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SCHOOL OF ENGINEERING

Department of Electrical Power Engineering and Mechatronics

Design optimization of a transformer

Trafo disaini optimeerimine

MASTER THESIS

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Tallinn 2021

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Department of Power Electronics and Mechatronics

THESIS TASK

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Thesis topic: (In English) Design optimization of a transformer

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Thesis main objectives:

1. Optimize the design of the transformer
2. Reduce the mass of ferromagnetic material.
3. Improve the efficiency of the transformer using the direct optimization method.

Thesis tasks and time schedule:

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3.	Simulation of the initial design using FEM	October 2021
4.	Parametrization	November 2021
5.	Sensitivity Analysis	November 2021
6.	Design optimization of the transformer using FEM model with Genetic Algorithm	December 2021
7.	Results discussion	December 2021
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LIST OF ABBREVIATIONS

DOM	Direct optimization methods
IOM	Indirect optimization methods
FEM	Finite element model
GA	Genetic algorithm
AC	Alternating current
VA	Volt-Ampere
MLT	Mean length per turn
NT	Numerical techniques
3-D	Three dimensional
2-D	Two dimensional
AM	Additive manufacturing
SGA	Simple genetic algorithm
IGA	Improved genetic algorithm
TOC	Total owning cost
DFSS	Design for six sigma
RSM	Response surface model
DoE	Design of the experiment
PSO	Particle swarm optimization
EAs	Evolutionary algorithms
EDAs	Estimation of distribution algorithms
DEAs	Differential evolution algorithms
NSGA	Non-dominated sorting GA
MOGA	Multi-objective genetic algorithm
API	Application programming interface
VB	Visual basic

1. INTRODUCTION

1.1. Context and state of the art

Transformers are widely used as tractable devices for transforming voltage and current. They are usually characterized as power and distribution transformers. With increasing electrical power generation, networks of electrical systems are spreading daily through the world. In this new and developing environment, there is an urgent need for more efficient use of transformer materials, reducing the size and overall material costs. At the same time, transformer reliability is mainly enhanced by accurately evaluating the leakage field, the short circuit impedance, and the forces on transformer windings under the short circuit. These enable to avoid mechanical damages and failures during short-circuit tests and power system faults [1]. Precise estimation of transformer losses and short-circuit impedance during the transformer design phase is crucial since it increases transformer reliability and manufacturer credibility; it secures the desired transformer efficiency; it reduces the material cost since a smaller design margin is used; it decreases transformer delivery time since there is no need for transformer prototype to confirm the accuracy of transformer design [2]. Transformers have an enormous capital cost, and a failing transformer arising from losses would impact power quality and increase the failure rate of other connected electrical systems. In recent years, there has been an increasing interest in shape optimization of transformer design which is widely presented in the literature. Design optimization techniques help to improve the efficiency of transformers while considerably reducing material utilization and, consequently, production cost [3].

Transformer design is a difficult task in which engineers must ensure that adaptability with the required terms is met while maintaining manufacturing costs low. Moreover, the design methodology may vary significantly according to the transformer type (distribution, power, or instrument transformer) and its operating frequency (ranging between 50/60 Hz and a few megahertz). In contrast, many alterations according to the core constructional characteristics, the cooling method, or the type of the magnetic material may be encountered. Transformer manufacturers use optimization techniques during the design phase to minimize material costs and satisfy the utility's loss evaluation requirement, facing the difficulty in achieving the optimum balance between the transformer cost and performance. The techniques employed for its solution must deal with the design considerations to provide a design optimum while remaining cost-

effective and flexible. The research associated with design optimization is, therefore, is highly developed and involves different optimization methods.

Design methodology varies according to the kind of transformer and its operating frequency. Many aspects can be considered within a transformer design, such as kVA rating, delta or wye connection, insulation type and temperature rating, effects of transformer failures, sizing, and cost. Moreover, many corrections and adjustments can be considered regarding the core type, cooling method, or type of magnetic material.

An increasing body of research has focused on design optimization of transformers with the aim to improve efficiency and reduce material costs. To date, many methods have been produced to optimize the design of transformers and other electrical devices. The leading names are direct and indirect optimization methods (DOM and IOM), multi-level, and robust optimization methods. In this thesis, the DOM accompanied by the genetic algorithm (GA) will be used. The DOM gives a clear and intuitive structure since it simply employs a finite element model (FEM) along with the GA. The unique characteristics of the GA, such as obtaining the global minimum, handling non-analytic formulation of optimization problems, and high flexibility, justify its popularity among researchers. This algorithm considerably narrows the solution space during optimization [4].

1.2. Objective and scope of study

This thesis aims to optimize the design of a transformer to reduce the mass of ferromagnetic material and improve the efficiency of the transformer using FEM and GA.

The proposed data can be referred as following

- Transformer limited to 30 VA
- Single phase isolation transformer
- Design of active parts only (copper windings and core)
- Primary inline voltage 230V
- Secondary inline voltage 25V

1.3. Thesis organization

The arrangement of the thesis will be as follows.

- Introduction to transformers and their design
- Literature review of transformer optimization
- Optimization methods
- Optimization algorithms
- Thesis design model study
- Thesis optimization model
- Genetic algorithm application to study
- Implementation of algorithm in MATLAB and Simcenter MAGNET environment
- Result discussion
- Conclusion
- Summary

2. TRANSFORMER STUDY

2.1. Transformer basics

According to [5], transformers have been defined as a static devices consisting of two or more coils of wire applied to transfer electrical energy using a changing magnetic field. Transformers are devices that change or transform voltage levels between two circuits. In the process, current values are also transformed; however, the power transferred between the circuits is unchanged, except for a typically slight loss that occurs in the process. This power transfer occurs only in AC or transient electrical conditions. The transformer is an electrical device based on the principle of induction discovered by Faraday in 1831. Faraday found that when a changing magnetic flux links a circuit, a voltage or electromotive force is induced in the course. This induced emf is proportional to the number of turns linked by the changing flux. Thus, when two systems are connected by an expected change and have different linked turns, different voltages will be induced; this is shown in Figure 2.1, in which an iron core carries the predicted flux. The induced voltages V_1 and V_2 will differ since the linked turns N_1 and N_2 differ [6].

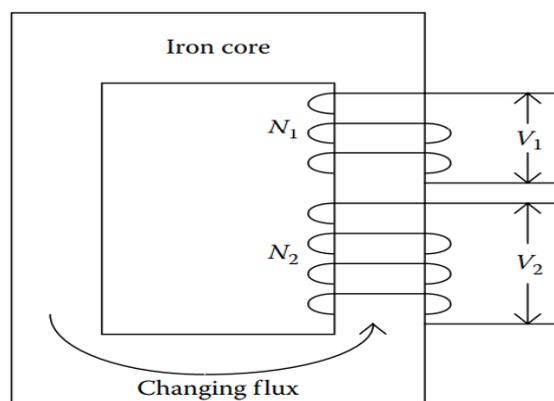


Figure 2.1 Transformer principle for an expected changing flux.

By transforming power to a high voltage, low current form, and back again, the transformer significantly reduces energy losses and enables the economical transmission line of power over long distances. It has thus modified the electricity supply industry, permitting generation to be located remotely from points of demand. Amongst the simplest of electrical machines, the transformer is also one of the most

efficient, with large units can achieve performances over 99.75%. Transformers come in various sizes, from a thumbnail-sized coupling transformer hidden inside a stage microphone to massive Giga VA-rated units that interconnect portions of national power grids. All operate with the same principles and many similarities in their parts, though various transformer designs exist to perform specialized roles throughout home and industry [7].

2.2. Transformer construction

Transformer referred in this thesis is single phase transformer, when electric current passed through the primary winding, an electric current creates a magnetic field, which induces a voltage across the secondary winding of a transformer. The single-phase transformer is used to either step up or down the voltage at the output. The single-phase transformer diagram is shown below Figure 2.2.

