Multi-Objective Design of High Efficiency Magnetic Flux Leakage Transformers Using Genetic Algorithms and FEM Validation

Mouhcine Lahame, Hamid Outzguinrimt, Rajaa Oumghar, Boubkar Bahani, Mohammed Chraygane

Abstract— The present study aims to develop and validate an optimal design for a 700 VA Magnetic Flux Leakage Transformer (MFLT), specifically tailored for industrial applications such as power supplies for microwave systems. The optimization method uses a Genetic Algorithm (GA) with a multi-objective function for minimizing the transformer's total volume and core and copper losses. Geometrical parameters are used as variables in the optimization process, with constraints applied to ensure the design complies with transformer sizing standards and operates effectively under appropriate load conditions. Following the execution of the algorithm, the optimal solution is validated through numerical simulation conducted using the Finite Element Method (FEM) in ANSYS software, confirming its consistency with the analytical results. The findings demonstrate that the suggested design reduces the transformer volume by 13%, leading to decreased manufacturing costs while maintaining an acceptable level of losses. This optimization process significantly improves the performance, efficiency, and cost-effectiveness of transformer production for industrial applications, particularly in sectors where energy efficiency is important.

Index Terms—**Magnetic Flux Leakage Transformer (MFLT), Genetic Algorithm (GA), Finite Element Analysis Method (FEM), ANSYS.**

I. INTRODUCTION

Transformers are essential in electrical equipment supplies. Their principal role is adjusting the voltage to the needs at which electrical loads operate. In addition, transformers offer electrical isolation between circuits for protection against surges and voltage fluctuations in sensitive equipment [1].

Magnetic Flux Leakage Transformers (MFLTs) represent a significant technological advancement, featuring a unique design that enhances transformer performance. A distinctive feature is the use of specially designed magnetic shunts with air gaps between the primary and secondary windings, which help reduce magnetic flux leakage, thereby minimizing energy losses and improving the overall efficiency of the transformer [2]. Beyond their primary role of voltage transformation, they offer numerous advantages, including their ability to ensure stable voltage under all load conditions, making them perfectly suited for applications that demand high-voltage stability. In addition, they offer overload protection to enhance the safety and service life the electrical equipment connected [3]. These advantages make MFLTs particularly suitable for electrotechnical devices that require current stabilization to accommodate significant variations in load or supply voltage.

Scientific research has extensively explored the versatility and benefits of this technology across various applications. For instance, in [4], the impact of different shunt geometries on the electromagnetic forces in a 16 kVA industrial transformer was examined, leading to efficiency improvements. Additionally, [5] and [6] proposed a new topology featuring a robust magnetic shunt integrated into a planar transformer, enhancing efficiency and performance. In [7], a detailed 3D study was conducted on the leakage magnetic fields of a transformer with beveled magnetic shunts, providing valuable insights into the distribution of these fields and their effects on performance. Other studies, such as those in [8] and [9], have advanced transformer sizing for microwave applications, particularly focusing on the performance of magnetrons, which are important components in microwave systems. Building on this research, the present study introduces a unique optimal design for a 700 VA MFLT. This design addresses key challenges, including reducing the footprint, minimizing failure risks, and lowering both production and maintenance costs. Particular emphasis is placed on its integration into magnetron power supplies for advanced microwave systems.

Optimization of power transformer designs is inherently complex, representing a balance between the need to meet design standards, reduce production costs, and improve energy efficiency. Previous optimization works, such as those performed in [10] and [11], have focused on using geometric parameter variations using an electrical model of magnetron power supplies to find suitable optimal configurations. These studies, in most cases, have not considered compliance with recommended design standards,

Manuscript received January 23, 2025; revised June 20, 2025.

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magnetic states, and detailed evaluations of core and copper losses. These shortcomings highlight the need for advanced techniques, such as magnetic simulation, providing an in-depth analysis of the complex interactions between the physical phenomena involved [12],[13]. Furthermore, multi-objective optimization methods can be directly applied in practice to identify balanced trade-offs among conflicting design goals, such as transformer energy efficiency, reliability, and cost-effectiveness [14]. The integration of these techniques will lead to the development of transformers with enhanced electrical and operational performance. This proposed research will fill these gaps and make new contributions to the next generation of efficient and cost-effective MFLTs for industrial applications.

In this study, a multi-objective optimization process is proposed to improve the design of a MFLT. The main goal is to reduce the overall transformer volume while achieving a balanced compromise in minimizing both core and copper losses. To accomplish this, a Genetic Algorithm (GA) is applied, where the objective functions are defined based on transformer volume and electromagnetic losses. The optimization process is based on detailed modeling, using key geometric parameters as decision variables. Moreover, a set of constraint functions is introduced to ensure that the optimized design complies with essential transformer design requirements, including the winding fill factor, magnetic saturation limits, and rated apparent power. After identifying the optimal solution, its electromagnetic performance and structural feasibility are validated using 3D Finite Element Method (FEM) simulations in ANSYS software. This step ensures that the optimized geometry satisfies both performance expectations and industrial design standards under realistic operating conditions.

This paper is structured as follows, after the introduction. Section 2 describes the methodology used for transformer optimization. Section 3 presents a detailed model of the transformer, outlining the formulas related to volume as well as core and copper losses. Section 4 focuses on applying the derived formulas to the GA. This section examines the various solutions obtained after applying the algorithm, aiming to find an optimal trade-off between volume and losses. Finally, Section 5 presents the validation of the obtained design using FEM analysis.

II. METHODOLOGY

The methodological approach of the optimization study presented in Fig.1 consists of three steps: modeling, optimization, and validation.

