities support more accurate inductance estimation and improved evaluation of reactor behavior under harmonic-rich operating conditions, contributing to compliance with IEEE 519 power quality requirements.

In addition to accuracy improvements, FEM provides substantial practical advantages for engineers and designers. The ability to perform both 2D and 3D analyses enables flexible investigation of different design configurations and operating scenarios. Furthermore, FEM significantly reduces design and analysis time by minimizing the need for iterative prototyping and experimental validation, allowing faster design cycles and more efficient optimization processes.

Overall, FEM has evolved into a powerful and indispensable tool in harmonic filter reactor engineering. Its capability to combine detailed physical modeling with computational efficiency offers significant benefits in terms of design reliability, performance assessment, and engineering productivity, making it a key enabler for modern reactor analysis and development practices.

References

1. IEEE Standard 519-2014. IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems. IEEE, **2014**.
2. Dugan, R.C.; McGranaghan, M.F.; Santoso, S.; Beaty, H.W., *Electrical Power Systems Quality*, 3rd ed.; McGraw-Hill: New York, NY, USA, **2012**.
3. Dönük, A., Optimum Design of Single and Three Phase Iron Core Shunt Reactors. *Journal of the Faculty of Engineering and Architecture of Gazi University*, **2022**, *vol. 37*, no. 2, pp. 1063–1076.
4. IEEE Standard 519-2022. IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems. IEEE, **2022**.
5. Bollen, M.H.J.; Gu, I.Y.H., *Signal Processing of Power Quality Disturbances*; Wiley-IEEE Press: New York, NY, USA, **2006**.
6. Rahman, M.S.; et al. Advanced Harmonic Mitigation Techniques in Power Systems with High Penetration of Power Electronics. *IEEE Access*, **2024**, *vol. 12*, pp. 14523–14540.
7. Zhang, Y.; Wang, L.; Li, H., Design and Optimization of Passive Harmonic Filters Using Simulation-Based Methods. *Electric Power Systems Research*, **2025**, *vol. 229*.
8. Dönük, A., Effect of Air Gaps on Iron Losses in Shunt Reactors. *Journal of the Faculty of Engineering and Architecture of Gazi University*, **2022**, *vol. 37*, no. 2.
9. Jin, J., *The Finite Element Method in Electromagnetics*, 3rd ed.; Wiley-IEEE Press: Hoboken, NJ, USA, **2014**.
10. Salon, S.J., *Finite Element Analysis of Electrical Machines*; Springer: New York, NY, USA, **1995**.
11. Sadiku, M.N.O. *Numerical Techniques in Electromagnetics*; CRC Press: Boca Raton, FL, USA, **2009**.
12. Kundur, P., *Power System Stability and Control*; McGraw-Hill: New York, NY, USA, **1994**.
13. Dönük, A., Determination of Leakage Inductance Percentage for Gapped Iron-Core Shunt Reactors with M4 Steel as Core Material. *Balkan Journal of Electrical and Computer Engineering*, **2020**, *vol. 8*, no. 2.
14. Alexander, G.W.; Hopkinson, R.H.; Welch, A.U., Design and Application of EHV Shunt Reactors. *IEEE Transactions on Power Apparatus and Systems*, **1966**, *vol. PAS-85*, no. 12, pp. 1247–1258.
15. Hao, Y.; Xu, Y.; Liu, Y.; Zhu, Y.; Xiao, X., Study of Nonlinear Model of Shunt Reactor in 1000 kV AC Transmission System. In *Proceedings of the International Conference on Energy and Environment Technology*, **2009**, *vol. 2*, pp. 305–308.
16. ANSYS Inc., *ANSYS Maxwell User's Guide*, Release 2025 R1, **2025**.

17. Khodadad, A.; Samimi, M., Acoustic Noise Estimation of Air-Core Reactors Using the Finite Element Method. In *Proceedings of the 5th International Conference on Electrical Machines and Drives (ICEMD)*, Tehran, Iran, **2025**.
18. ANSYS Inc. *ANSYS Maxwell Theory Guide*, Release 2024 R2; ANSYS Inc.: Canonsburg, PA, USA, **2024**.
19. ANSYS Inc. *ANSYS Maxwell User's Guide and Theory Manual*, Release 2024 R2; ANSYS Inc.: Canonsburg, PA, USA, **2024**.
20. Dönük, A.; et al., Defining and Computing Equivalent Inductances of Gapped Iron Core Reactors. *Przegląd Elektrotechniczny*, **2012**, *vol. 88*, pp. 52–55.
21. Azizian, D.; Bigdeli, M.; Saberi, S., Calculation of Inductance and Winding Losses of Dry Type Detuned Reactor Using Finite Element Method. In *Proceedings of the 28th International Electrical Power Distribution Conference (EPDC)*, Zanjan, Iran, **2024**.
22. Kumar, A.; Singh, P., Finite Element Analysis of Reactor Losses Under Harmonic Conditions. *IET Electric Power Applications*, **2024**, *vol. 18*, no. 2, pp. 210–222.
23. Müller, J.; et al. FEM-Based Optimization of Power Reactors for Harmonic Filtering Applications. *IEEE Transactions on Magnetics*, **2025**, *vol. 61*, no. 3.
24. Silvester, P.P.; Ferrari, R.L., *Finite Elements for Electrical Engineers*; Cambridge University Press: Cambridge, United Kingdom, **1996**.