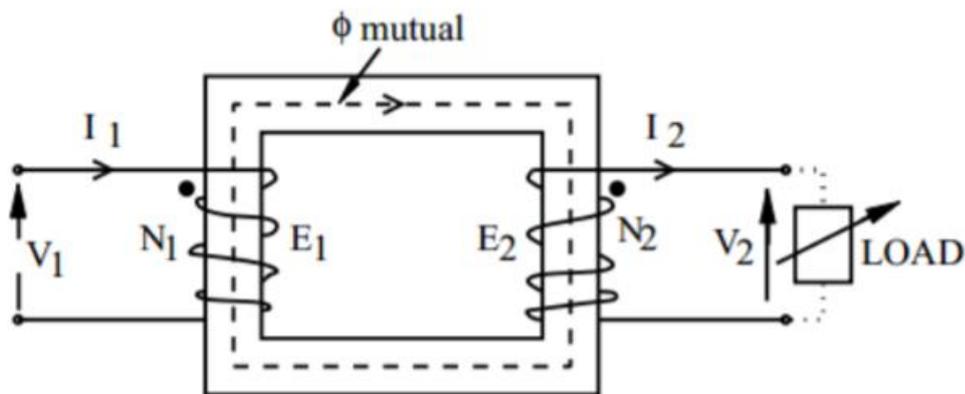


Figure 2.2 Transformer operation principle.

The single-phase transformer acts on the principle of mutual inductance. Typically, mutual induction within primary and secondary windings is responsible for the transformer operation in the electrical transformer. When the primary transformer is connected to an AC supply, the current flows in the coil, and the magnetic field build-up. This condition is known as mutual inductance. The flow of current is as per Faraday's Law of electromagnetic induction. As the current rises from zero to its highest value, the magnetic field increases and is given by $d\phi/dt$. This electromagnet creates the magnetic lines of force and expands outward from the coil, creating a magnetic flux path. The turns of both windings get connected by this magnetic flux. The intensity of

a magnetic field produced in the core depends directly on the number of turns in the winding, including the amount of current. The current and magnetic flux is proportional directly to each other [7].

A primary single-stage transformer has each winding twisted circularly on a delicate iron appendage independently to give an essential attractive circuit, usually alluded to as "transformer core." It offers a way for the progression of the attractive field to initiate voltage between two windings. Figure 2.3 shows that the two windings are too far off to have a proficient attractive coupling. Hence, combining and expanding the attractive circuit close to the curls can upgrade the attractive coupling among essential and optional windings [8].

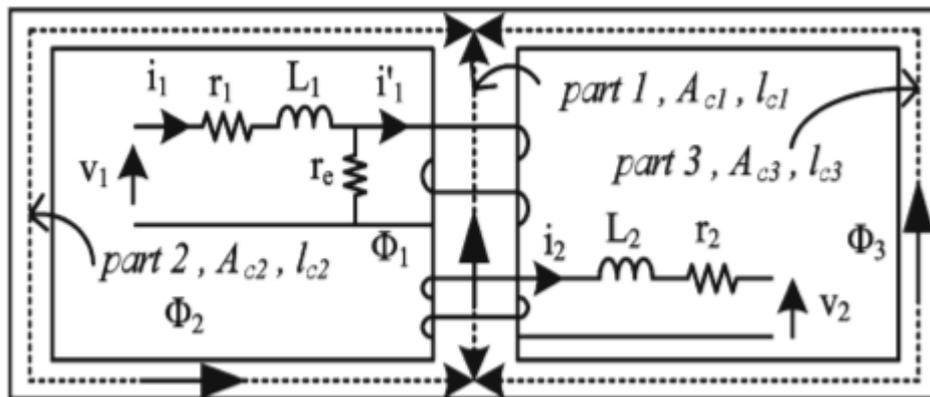


Figure 2.3 Shell type transformer

In shell-type of transformer construction presented in Figure 2.3 [9], the primary and secondary windings are positioned cylindrically on the centre limb resulting in twice the cross-sectional area than the outer limbs. There are two closed magnetic paths in this type of construction, and the outer limb has the magnetic flux $\phi/2$ flowing. Shell-type transformer overcomes leakage flux, reduces core losses, and increases efficiency. The applications of a single-phase transformer are diversified. It can be used to step-down long-distance signals to support residential and light-commercial electronic devices, in television sets for voltage regulation, to step-up power in home inverters, supply power to non-urban areas, isolate two circuits electrically as primary and secondary are placed far from each other.

2.3. Design parameters of transformer

This section describes a brief outline of transformer design methodology for shell core dry-type single phase core type transformer. Figure 2.4 suggests the geometry of the transformer with the dimensions of core, primary (N1) core winding, and secondary (N2) windings. In the subsequent, a classical form of transformers design is provided. Some transformer parameters are associated with the spatial dimensions defined as shown below.

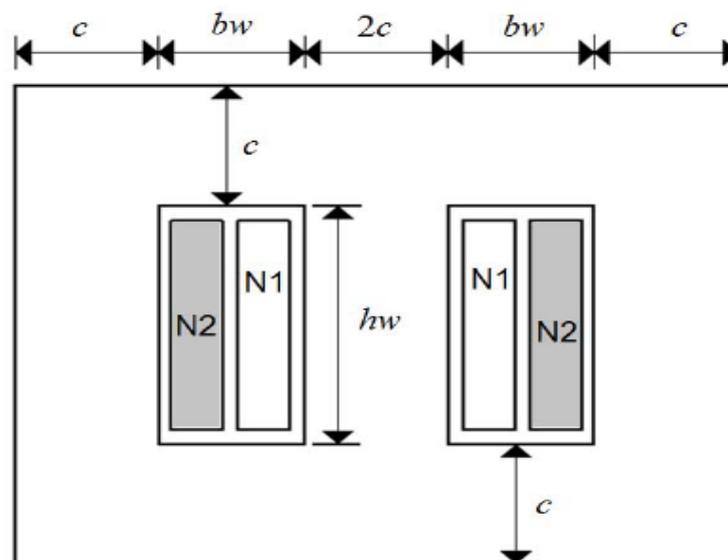


Figure 2.4 Transformer geometry

The central leg core area (central limb transversal area) calculated,

$$A_c = 2ct \tag{2.1}$$

where t is the deepness of the transformer.

Effective central leg core area A_e can be calculated,

$$A_e = K_f A_c \tag{2.2}$$

where K_f is the core stacking factor, copper winding length (mean length per turn): $MLT = 4c + 2t + \pi b_w$; window area (frontal window area where the windings will be fitted): $W_a = b_w h_w$; winding volume: $V_w = W_a MLT$; core volume: $V_c = A_c (2h_w + 2b_w + 4c)$. First, the number of turns for primary ($N1$) and secondary ($N2$) windings are obtained as follows:

$$N_1 = \frac{V_1}{\sqrt{2\pi} k_f f B A_c} \quad (2.3)$$

where B is the magnetic flux density in T. The number of turns of secondary winding is given by the voltage ratio: $N2 = N1(V2/V1)$. The efficiency is obtained by calculating the transformer core losses (including hysteresis and eddy currents) and the copper losses (Joule losses) in the windings. The core losses are given by

$$p_c = k_c B^\alpha f^\beta \quad (2.4)$$

where p_c are the ferromagnetic losses in W/kg, B is the magnetic flux density in T and f is the frequency in Hz. The coefficients k_c , α , and β are constant's characteristics for each core magnetic material. The total core losses in the transformer volume are given by

$$P_c = \rho_c k_f V_c k_c B^\alpha f^\beta \quad (2.5)$$

where P_c are the power losses and ρ_c is the core density, the primary and the secondary currents are obtained by the ratio between power and voltages of transformer: $I = S/V$, with S in VA.