- The first part focuses on the modeling of the MFLT, where mathematical functions representing the transformer are developed based on the design specifications. This phase includes the modeling of the volume and losses in the core and copper. The results of this modeling serve as a basis for the optimization, also taking into account the geometric parameters.
- The second part deals with the optimization of the MFLT using a multi-objective genetic algorithm, which is designed in such a way that the parameter space will be searched for an optimal configuration. Objective functions and constraints can be clearly defined to guide the search. This iterative process details the evolution of the algorithm to selecting the most suitable solution according to the established criteria.
- The third part describes the validation using a numerical approach by FEM, carried out in ANSYS. The method offers high accuracy to simulate the physical phenomena occurring in the MFLT, mainly electromagnetic fields and core and copper losses. Numerical validation provides insight into the relevance and robustness of the optimized solutions by comparing the optimization results with the actual simulations performed.

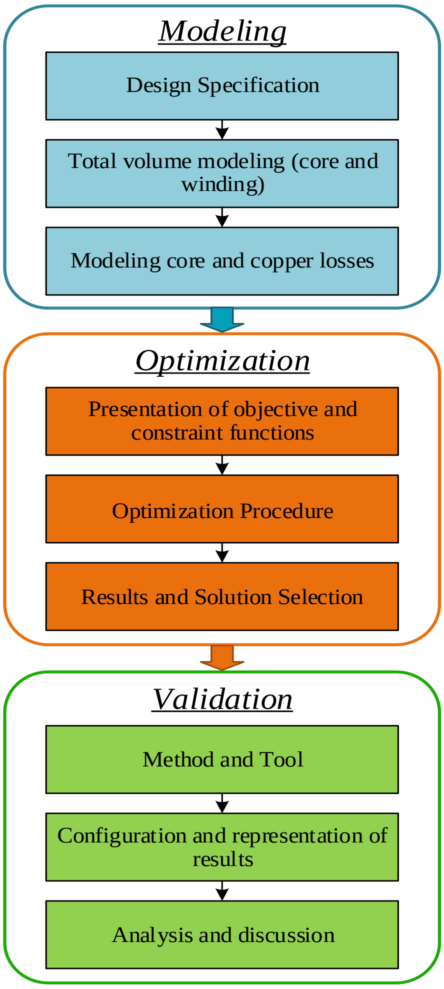

Fig. 1. Presentation of the methodological approach for MFLT optimization

III. TRANSFORMER MODELING

A. *Transformer Geometry*

In this study, the MFLT shown in Fig. 2 has a rated power of S=700VA. Its core is constructed from stacked steel sheets in an E-shape, arranged in an EI configuration. The primary winding, with N_1=230 turns, is placed around the center of the core and is supplied with an input voltage of U_1=220V. The secondary windings, consisting of N_2=2200 turns, provide an output voltage of U_{20}=2100V and are well insulated from the primary windings. A filament winding, coupled to the secondary, powers the magnetron filament, ensuring stable electron emission and reliable

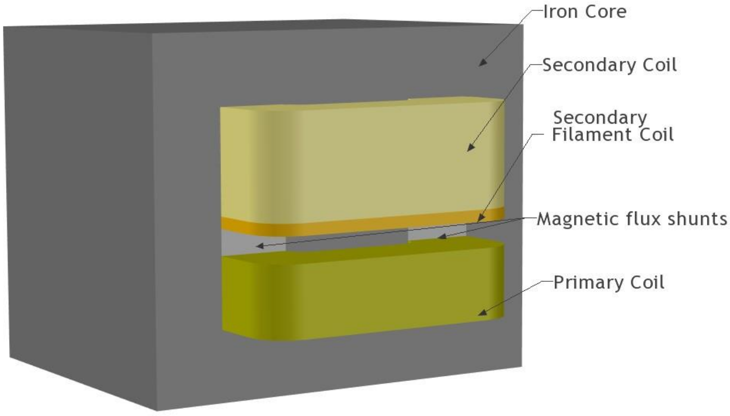

Fig. 2. Structure of the MFLT

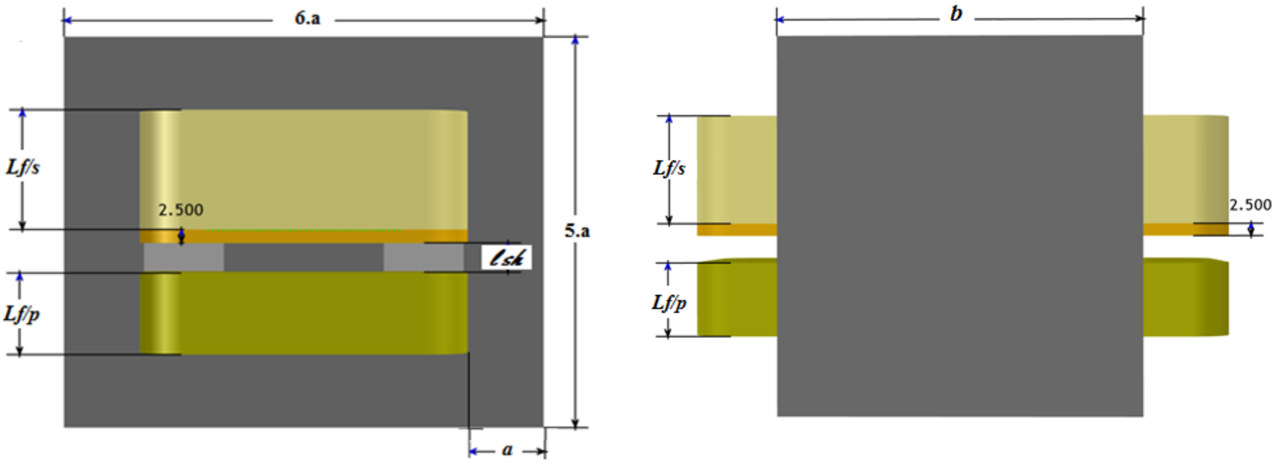

Fig. 3. 3D dimension of the MFLT

operation. Flux shunts made of steel are positioned in the core's side windows to reduce parasitic losses and enhance performance [15]. This design is particularly well-suited for a microwave transformer operating under magnetic saturation, which helps stabilize the average anode current of the magnetron while minimizing energy losses. Known for its durability and reliability, this transformer maintains high efficiency even under variable loads. Fig. 3 shows the 3D dimensional structure of the MFLT in letters.