Once defined the currents densities d (in A/mm²), one can calculate the conductors section areas, for primary and secondary windings, as $A_{cd} = I / d$, in mm². Once obtained, the number of turns of the primary and secondary windings and the conductors section areas, it is possible to calculate the copper-occupied area W_{cu} . For a transformer with a primary winding and secondary windings, the area occupied by the copper is given by

$$W_{cu} = N_1 A_{cd1} + N_2 A_{cd2} \quad (2.6)$$

where A_{cd1} and A_{cd2} are the primary and the secondary conductor section areas, respectively. The copper mass m_{cu} , considered, the primary and the secondary windings is given by

$$m_{cu} = \rho_{cu} W_{cu} L M T \quad (2.7)$$

For a copper density of 8890 kg/m³ and a resistivity of $2.3 \times 10^{-8} \Omega m$ at 75 °C, one can calculate approximately the copper losses by

$$P_{cu} = 2.43 d^2 m_{cu} \quad (2.8)$$

where P_{cu} is the copper losses in W and m_{cu} is the copper mass in kg, hence the total losses are the sum of core and copper losses will be as follows,

$$P_T = \rho_c k_f V_c k_c B^\alpha f^\beta + 2.43 d^2 m_{cu} \quad (2.9)$$

If one considers a total power transfer for a unitary power factor load, the transformer efficiency η will be given by

$$\eta = \frac{P_{out}}{P_{out} + \rho_c k_f V_c k_c B^\alpha f^\beta + 2.43 d^2 m_{cu}} \quad (2.10)$$

where P_{out} is the output power in Equation 2.10

The ferromagnetic core mass m_c is given by

$$m_c = \rho_c V_c \quad (2.11)$$

The transformer mass M_T is calculated as the sum of core and copper mass as

$$M_T = \rho_c V_c + \rho_{cu} W_{cu} LMT \quad (2.12)$$

The MOP is to minimize mass (f_1) and the losses (f_2) while ensuring the operational requirements. The design variables are the core dimensions, turns of windings, and currents densities. In this way, the objective functions are

$$f_1 = \min (\rho_c V_c + \rho_{cu} W_{cu} LMT) \quad (2.13)$$

$$f_2 = \min (1 - \eta) \quad (2.14)$$

From the previous equations, it is observed that the number of variables involved in the design of a transformer is relatively large, even for a simple single-phase structure, which would justify the use of an optimization methodology for the structure. The authors also neglected the leakage reactance's, the phenomenon of saturation, costs, and temperature restrictions. The inclusion of these phenomena and additional restriction will become more complex and complicate the work of the designer. In addition, two factors which determine the effective core area, weight, and losses. First, the core stacking factor, which is a correction number representing the space lost between laminations. Second, building factor, which is a number that should be multiplied by the ideal core loss, are also neglected. Hence design parameters summarize the Equations 2.10 and 2.12 for transformer efficiency and mass respectively, which results the objective function Equations 2.13 and 2.14.

2.4. Transformer FEM based studies

Many computational methods and engineering models proposed for transformer analysis and the accurate prediction of their characteristics can be roughly categorized into six main groups in which numerical techniques (NT) are first, which uses the most comprehensive tools for transformer simulation. Among the proposed strategies of this group, the finite-element method (FEM) is the most prevalent one; and used to include semiempirical descriptions of the core and winding characteristics that affect the accuracy of calculations [10]. The FEM is a numerical analysis technique for obtaining approximate solutions to various engineering problems. A finite element model of a situation gives a piecewise approximation to the governing equations. The basic principle of the FEM is that a solution area can be analytically modelled or assumed by

replacing it with an assemblage of discrete elements (discretization). Since these elements can be placed together in various ways, they can represent exceedingly complex shapes [11]. The FEM analysis is commonly used for any loss calculations [12]. In [13], an accurate 3-D formulation to study the boundary eddy current field arising from the heavy winds and terminal lead currents in a compact power transformer is developed. The 3-D reluctance network method is also proposed for transformer load loss prediction in [14] as a fast, low-cost tool for obtaining power and hottest-spot output data. There are some more examples [15], [16] in which FEM has played an essential role in achieving the research result because of its various advantages. For example, FEM allows easier modelling of complex geometrical and irregular shapes, adaptability, Accuracy, Time-dependent simulation, Boundaries, Visualization.

2.5. Advantages of additive manufacturing for transformer production

Additive manufacturing can be used for transformer production as AM gives much freedom to design core shapes comparing to the conventional manufacturing methodologies. In conventional manufacturing, prototyping is relatively expensive as it requires tools, moulds, and specialized operators. At the same time, AM significantly improves prototyping in terms of cost and time. Moreover, AM can design more intricate optimized parts. AM makes multiple components in more straightforward configurations; it provides more accessible assemblies and free-form structures. The main advantage of AM processes includes ease of manufacturing, higher operational efficiency, enhanced functionality, and improved durability [17]. Moreover, AM facilitates the manufacturing of geometrically complex parts, which reduces material consumption by up to 40% [18].

Additive manufacturing (AM) enables the fabrication of solid and lightweight structures with unachievable geometry by traditional manufacturing methods, including complex lattice structures [19]. The lattice structures can generally be categorized based on their mechanical response as being either bending-dominated or stretch-dominated. Bending-dominated structures experience bending moments within their structure and so are compliant. In contrast, stretch-dominated structures experience axial loads, which are stiffer and more robust than bending-dominated structures [20]. A lattice structure's cell topology defines whether it will be bending or stretch-dominated [21].

This chapter summarized the introduction to the transformer, defined the basic working principle of the transformer, its design parameters, core factors. Moreover, the finite element method study, and advantages of additive manufacturing for transformer production were also reviewed.

3. TRANSFORMER DESIGN OPTIMIZATION REVIEW

3.1. Introduction

This chapter aims to present a literature survey on design optimization of transformer and discusses the challenges and directions of the design optimization methods for any electrical machines. Section 3.2. consists of transformer design optimization studies based on manufacturing and operating cost. Section 3.3. introduces the basic design optimization procedure for the electromagnetic devices and classification of optimization problems. Section 3.4. discusses optimization models, Section 3.5. lists the optimization methods and discusses the direct optimization method which is scope of study. Section 3.6 involves the optimization algorithms.

3.2. Transformer design optimization

Many studies were done to optimize the transformer design; many were in materials properties improvement, which is not practicable or valuable for our situation. Other studies used optimization techniques for selecting the optimum values of design variables using the available properties of materials. In [22], authors used the decision tree optimization approach, which is easy to work with, but so difficult to program it, since it requires building a knowledge base structured on more than 2500 previous designs. Another research was done in the paper [23], representing an Improved Genetic Algorithm (IGA) optimization method applied to the power transformer design problem. The target of this method was to overcome the Simple Genetic Algorithm (SGA) joint problems. The design was limited to the use of rectangular copper strips in primary and secondary windings. Below are some studies discussed based on various factors.

3.2.1. Optimization research based on manufacturing cost

Some studies related to transformers' manufacturing costs were carried out; In study [24] presented a technique for designing transformers with a given size and type of construction to have maximum volt-ampere (VA) output while at the same time ensuring the satisfaction of several design constraints. The resulting design technique

reduces overdesign problems in that the minor physical size structure will regularly result in the design objectives. At the same time, an improved solution to the described problem was presented in [25]. According to [26], it shows the difference in the transformer price depending on the primary turns, which is an approximately hyperbolic function. Also, the cost trajectories of the transformer against the magnetic flux density and the current density are presented. The study [27] makes a functional proposal with students in electrical engineering, the students design, build and test a 10-VA transformer with multiple design sessions. In a nutshell, the transformer design optimization problem remains an active research area.

3.2.2. Optimization research based on operating cost

Besides the transformer manufacturing cost, another criterion used for transformer evaluation and optimization is the total owning cost (TOC) or operating cost, considering the purchase cost and energy losses throughout the transformer lifetime [28]. The TOC technique is the most broadly used transformer evaluation method to determine the cost-effectiveness of energy-efficient transformers, balancing the cost of purchase and energy losses. The TOC evaluation process has been developed as a helpful tool to reflect the unique financial environment covered by each electric utility when purchasing distribution transformers. According to this process, the variability of the cost of electric energy, capacity, and financing costs is shown through two evaluation factors, corresponding to the unit cost of no-load and load losses, respectively. It is essential to record that the system that describes these two factors changes according to the purpose of the transformer purchaser in the energy market (two significant classifications can be recognized: electric utilities and industrial users) and the depth of the study (depending on the accuracy of the image of the transformer loading characteristics) can be carried out. It is essential to recognize that the electric utility perspective is different from transformers' industrial and commercial users. The transformer loss evaluation system for the electric utility involves understanding and evaluating the entire cost of generation, transmission, and distribution transformer losses. In contrast, the transformer loss evaluation procedure for the industrial and commercial user needs to understand and assess the electric rates they pay to the electric utility. An essential part of the transformer cost optimization research is devoted to the TOC minimization, as follows. Distribution transformer TOC optimization is analysed further in [28].

3.3. Basic procedure for design optimization

The general process of design optimization of electrical machines includes two main stages: design and optimization. The main aim of the design stage is to find the feasible designs for a given application through the expert knowledge and investigation of different materials and dimensions, and topologies, multidisciplinary analysis, and much more. The analysis of this stage will provide information on the performances of the proposed design to develop optimization models that will be used in the optimization stage. The previous chapter discussed this thesis research, including all aspects of the transformer in the design parameter section.

The main target of the optimization stage is to improve the performance of the transformer proposed in the design stage through optimization algorithms and methods. As the outcome, an optimal solution will be obtained for the single objective optimization. For a multi-objective design optimization, the non-dominated solutions (called Pareto optimal solutions) will be gained after the completion of this stage. There is no fixed procedure for the design optimization of electromagnetic devices. However, there are some common steps to be followed. These steps are briefly described as follows, which may also interact with each other [29].

1. Determine the specifications of the application.
2. Select/determine possible initial designs, including types, topologies, and materials, qualitatively according to the application's specifications.
3. Implement multidisciplinary modelling and analysis for the potential designs and evaluate the performance included in the objectives and constraints.
4. Model the optimization problem according to the design specifications, initial designs, and multidisciplinary performance modelling.
5. Conduct optimization and obtain an optimal solution or some optimal solutions.
6. Validate the design with prototypes and experiment results.

This concludes the design optimization into the mathematical model, which can be expressed as Equation 3.1. We can separate the optimization problems into four main steps, that is determination of the initial design, definition, and calculation of objective and constraints, selection of design variables, optimization by algorithms. The following introduction is about the problems in this procedure [30].

3.4. Optimization models

3.4.1. Single and multi-objective optimization models

Considering a single-objective optimization problem with m constraints, its optimization model can be expressed as following

$$\begin{aligned} & f(x) && (3.1) \\ & g_j(x) \leq 0, j = 1, 2, \dots, m \\ & x_l \leq x \leq x_u \end{aligned}$$

where x , f and g_j are the design parameter vector, objectives, and constraints, and x_l and x_u are the lower and upper limits of the design variables, respectively. Similarly, the optimization model of a multi-objective design problem with p objectives and m constraints has the form

$$\begin{aligned} & \{f_1(x), f_2(x), \dots, f_p(x)\} && (3.2) \\ & g_j(x) \leq 0, j = 1, 2, \dots, m \\ & x_l \leq x \leq x_u \end{aligned}$$

The objectives in Equation 3.2 are always conflicting due to the nature of multi-objective optimization. Thus, the optimal solutions of Equation 3.2 compromise these objectives, which are non-inferior solutions theoretically and can be called Pareto solutions [31].

3.4.2. Deterministic and robust optimization models

From the industrial design and manufacturing perspective, the design optimization models in Equations 3.1 and 3.2 are deterministic because they have not investigated the variations of parameters [32]. However, new criteria are required to evaluate the robustness of a design, such as a gradient index [33], the mean and standard deviation of the objectives, and constraints. Two popular design optimization methods are the

Taguchi method and the design for six sigma (DFSS) method. However, as robust design optimization is a challenging topic for electrical machines, we do not present too many details here [34].

3.5. Optimization methods

Optimization is the action of obtaining the best result under given circumstances. Also, it could be defined as a body of analytical results and numerical methods for identifying the best candidate from a group of alternatives. There is no single method for solving all optimization problems efficiently. With the models discussed in the previous section, an optimization can be implemented with an optimization method or strategy. Hence various optimization methods have been produced for solving different types of optimization problems [35]. There are many types of optimization methods/strategies, and several popular ones are Direct (design model-based) optimization method, Indirect (surrogate model-based), Sequential optimization method based on the space reduction method, Multi-level optimization method [36], Space mapping method [37], In this thesis, direct optimization method will be used and briefly discussed below,

The conventional direct optimization method uses design analysis models (such as FEM and thermal network model) to evaluate the objectives and constraints in the model Equations 3.1 or 3.2. It optimizes all parameters at once by employing an optimization algorithm like GA. This method is simple in implementation. For example, it can be realized by integrating MATLAB and Simcenter MAGNET, i.e., using MATLAB to call the Simcenter MAGNET code in the optimization program. As FEM is generally used nowadays in the design analysis of electrical machines due to its high accuracy, the main issue of this method is the computation cost. For example, to optimize ten parameter designers must spent about 10000 min i: e 166 hrs to get optimal solution. Hence there is a considerable computation burden for most designers.

To address this issue, some surrogate models like the response surface model (RSM) and Kriging model have been developed and applied to optimize electrical machines. These surrogate models can replace the FEM required in the optimization implementation of Equations 3.1 and 3.2. However, the design of the experiment (DoE) technique is necessary to construct the surrogate models, which requires the FEM simulation [31], In this thesis scope is limited to direct optimization, Hence all aspects are not covered.

3.6. Optimization algorithms

Optimization algorithms can obtain optimal results based on the optimization models in Equations 3.1 and 3.2. Figure 3.1 shows some traditional optimization algorithms for the design optimization of electromagnetic devices. As shown, there are two main types, intelligent optimization algorithms and gradient-based algorithms. Conjugate-based algorithms, such as conjugate gradient algorithms and their nonlinear versions, are simple in implementation. For example, Equation 3.1 can be optimized with motor performances estimated based on the magnetic circuit model.