The precise modeling of the geometric configuration of the transformer will be conducted with a focus on the parameter denoted as (a), which specifically determines the geometry of the magnetic core sheets. This parameter defines the width of the sheets, which form the foundational structure of the transformer core.

Additional critical parameters, alongside (a), include the length of the sheet pack, represented by(b), and the thickness of the air gap, symbolized by (e). These parameters play a significant role in shaping the magnetic properties of the transformer, ultimately affecting its efficiency. Indeed, they influence the core's capacity to concentrate magnetic flux and the air gap's ability to prevent magnetic saturation.

The total volume of the transformer, denoted as V_T, in equation (1) is considered as the sum of the volumes of its key components (core and winding).

$$V_T = V_c + V_w \tag{1}$$

With:

- V_c: represents the total volume of the magnetic core of the transformer.
- V_w : corresponds to the combined volume of the primary and secondary windings.

The core volume V_{core}, defined in equation (2), is calculated as the magnetic core volume V_{CM} minus the volume of the two windows V_f, plus the volume of the magnetic shunts V_{SM}.

$$V_c = V_{CM} - V_f + V_{SM} \tag{2}$$

Substituting the expressions for each component:

$$V_c = \left(30a^2 \times b\right) - 2\left(3a^2 \times b\right) + 2\left(\left(a - 2e\right) \times \ell_{sh} \times b\right) \tag{3}$$

The total volume of the windings is calculated as the sum of the volumes of the primary winding $V_{w/p}$, the secondary winding $V_{w/s}$, and the filament winding $V_{w/f}$, as expressed in equation (4).

$$V_w = V_{w/p} - V_{w/s} + V_{w/f} \tag{4}$$

The volume of each winding is determined by the number of turns per column N_s, the number of columns per winding N_c, conductor diameter (d), and the cross-sectional area S_{wire} of the conductor, as illustrated in Fig.4.

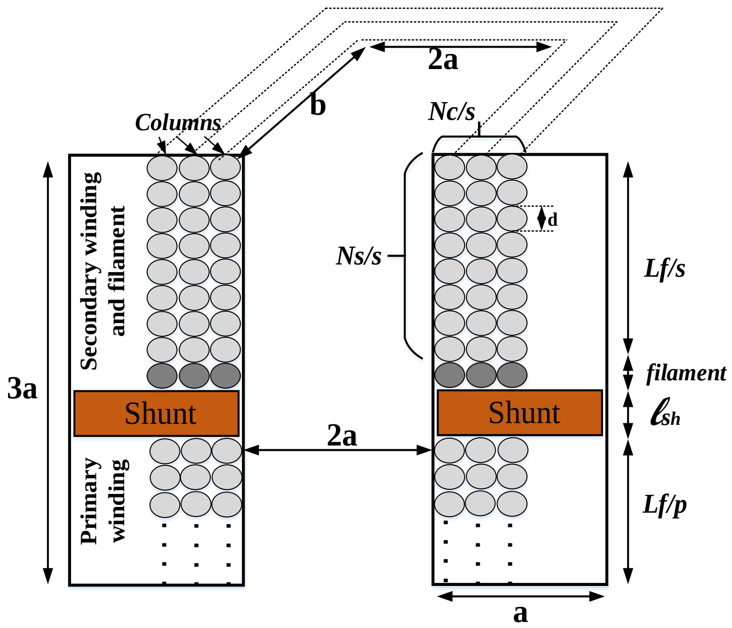

Fig. 4. Geometric Overview of the Primary, Secondary, and Filament Windings.

The formula used to calculate the volume of each winding (primary, secondary or filament) is defined by equation (5) and is expressed in the form $V_{w/j}$. j which can take the value primary, secondary or filament.

$$V_{w/j} = S_{Wire/j} \times N_{s/j} \times \sum_{i=0}^{N_{c/j}} \left[2 \times \left(b + 2a + \left(4d_j + i \right) \right) \right] \quad (5)$$

With:

$$S_{Wire/j} = \pi . \left(\frac{d_j}{2} \right)^2 \quad (6)$$

$$N_{s/j} = \frac{L_{f/j}}{d_j} \quad (7)$$

$$N_{c/j} = \frac{n_{(1/2)}}{N_{s/j}} \quad (8)$$

$n_{(1/2)}$ presents the number of primary n_1 or secondary windings n_2 and $L_{f/j}$ is the winding window length, with:

$$L_{f/p} = a \quad (9)$$

$$L_{f/s} = 2a - \left(\ell_{sh} + 2.5 \right) \quad (10)$$

The fill factor $K_{f/j}$ presented in equation (11) is a key geometric parameter in transformer design. It is defined as the ratio of the surface area occupied by the winding $S_{b/j}$ to the total surface area available for the primary or secondary winding S_{air} presented in (12). For an optimal design, the fill factor should typically range between 0.4 and 0.7 [16]. The formula for the fill factor is given by:

$$K_{b/j} = \frac{S_{b/j}}{S_{air}} \quad (11)$$

With

$$S_{b/j} = \left(N_{s/j} \times N_{C/j} \right) . S_{fil} \quad (12)$$

$$S_{air} = \left(L_{f/j} \times a \right) \quad (13)$$

This parameter plays an essential role in transformer design, as it directly influences the winding arrangement, magnetic flux distribution, and thermal performance. An optimal fill factor ensures efficient utilization of the winding space while maintaining adequate insulation and cooling pathways.

The geometric parameters of the MLFT, denoted by symbols and accompanied by their numerical values, are provided in Table I:

TABLE I
GEOMETRIC PARAMETERS OF THE MLFT STUDIED

Transformer parameters	Symbols	Values
Width of the wound core	a	15 mm
Depth of the magnetic circuit	b	72 mm
Length of shunts	ℓ_{sh}	5.5 mm
Air gap dimension	e	0.75mm
LV wire diameter	d_p	1.5 mm
HV wire diameter	d_s	0.5 mm
Transformer volume	V_T	480.2 cm^3
Apparent power	S	700 VA
No-load current	I_1	3.18A

B. *Core and copper losses*

Transformer core losses are calculated using empirical equations based on design material properties and geometric data, such as the original Steinmetz equation, which is applicable to sinusoidal excitation [17–19]. The core losses are composed of eddy current loss, hysteresis and residual loss. These losses are linked to the operating frequency f and the peak magnetic flux density B_m as indicated in (14).

$$P_{core} = K.f^{\alpha}.B_m^{\beta} \tag{14}$$

The coefficients K, α and β are called Steinmetz coefficients, they are obtained from the material technical sheet by curve adjustment. A more detailed way of expressing the basic losses is to divide (14) into three components: magnetization hysteresis loss P_h, eddy current loss P_e, and excess loss P_{ex}, as shown in (15).

$$\begin{aligned} P_{core} &= P_h + P_e + P_{ex} \\ &= K_h.f^{\alpha}.(B_2)^2 + K_e.(f.B_m)^2 + K_{ex}.f^{\alpha}.(f.B_m)^{1.5} \end{aligned} \tag{15}$$

Table.2 presents the Steinmetz equation coefficients for the M125-027 material type used for core design [20],[21].

TABLE II
MAGNETIC CHARACTERISTIC OF MATERIAL M125-027

Series	K_h	K_e	K_{ex}	Material density
M125-027	65.48 W/cm³	0.59 W/cm³	2.88 W/cm³	7650 kg/m³

In the case where the transformer is excited by a non-sinusoidal voltage waveform, the core loss is calculated using the formulas given in equations (16) and (17). The coefficients K, α and β are the same indicated in table II.

$$P_{core} = \frac{1}{T}\int_0^T K_i.\left|\frac{dB(t)}{dt}\right|^{\alpha}.|\Delta B|^{\beta-\alpha}.dt \tag{16}$$

$$K_i = \frac{K}{(2\pi)^{\alpha-1}.\int_0^{2\pi}|\cos\theta|^{\alpha}.2^{\beta-\alpha}.d\theta} \tag{17}$$

The power P_{copper} dissipated in the primary, secondary and filament windings of transformer is generally called joule losses or copper losses. When current flows through these wires, it encounters resistance which generates heat. These thermal losses are an important factor to take into account when designing a transformer to ensure its energy efficiency. The copper loss formula is presented in (18).

$$P_{copper} = I_1^2 R_p + I_2^2 R_s + I_f^2 R_f \tag{18}$$

Where I_1, I_2 and I_f represent the currents in the primary, secondary and filament windings respectively, while R_p , R_s and R_f denote the corresponding total resistances of these windings.

IV. MFLT OPTIMIZATION

A. Multi-Objective Optimization

The primary objective of this optimization study is to find an optimal balance between the transformer's volume and its associated losses, which include both core and copper. A significant challenge arises from the inherent trade-off between these two parameters: reducing the transformer's volume often leads to increased losses, while minimizing losses generally requires a larger transformer. This duality complicates the simultaneous minimization of volume and losses. To address this issue, the proposed study employs a GA that is inspired by natural evolution processes. Thus, it can handle efficiently the complex solution space and converge toward the optimum solution.

In multi-objective optimization, there is not a single "optimal" solution but instead an aim to find a set of Pareto optimal solutions where no solution is strictly better than any other across all objectives [22]. That is, if one improves one objective in any of the solutions along the Pareto front, a deterioration in another objective is observed. Therefore, the decision maker has to select the most satisfying solution from this set with the help of some specific preferences, rather than finding a single optimum.

Multi-objective optimization methods have been conventionally divided into two classes: those based on a decision-maker's perspective and those following a more theoretical approach. From the point of view of the decision maker, the classification depends on how preference information is integrated which leads to three approaches: a priori, a posteriori, and interactive [23–25]. A priori incorporates the decision-maker's preferences at the start of the optimization process to orient the search for solutions towards his or her goals. The a posteriori approach, on the other hand, does not make any a priori considerations regarding preferences, executing the optimization and then presenting the obtained set of solutions for further analysis. The interactive method lets the decision-maker give feedback while the optimization proceeds, thus tuning the search for preferred solutions according to her goals during the process. Each method offers a distinct way to incorporate the preferences of the decision-maker, depending on the time at which the information is used in the process.

In this work, the a posteriori method is used. This means that the optimization process is performed without any initial preference information. In such a case, the algorithm will return a set of Pareto optimal solutions, representing various compromises between conflicting objectives. Among such solutions, the decision maker can choose the best one, according to their specific criteria or preferences instance, the volume and acceptable losses of the transformer.