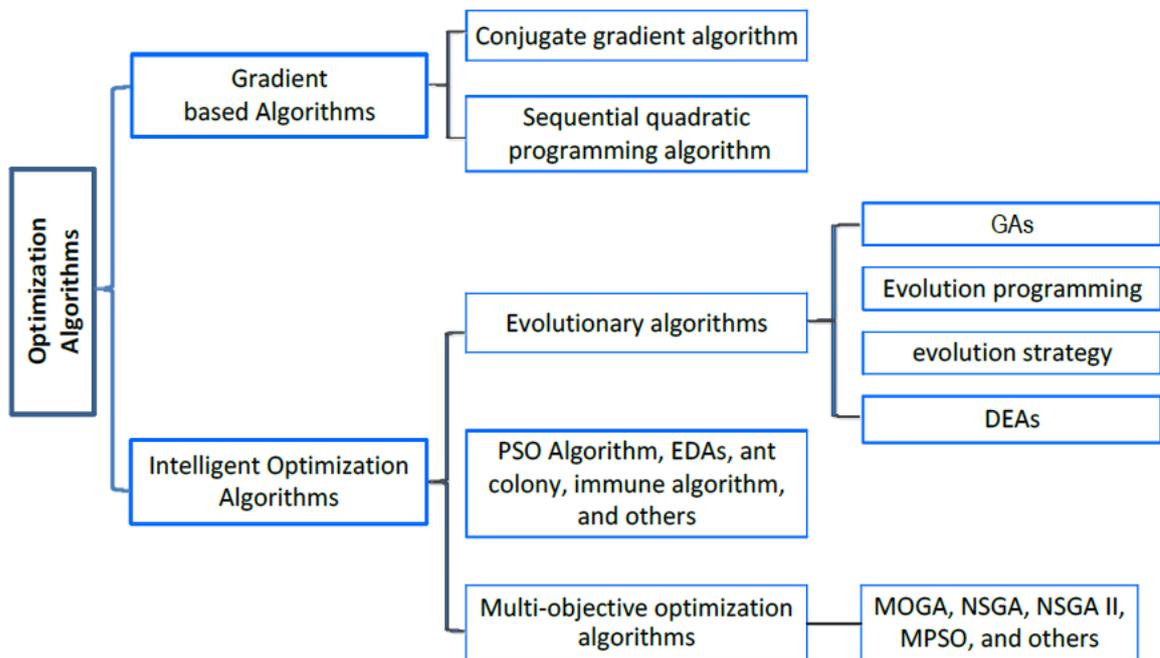


Figure 3.1 Types of optimization algorithms

Meanwhile, these algorithms apply constraints, for example, analytical expressions for the constraints and objective functions. However, nowadays, many analysis models for electromagnetic devices are based on FEM instead of the analytical circuit models. Therefore, intelligent optimization algorithms have been used for the optimization of electrical machines in the past several decades, such as particle swarm optimization (PSO) algorithms, the evolutionary algorithms (EAs), estimation of distribution algorithms (EDAs), immune algorithms, and ant colony algorithm, and their improvements. The widely used GA and differential evolution algorithms (DEAs) are two of four significant subclasses of EAs. The other two subclasses are evolution programming and evolution strategy.

Multi-objective optimization has become common in this field nowadays, as design optimization of electrical machines is multi-objective, such as maximizing the torque and minimizing the torque ripple, maximizing the power density, and minimizing operational material cost. For solving this kind of optimization problem, multi-objective optimization algorithms are required. They can provide a Pareto solution set with a single run. This solution set consists of many non-dominated optimal design solutions for the designer to select based on a specific application (meaning specific weighting factors). Some popular multi-objective optimization algorithms are originated from GA and PSO, such as multi-objective GA, non-dominated sorting GA (NSGA) and its improvements (NSGA II), and multi-objective PSO algorithm [38].

4. CASE STUDY

4.1. Initial parameters consideration of transformer

A transformer's mathematical modeling and simulations are essential, as it is a fundamental milestone for design and control procedures. The more accurate the mathematical model of the transformer is, the more precise its practical design and control would be. With the growth in computational power, numerical models such as FEM are gaining more and more popularity in modeling and simulations. These models are good approximations of an actual system, as they consider all possible parameters, but at the cost of complexity and long computational time, which is more discussed and expressed in chapter 2 above, In order to proceed with the case study, some initial considerations are made according to [17], can be referred below in detail.

The initial parameters keep the unit and length defined, which helps to perform smooth mathematical calculations. This thesis is referred to 30 VA single phase isolation transformers, and the transformer was chosen to continue work on optimization, whereas it is a shell-type transformer with E-type stamping consisting of primary, secondary, secondary 1 types of coil. Below in Table 4.1 are nominal parameters, which are considered as initial nominal parameters in this work.

Table 4.1 Nominal parameters of transformer

Windings	Primary	Secondary	Secondary 1
Turns	1370	151	56
Resistance (Ω)	98	1.35	2.7
Nominal Voltage (V)	230	25.1	9.3
Nominal Current (A)	0.17	1.3	0.25
Insulation Class	H	F	F

4.1.1. Dimension considerations of transformer

For drawing design, there is a need of overall dimensions of the transformer, assumed weight of the core according to Equation 2.11, whereas mass density is 7700 kg/m³ for printed steel from Simcenter MAGNET properties, and weight of the coil, which can be referred from below Table 4.2.

Table 4.2 Dimension of core assumption

	Dimensions (mm)	Weight Core (kg)	Weight Coil(kg)
Core	54 × 44.5 × 26.0	0.385	0.095

It is also necessary to know the physical meaning of all the transformer dimensions. Which can be referred to as follows and used in the thesis,

Core area – It refers to the area where power is transmitted from one source to another via electromagnetic induction.

Window area – It is the area used for housing of windings or coils and insulation.

Container – It is used for two purposes, first, to protect the core and to wind from the external environment and Second, is to support a place of oil and other accessories of the transformer.

Winding – Transformer consisting of two coils, primary and secondary, one coil draws power from the source, and another coil delivers the power or energy at different loads.

The above-discussed parts of the transformer are the main parts, and below in Figure 4.1 are the assumed dimensions, which are distributed in parts and considered accordingly in Table 4.3 for making the initial design of the transformer core in Simcenter MAGNET software.

Table 4.3 Parameters initial dimensions

	c	bw	bwa	hw	hwa	r
Dimensions(mm)	9	9	1.5	26.5	22.5	2

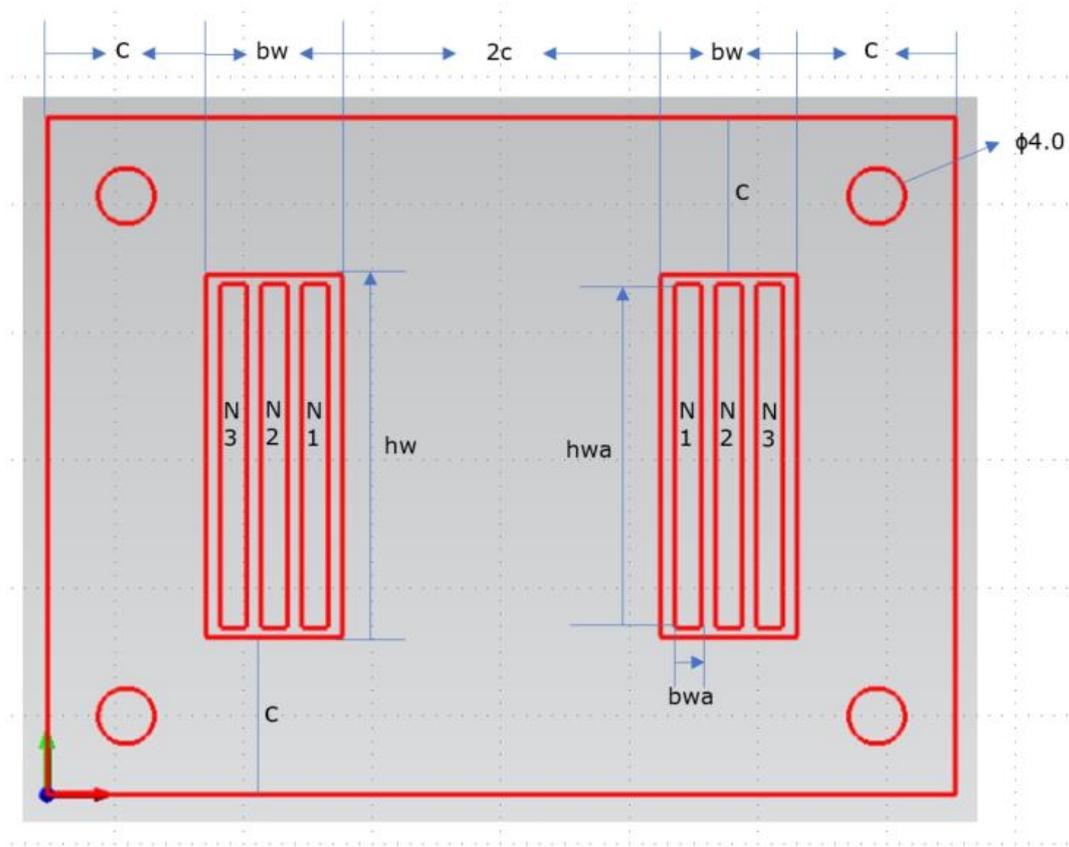


Figure 4.1 Initial design parameters

Table 4.3 above shows the assumed dimensions of bwa (x -axis) and hwa (y -axis) of the coil, placed in the window area. Each coil has two parts, primary coil, part one, and part two. Similarly, there are two parts for the secondary coil and secondary coil1 in the window area, part one and part two. The spacing distribution between the coils and endpoint of window area x and y is assumed to be equal for each. The spacing is assumed considering insulation and other factors.