Therefore, in conformity with formulas (1) to (18), a three-dimensional with constraint optimization model is developed based on volume and losses of core and copper, represented in equation (19). This model takes into consideration the particular parameters of each objective-volume and losses-while satisfying the constraints of the transformer, thus allowing for full exploration of the solution space and the selection of an optimal solution.

$$\begin{cases} F_{\min}(x) = F_{\min}\left[f_1(X), f_2(X), f_3(X)\right] \\ f_1(X) = V_T \\ f_2(X) = P_{core} \\ f_3(X) = P_{copper} \end{cases} \tag{19}$$

The constraints of equations (20) -(22) are defined to comply with recognized standards of proper sizing. They aim to preserve the transformer performance by taking into account the filling of the winding windows, avoiding core saturation and maintaining the apparent power of the transformer.

$$0.3 \le k_{b/j} \le 0.7 \quad (20)$$

$$B_m \ge B \quad (21)$$

$$S_{ref} = S_{optimized} = U_{20}.I_2 = U_1.I_1 \quad (22)$$

With

$$B = \frac{U_{20}}{(4.44).N_2.S_2.f} \quad (23)$$

$$m = \frac{U_{20}}{U_1} = \frac{N_2}{N_1} = \frac{I_1}{I_2} \quad (24)$$

$$U_{20} = 2100V \quad (25)$$

Other parameters have not been presented previously. S_{ref} and $S_{optimized}$ represent the apparent powers of the non-optimized and optimized transformers, respectively. B denotes the flux density, while S_2 refers to the cross-sectional area of the secondary core.

B. Optimization Procedure

Using the MATLAB platform, the MFLT optimization process as illustrated in Fig.5.

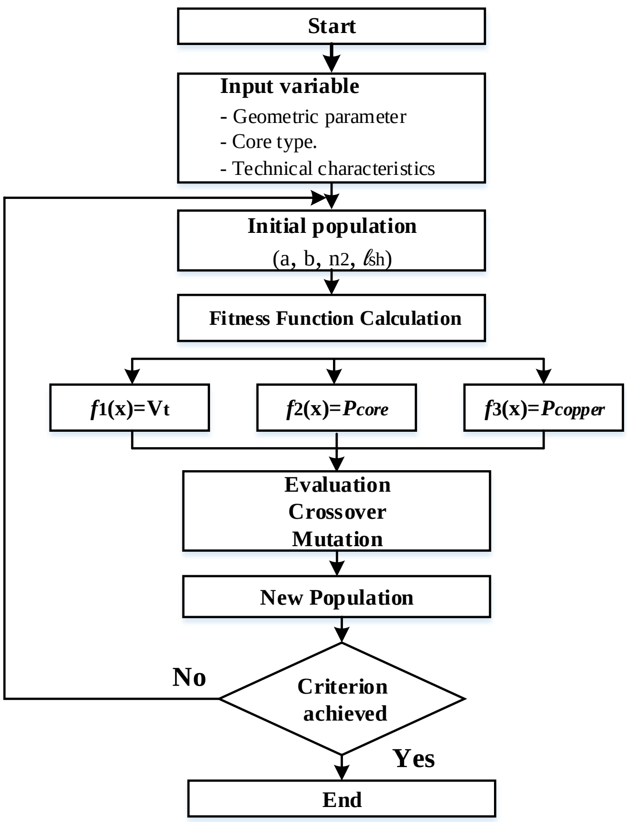

Fig. 5. MLFT optimization flowchart

Geometric parameters and material properties of the transformer are initially defined in the system. These geometric parameters embedded in the objective functions form the initial population. In order to minimize the computation time, they are restricted to specific ranges, as shown in Table III. This allows to limit the search space, thus ensuring a faster and more efficient optimization.

TABLE III
RANGE OF VARIATION FOR TRANSFORMER GEOMETRICAL PARAMETERS

Geometric Parameters	Symbols (x)	Initial	Bounds
Width of the wound core	a(mm)	15	[10 15]
Depth of the magnetic circuit	b(mm)	72	[60 72]
Secondary Windings	n_2	2200	[1500 2500]
Length of shunts	ℓ_{sh} (mm)	5.5	[4 8]

Next, the initial population is randomly generated, and the fitness function is calculated. The predefined constraints are taken into account, generating a new population by the use of crossover and mutation operators. If a population generation meets the defined convergence criteria, the calculation is interrupted, and the individual with the highest fitness is then considered the optimal solution. If the convergence criteria are not satisfied, the calculation process is restarted.

C. Chosen Design

After executing the algorithm, a set of optimal solutions found, called Pareto-optimal solutions form the Pareto front [26], shown in Fig.6. Each transformer parameter combination presents a solution that meets the predefined optimization requirements

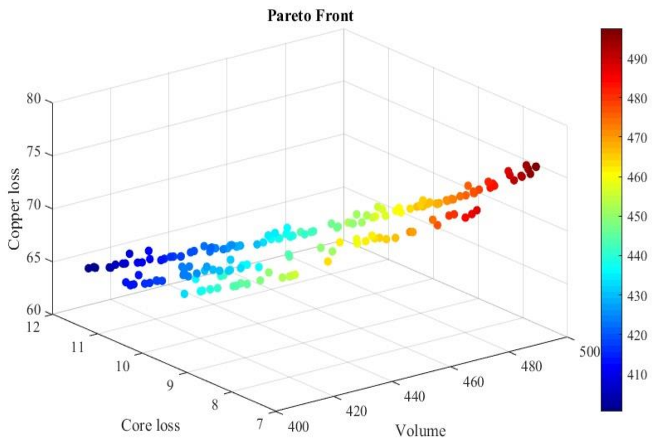

Fig. 6. 3D Pareto Front for the optimized solutions

Once the solutions on the Pareto front are identified, the next step is to select the optimal solution using the chosen selection method (a posteriori). This approach provides the decision maker with the opportunity to choose the best option. The objective is to minimize the volume while maintaining reasonable levels of core and copper losses. To select this solution, a script on MATLAB is developed

TABLE IV
GEOMETRIC PARAMETER COMPARISON: OPTIMIZED AND REFERENCE MFLT DESIGNS

Transformer parameter	Symbols	Optimized MFLT	Reference MFLT
Width of the wound core	a	18.5 mm	15 mm
Depth of the magnetic circuit	b	64.5 mm	72 mm
Primary Windings	n_1	228	230
Secondary Windings	n_2	2188	2200
Length of shunts	ℓ_{sh}	4.5 mm	5.5 mm
Air gap dimension	e	0.75	0.75
Average magnetic flux density	B_{avg}	2.18 T	1.99 T
Core loss	P_{core}	10.87 W	8.4 W
Copper loss	P_{copper}	64.79 W	70.52 W
Primary window filling coefficient	$K_{b/p}$	0.67	0.6
Secondary window filling coefficient	$K_{b/s}$	0.44	0.39
Transformer volume	V_T	418.4 cm^2	480.2 cm^2
Apparent power	S	700 VA	
Primary and Secondary voltage	U_1 / U_{20}	220V/ 2100 V	

which normalizes the values, calculates the overall scores and finds the best compromise which favors the reduction of volume but with optimal and reasonable core and copper losses. The script follows these steps:

- Loads the Pareto solutions into a matrix called data.
- Separates the matrix columns into three columns for volume, core and copper losses.
- Calculate the minimum and maximum values for each column.
- Normalizes the values for each criterion.
- Calculates an overall score for each solution by summing the normalized values.
- Finds the index of the solution with the lowest overall score.
- Displays the values of the best solution.

The simulation of the developed script allows the user to choose the solution adapted to the predefined choice. Table IV compares the parameters of the optimized solution with those of the reference MFLT. The optimization of the transformer volume allowed to find a volume of 418.4 cm² with a reduction rate of 13%. The average magnetic flux density (B_{avg}=2.11 T) is in the acceptable range for the chosen material. The losses in the core increased due to the increase in the magnetic field B, the copper losses decreased thanks to the reduction in the number of turns in the primary and secondary, while maintaining the primary and secondary electromotive forces at the initial values. The constraints predefined concerning the window filling factor, the transformer ratio and the voltage at the primary and secondary terminals was respected.

V. VALIDATION AND DISCUSSION

A. Method and Tool

Validating the optimal geometry requires the use of advanced tools to assess actual performance following fabrication. In this study, we employ the FEM, an essential technique for analyzing electrical machines. A detailed model of the optimized and reference MFLT geometry, incorporating its material and electromagnetic properties, is used. This approach offers significant advantages, particularly in handling complex behaviors such as nonlinear phenomena like magnetic saturation and hysteresis. FEM enables precise analyses, including the distribution of magnetic flux density and the calculation of losses [27], [28]. This ensures a thorough evaluation, confirming the effectiveness of the optimized geometry proposed in this paper.

We use the ANSYS software, the different steps to follow to properly apply this validation methodology are presented as follows [29], [30]:

- **Geometry design:** The transformer model is structured in ANSYS Maxwell, ensuring accurate representation of dimensions. A refined mesh is created to enhance numerical precision, particularly in critical areas such as the core and windings. Mesh density is adjusted to balance accuracy and computational efficiency. The final model is verified for consistency and correctness.
- **Material setup**: Magnetic, electrical, and thermal properties are assigned to all model regions. The material library of ANSYS Maxwell is used, or custom properties are defined if necessary. Core material is characterized by its B-H curve, considering magnetic saturation and hysteresis effects. Conductivity and resistivity are set for the windings to accurately model Joule losses.
- **Boundary conditions**: Symmetry constraints and electrical contacts are set to ensure accurate current flow. Open boundaries and absorbing surfaces are applied to simulate a realistic environment. These conditions help minimize computational complexity while preserving precision.
- **Specification of electromagnetic sources**: Excitation currents and voltages are applied on the windings based on

working scenarios. Sources are defined for steady-state or transient analysis to achieve real-world conditions. External influences are considered for increased accuracy.

- **Analysis and validation**: Magnetic flux distribution is examined to detect areas of high saturation. Core and copper losses are calculated to evaluate energy efficiency and thermal behavior. Results are compared with theoretical expectations and reference designs. Performance metrics are assessed to confirm the advantages of the optimized geometry.

B. Results and discussion

(1) Flux Distribution in MFLT

The magnetic flux distribution plays a critical role in electromagnetic coupling and the efficiency of energy transfer between the primary and secondary windings. It is influenced by the geometry of the core and windings, the magnetic properties of the materials, and operating conditions such as current frequency and the number of winding turns.

As part of this study, a finite element model was developed using ANSYS software to simulate and visualize the magnetic flux density within the MFLT. This type of modeling provides an accurate representation of the magnetic field lines, saturation zones, and potential magnetic losses within the circuit. To optimize computation time while maintaining the model's accuracy, only half of the structure was considered in the simulations. This reduction was made possible by exploiting the geometric symmetry of the transformer, without compromising the reliability of the results obtained.

The simulation results facilitate a comparative analysis between the reference (Fig.7) and optimized (Fig.8) configurations, highlighting changes in magnetic flux paths and saturation zones. This numerical approach serves as a crucial tool for validating the transformer design.