The above summarizes the transformer's initial geometric considerations, which are used as a preliminary reference to draw the transformer geometry in real-time, while this defines the dimensions are assumed and will be changed or adjusted to get the optimized results.

4.2. Modelling of the transformer using Simcenter MAGNET software

Simcenter MAGNET 2D/3D is an effective electromagnetic field simulation software for the performance projection of motors, generators, sensors, transformers, actuators, solenoids, or any component with permanent magnets or coils. With this easy-to-use and special software, one can optimize, design, and investigate simply complex electromagnetic and electromechanical devices. Simcenter MAGNET virtual prototyping is both time and cost-efficient. Parametric and optimization studies authorize the exploration of multiple designs for performance improvements. The accurate replication of the severe operating conditions provides insight into loss and temperature hotspots, permanent magnet demagnetization, new material, and failure analysis through fault situations. Due to these reasons, the Simcenter MAGNET software is perfect for this thesis objectives to obtain optimized output.

4.2.1. Modelling plan for geometry in Simcenter MAGNET software

It is necessary to plan further with the Simcenter MAGNET software interface to optimize the 2D shell-type transformer. The problem comprises nine rectangles and four holes, while the coordinates and dimensions differ for each. The model starts with the core, window area, coils, holes, container or tank, circuits, and simulation-results.

4.2.2. Simcenter MAGNET graphical interface for geometry and component creation

To build the geometric model, the Keyboard Input bar is selected on the Tools menu and set it too Cartesian and Absolute. Then on the Draw toolbar, Line drawing tool is clicked and on the View toolbar Automatic View All is opted for better display. Following coordinates for each component in the Keyboard Input bar to draw geometry. Co-ordinates of all the transformer parts are shown below in Tables 4.4-4.6 and entered after entering each co-ordinate or center for each transformer component to the keyboard input bar and ESC after finishing for each component. The Line tool is used to create a boundary for each component, except holes in which the circle tool is used.

Table 4.4 Co-ordinates of core and window areas

	Window area		
	Core	Part#1	Part#2
Start (x,y)	(0,0)	(9,9)	(36, 9)
End (x,y)	(54,0)	(18,9)	(36, 35.5)
End (x,y)	(54,44.5)	(18, 35.5)	(27, 35.5)
End (x,y)	(0,44.5)	(9, 35.5)	(27, 9)
End (x,y)	(0,0)	(9,9)	(36, 9)

Table 4.5 Co-ordinates of coils

	Primary Coil		Secondary Coil		Secondary Coil1	
	Part#1	Part#2	Part#1	Part#2	Part#1	Part#2
Start						
(x,y)	(15.375,11)	(37.125,11)	(12.75,11)	(39.75,11)	(10.125,11)	(42.375,11)
	(15.375,33.	(37.125,33.	(12.75,33.	(39.75,33.	(10.125,33.	(42.375,33.
End (x,y)	5)	5)	5)	5)	5)	5)
	(16.875,33.	(38.625,33.	(14.25,33.	(41.25,33.	(11.625,33.	(43.875,33.
End (x,y)	5)	5)	5)	5)	5)	5)
End (x,y)	(16.875,11)	(38.625,11)	(14.25,11)	(41.25,11)	(11.625,11)	(43.875,11)
End (x,y)	(15.375,11)	(37.125,11)	(12.75,11)	(39.75,11)	(10.125,11)	(42.375,11)

Table 4.6 Co-ordinates for pinholes

	Pinholes			
	Part#1	Part#2	Part#3	Part#4
Center point	(4.5, 4.5)	(4.5, 40)	(49.5, 40)	(49.5, 4.5)
Point on the radius of the circle	(6.5,4.5)	(6.5,40)	(51.5,40)	(51.5,4.5)

After following all the tables co-ordinates and center points geometry is formed as shown below in Figure 4.2.

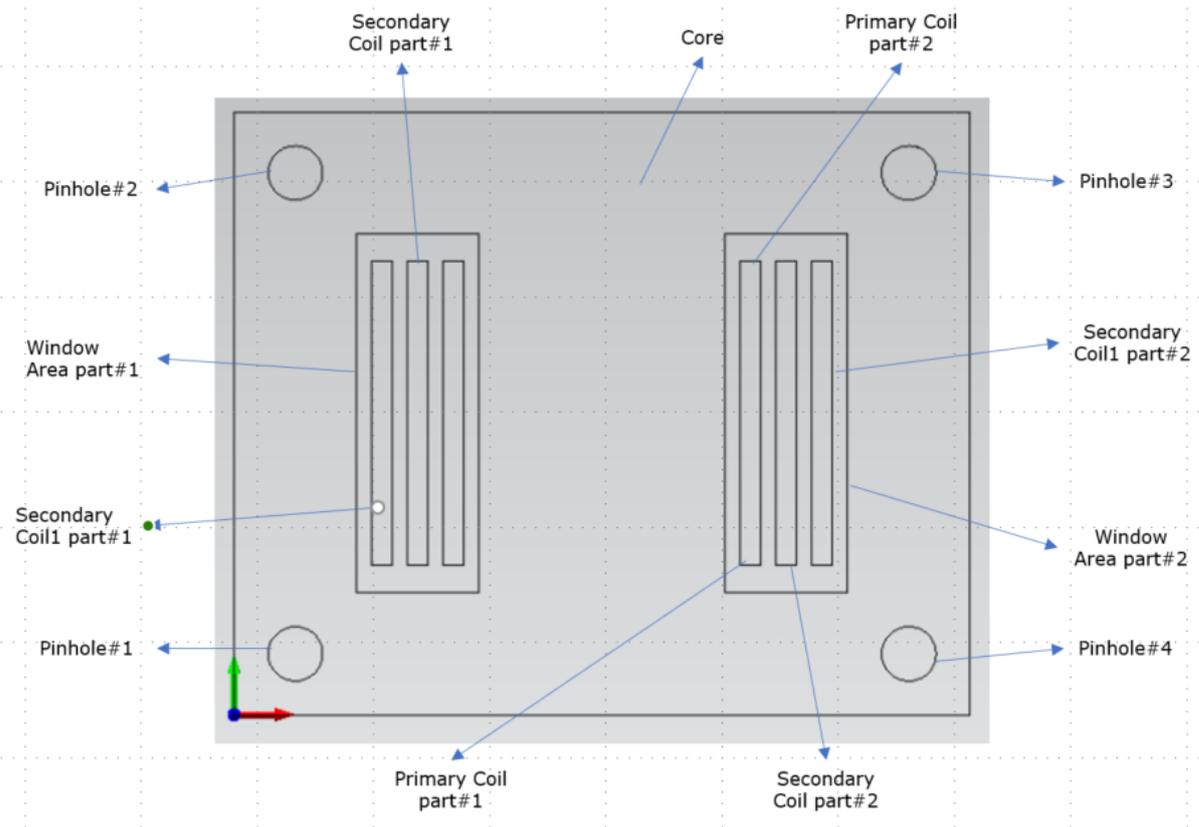


Figure 4.2 Simcenter MAGNET geometry design parts

A component can now be made from the surface that was drawn above in Figure 4.2. The surface is swept over a length of one meter. Components are created using the Make Component dialog box. On the Edit menu, Select Construction Slice Surfaces opted. Clicking the mouse pointer inside the surface of the air space. The surface is highlighted when selected with red color. Then (Make component in a Line tool) on the Model toolbar is chosen. The (Make Component in A Line) dialog box appears as below in Figure 4.3. Hence should be followed for each component, but the material can differ, for the core area, printed steel is selected; for window areas, air material is selected; for all coil parts, Copper: 5.77e7 Siemens/meter is selected; for all holes, the air is selected with the constant width of 26 mm.

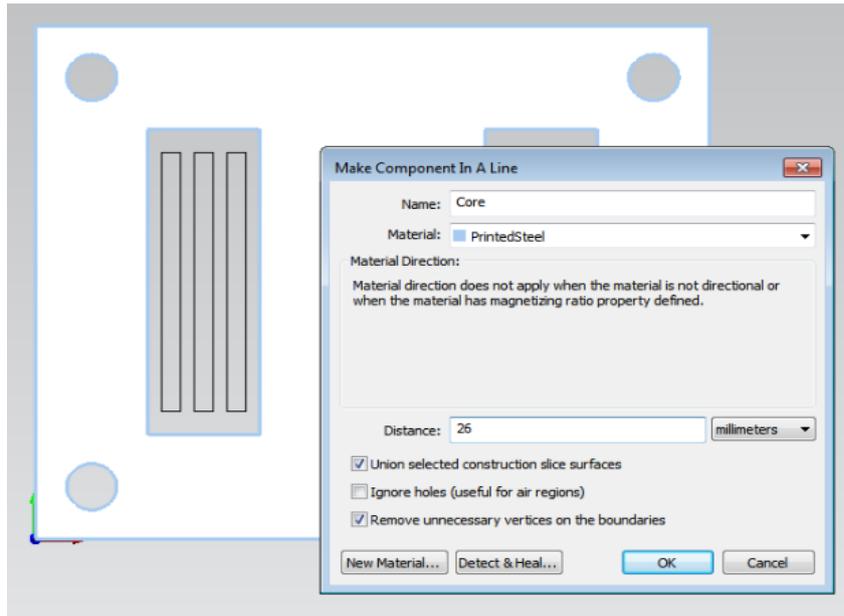


Figure 4.3 Make component in line in Simcenter MAGNET

4.2.3. Component settings and circuit.

The component materials selected based on standards such as steel commonly used for core, and for coil copper is used, but there should be defined coil properties which can be found after creating the coil, each coil consisting of two-part in each of the window areas, such as primary coil part#1 and part#2, same for secondary coil and secondary coil1.

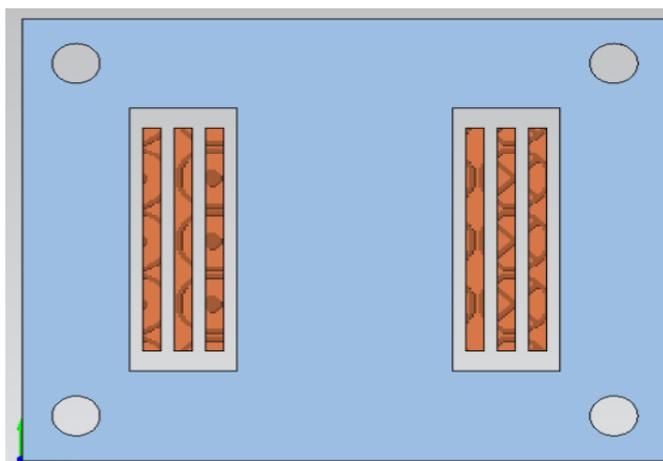


Figure 4.4 2D view of core and winding after settings

Then selected each pair to create one coil on the model menu (Make Simple Coil) is opted, renamed for each iteration for primary coil, secondary coil, and secondary coil1 respectively and saved, then right-click on the menu the properties selected to change the properties of each coil according to Table 4.1, above Figure 4.4 is generated. Construction edges are then deleted for all the parts transformer core and windings, and then the container is formed with air material and width of assumed 28mm, below co-ordinates in Table 4.7 using keyboard input bar and line tool.

Table 4.7 Co-ordinates for container

	Start (x,y)	End1 (x,y)	End2 (x,y)	End3 (x,y)	End4 (x,y)
Container/Tank	(-10, -10)	(-10, 60)	(70, 60)	(70, -10)	(-10, -10)

The circuit for this thesis consists of a current source with a sinusoidal waveform. As the thesis consists of transient analysis, the circuit is defined in the circuit window, On the window menu, a new circuit window is selected, and from the toolbar, the current source has opted which is connected to primary and current source settings is also adjusted according to the primary coil, while secondary coil and secondary coil1 relate to their both ends respectively as shown below in Figure 4.5.

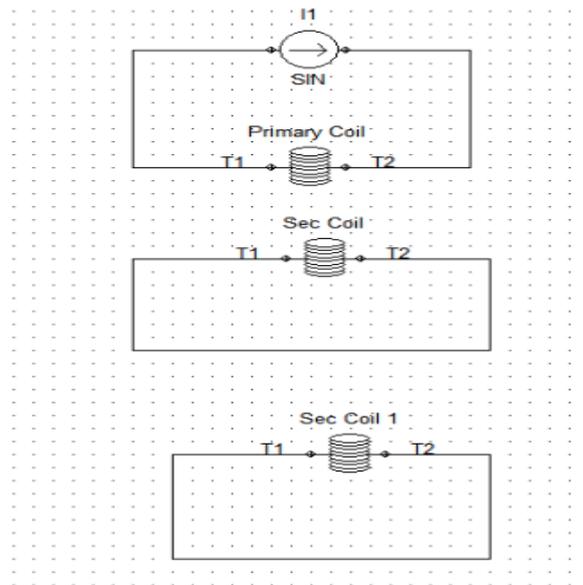


Figure 4.5 Circuit connection for coils with current source

4.2.4. Simulation solver options and results

For transient 2D analysis, transient options assumed at start = 0ms, stop = 20ms, and step = 1ms, times are defined at solve menu. To obtain the result, Transient 2D is selected in the solve menu, results start calculating according to transient options, and a new result window with iron losses is obtained as below in Figure 4.6 calculating the time average hysteresis loss in W/kg at 20ms.

Problem ID: Problem 1			Graph Selection...	In new window	<input type="checkbox"/> Overlap curves			
Time: 0 ms			Export Data...	Display precision: 15	<input type="checkbox"/> Logarithmic scale			
Energy	Body Force	Component Force	Flux Linkage	Ohmic Loss	Iron Loss	Current	Voltage	Temperature
	Time Averaged Hysteresis Loss		Time Averaged Lamination Eddy Current Loss					
Core	7.68021968280765		0					

Figure 4.6 Time average iron loss.

The mechanism or the assumption to achieve the iron losses in Simcenter MAGNET was calculated according to the material properties and the mass density of the material. In this thesis, printed steel was used, and the properties of iron loss for printed steel can be seen in Figure 4.7 below as Equation 2.5.

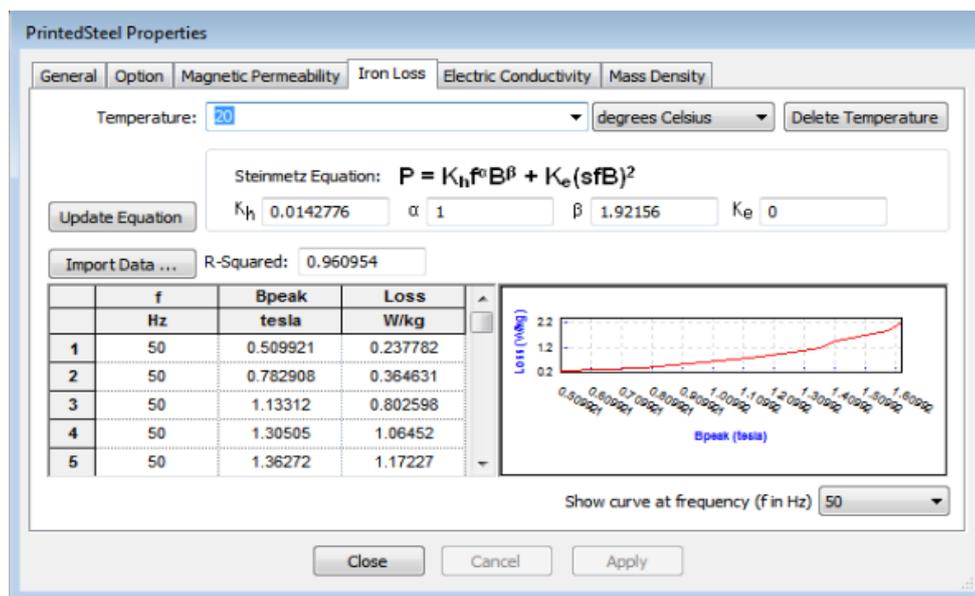


Figure 4.7 Printed steel properties for iron loss

As shown in Figure 4.7 above, B_{peak} is at 1.6092 T, and the loss obtained was time averaged. Hence, Figure 4.8 shows that the central limb carries the whole flux while the sides have less than half.