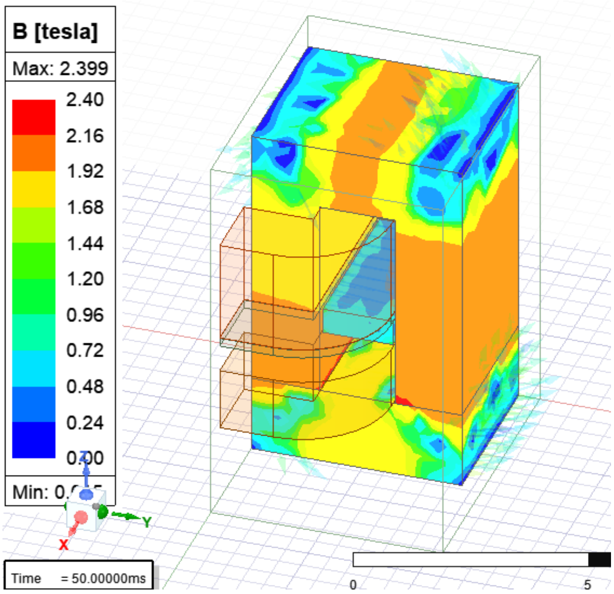

Fig. 7. Magnetic Flux Density Distribution for the Reference MFLT Designs

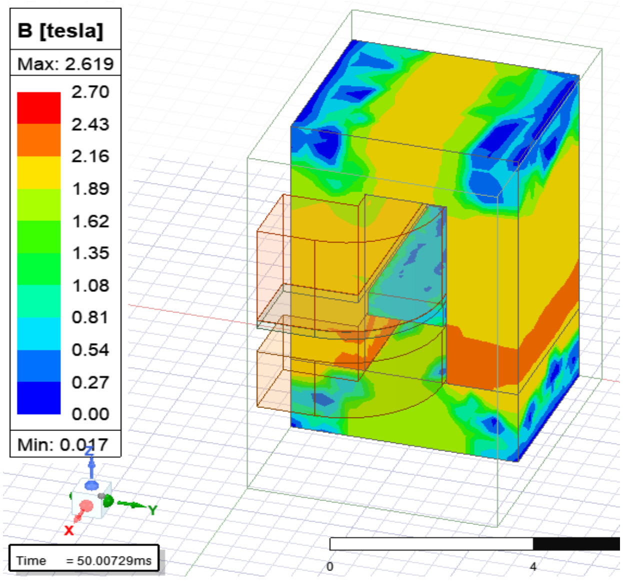

Fig. 8. Magnetic Flux Density Distribution for the Optimized MFLT Designs

The results obtained from these two figures allow for a detailed comparison of the behavior of an optimized MFLT transformer versus a reference model. The focus is on the distribution of the magnetic field density, a key element in validating the theoretical assumptions made beforehand. The results show that the optimized transformer exhibits a homogeneous distribution of the magnetic field, ensuring its efficiency and proper functioning. Indeed, the maximum magnetic field value (B_{max}) measured in some areas remains well below the critical limit of the material used, which is 2.33T, ensuring safe operation without saturation of the magnetic core. Furthermore, the average magnetic field value (B_{avg} = 2.11) is very close to the value estimated in the theoretical studies, confirming the accuracy of the optimized model. These results are essential for validating the transformer's performance, especially in applications where loss management and magnetic stability are important. Fig.9 presents the B(H) curve obtained through experimental testing on the material, further supporting the validity of this study [20].

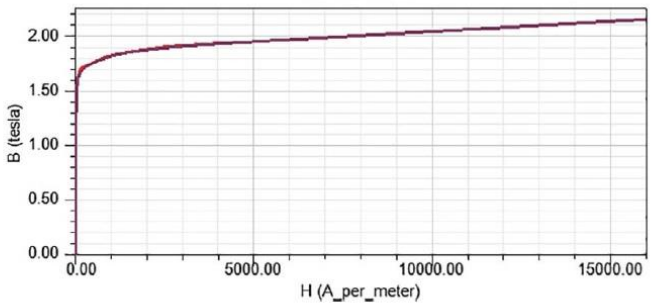

Fig. 9. B(H) curve of transformer core material

(2) Core and copper losses

Simulation of electromagnetic fields using the FEM in transformers allows the determine of core and copper losses [31]. It divides the domain into smaller elements and solves Maxwell's equations to obtain the distribution of the fields. The calculation of losses accurately is done after taking into account the characteristics of the materials such taking into account the characteristics of the materials such as permeability and conductivity, as well as nonlinearity. The loss curves in the core and copper found after simulation in ANSYS for the optimized and reference MFLT shapes are presented in Fig. 10 and 11.

Using the obtained curves, the average core and copper losses calculated for the two MFLT configurations show good agreement with the theoretical values. Table V compares the theoretical values of these losses as well as the average magnetic induction field, with those obtained from the FEM simulations.

TABLE V
VALUES OF LOSSES AND MAGNETIC INDUCTION OBTAINED IN THE THEORETICAL AND FEM CALCULATIONS

	Theoretical	**FEM**
Average magnetic induction field (B_{avg})	2.18 T	2.11 T
Core loss (P_{core})	10.81W	10.41 W
Copper loss (P_{copper})	64.79 W	64.22 W

(3) Discussion of results

The results obtained demonstrate the effectiveness of the proposed optimization approach in addressing the conflicting challenges associated with transformer design. By using a GA, the transformer volume was reduced by 13%, from 480.20 cm^3 to 418.49 cm^3, while maintaining the same apparent power of 700 VA. This improvement was accompanied by a significant reduction in copper losses, decreasing from 70.52 W to 64.79 W, thanks to an optimized winding configuration. Although core losses slightly increased (from 8.4 W to 10.87W), this compromise remains acceptable within the design constraints. Furthermore, the average magnetic flux density increased from 1.99T to 2.18T, indicating a more intensive yet controlled use of the magnetic material. Fig.12 illustrates the comparison between the two MFLT configurations: the optimized and the reference designs.

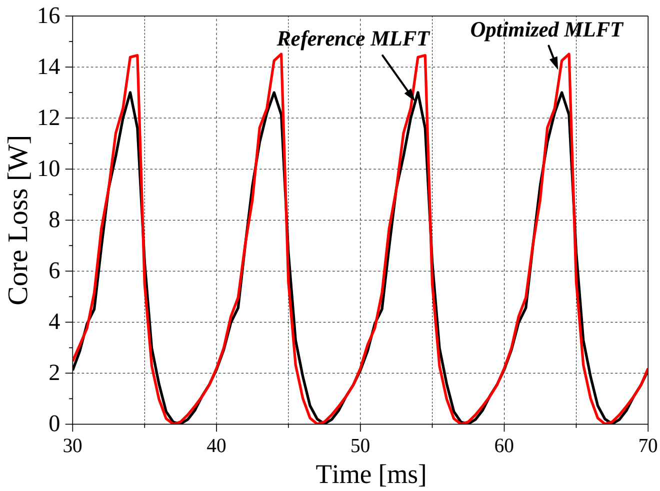

Fig. 10. Core losses in optimized and reference MFLT

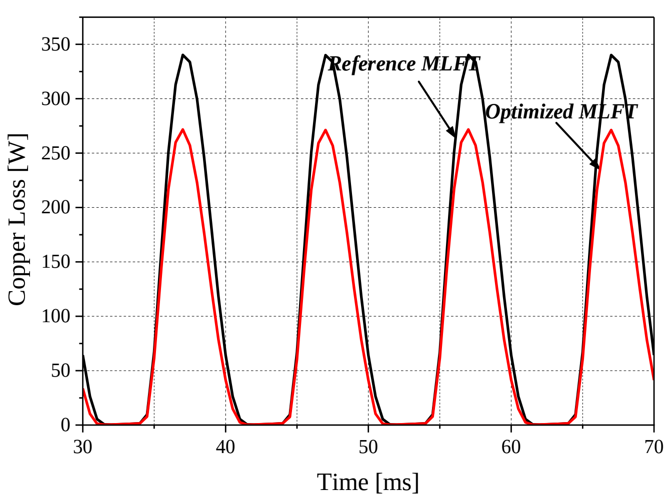

Fig. 11. Copper losses in optimized and reference MFLT

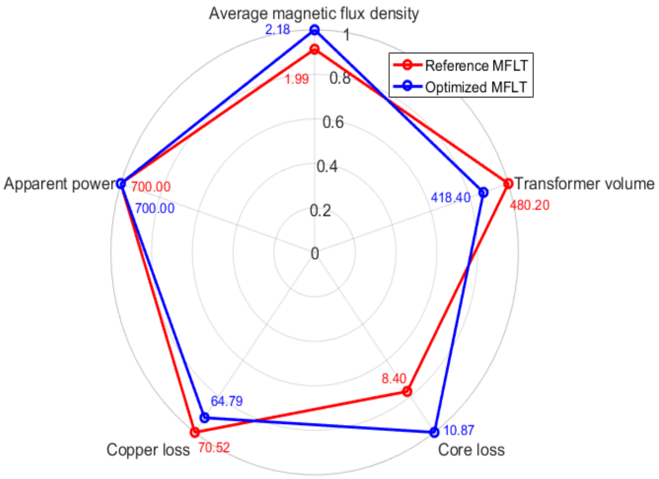

Fig. 12. Comparative report between optimized and reference MFLT.

FEM validated these results, showing good agreement with the theoretical results of magnetic flux density and losses in the core and copper. This validation reinforces the reliability of the optimization process and confirms the relevance of the adopted approach.

The optimized model exhibits a homogeneous distribution of magnetic flux, which helps limit thermal concentration points, thus reducing the risk of overheating and improving the transformer's operational stability. With these improvements, the model is well-suited for industrial applications that require both compactness and high energy efficiency.

However, certain limitations must be taken into account. The study focused on a single transformer configuration without including thermal or mechanical analysis. These aspects could influence the device's performance under varying operating conditions. A more in-depth investigation of these aspects would be necessary to further refine the optimization and enhance the model's robustness in real-world applications.

Despite these limitations, the study demonstrates the potential for designing more compact and efficient transformers. It thus paves the way for new optimization and innovation prospects in the transformer field, offering viable solutions to industrial challenges related to energy efficiency and the miniaturization of electrical equipment.

VI. CONCLUSION

This study focuses on the optimization of a 700 VA MFLT using a multi-objective GA based approach. Following an a posteriori methodology, the optimization targets both the reduction of overall volume and the minimization of core and copper losses. The obtained results highlight a notable volume decrease of up to 13%, while maintaining energy losses within acceptable limits. Furthermore, the optimized transformer satisfies key design constraints, including the filling factor, magnetic flux density thresholds, and the requirement for apparent power equivalence with the reference transformer.

Validation using FEM confirmed the reliability of the results, especially regarding magnetic flux distribution and energy losses. This optimization approach facilitates the design of more compact, efficient, and cost-effective transformers, making them well-suited for industrial applications such as microwave power supply systems.

However, the lack of thermal and mechanical analyses limits the scope of this study. Future research should incorporate these aspects, particularly for higher power applications. In conclusion, this optimization paves the way for more efficient transformers that meet the growing demands of modern industrial sectors in terms of compactness, performance, and efficiency.

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