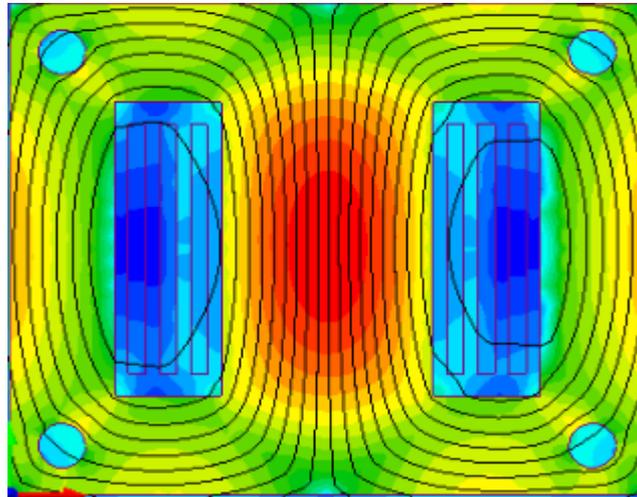


Figure 4.8 Flux distribution for initial design

In this thesis, mesh properties are set at 2 percent, according to [39], 2mm mesh size was accurate for length 100mm, hence the size of a mesh i:e 1.08 mm in this work assumed for 54 mm length. Thus, the actual mesh influences the accuracy speed and convergence of the simulation. After defining the finite element size of the model, the impact on iron losses increased from 7.68 W/kg in Figure 4.6 to 7.71 W/kg in Figure 4.9 below. To conclude, this part simulation was successful and showed elementary results of iron losses which are the first success of this work. While this process takes a lot of time, if we do manually and analyze different geometries, hence below in Section 4.3, Simcenter MAGNET simulation to MATLAB is organized and discussed to achieve these results in seconds or minutes.

	Time Averaged Hysteresis Loss	Time Averaged Lamination Eddy Current Loss
Core	7.71671970471562	0

Figure 4.9 Results after defining mesh size

4.3. Transformer parameterization

4.3.1. Scripting in Simcenter MAGNET

The scripting feature in Simcenter MAGNET helps to automate modeling, solving, and post-processing tasks. Simcenter MAGNET is customized to meet user requirements and enable a direct link between the application and any other software, such as MATLAB. Scripting helps to automate the process of building models. In Simcenter MAGNET, Complex and repetitive tasks can be simplified with scripting. In addition to building models, scripting can be used to solve models and extract post-processing information such as simulation results. To parameterize the transformer which was concluded in the above Section 4.2 scripting feature of Simcenter MAGNET is used to obtain the results, below in Figure 4.10 can be seen the logic for VB script,



Figure 4.10 Logic for VB script

The benefit of the scripting feature is no additional coding is required, and the script is automatically generated by selecting start recording user script and then drawing the model and adjusting the properties, the application then records all the commands and actions performed during initial design modeling in Simcenter MAGNET and code can be seen using notepad or word. The code generated is then used as a reference in MATLAB for instance. Although languages in the Visual Basic family are primarily used in ActiveX applications, such as Simcenter MAGNET and Excel, this is not still the case. One example is MATLAB. This ActiveX compliant software runs its scripting language. As a result, the way arrays and input parameters are handled differently than the way they are in Simcenter MAGNET programs. Therefore, some of the Simcenter MAGNET APIs cannot be called directly from MATLAB. However, specific APIs in Simcenter MAGNET applications can be used as workarounds.

4.3.2. Simcenter MAGNET-MATLAB environment

Using MATLAB application for parameterizing and Simcenter MAGNET as a remote server, the above code in Figure 4.11 could be executed by following the command sequence, to be noted that in MATLAB, all strings are closed in single quotes, which is very well described and followed from scripting manual [40].

```
%% Open Magnet necessary to put in the begining
MagNet = actxserver('MagNet.Application'); % connect to MAGNET
set(MagNet, 'Visible', 'True'); % open MAGNET
invoke(MagNet, 'processCommand', 'Call newDocument()'); % create a new document
setupunits='Call getDocument().setDefaultLengthUnit("millimeters")'; %units
```

Figure 4.11 Process Command API

Following the command API, the Simcenter MAGNET script is copied in MATLAB to automate Section 4.2. The main logic is to code in MATLAB so that if we run code, it gives the same output as the VB script. As modeling above planned with the sequence and initial considerations, coding in MATLAB follows the same series of consideration. Only addition will be function for each possible stage as shown below.

Geometry – Simcenter MAGNET modeling starts with geometry so does the code, hence each line of geometry, such as newline and co-ordinates, are converted in MATLAB or called in a single quote to run the simulation and get the geometry. The function *strcat* is used to combine string and character vector to duplicate the Simcenter MAGNET's VB script. The logic for the function is applied as the transformer consists of a rectangle and circle. Two new functions for creating the circle and rectangle are created and used for each part of the transformer, such as rectangle for core and circle for pinholes.

Component creation - After geometry, for each part, the material is selected using a function to make a component which simplifies the selection co-ordinates at x and y-axis, name of the material such as core, a width of the material, and type of material such as printed steel for the core.

Making coil and its properties - Coil is created by selecting the transformer parts. Hence same logic is duplicated as used in component creation at first, and declaring the properties of each coil, an array of values is used to select the coil parts and define the name of the coil, initial voltage ($v0$), voltage (v), frequency (f), waveform (w), resistance (r), number of turns for coil, and lastly invoking command in the loop due to massive number of properties or iterations. The problem was faced during this coding due to quotes hence function unquoted to remove quotes are used.

Circuit, container, and transient options - All these lines of code in the VB script will remain constant, and nothing much can be automated or needs particular attention. Hence this part of the code is copied in a new **.txt* file, readlines function, and for loop to invoke command is used to run this part.

Simulation - This part of the script is copied to a new **.txt* file because the set of commands included in this part is similar for all operations and *fscanf* function is used which reads the according to the format, at this part of code consist of different format compare to circuit, hence it is separated.

After all these steps, the code is ready to run the FEM Simcenter MAGNET model in the MATLAB environment, and considering putting initial values and formulas for geometry, simulation is performed. A successful model is created in Simcenter MAGNET with the help of MATLAB in seconds. Still, the only limitation is that the values and formulas are independent, consisting of manually changed values; hence, parameterization is essential which is discussed in below sub-section. After changing some matters, it is possible to create a design with different sizes and properties to identify the additional losses.

4.3.3. Parameterization of MATLAB code

The code consists of many independent coordinates values and other properties to parameterize or to convert in one vector Figure 2.4 transformer geometry is referred, consisting of c , bw , hw , $N1$, $N2$. Some added parameters referring to our initial design Figure 4.1 and Table 4.1, the radius of pinholes (r), number of turns for secondary coil1 ($N3$), dimension at x for each coil part (bwa), dimension at y for each coil part (hwa), These all nine variables to the transformer are considered as one below,

$$\text{vector_x (1:9)} = \text{vector_x (c, bw, bwa, hw, hwa, r, N1, N2, N3)} \quad (4.1)$$

Now all the parameters are replaced with vector_x (1:9) in above Equation 4.1, from geometry to making coil according to the parameter used, respectively. While the formula reference is taken from chapter 2 and Figure 2.4, Additionally, the distance between coil part in window areas for coil parts at x-axis as in below Equation 4.2, the distance between the coil part and window areas at the y-axis as in below Equation 4.3 are added for proper and equal spacing between the coil parts in window area one and two, as the coils in each window area is three.

$$\text{espace_left_x} = (\text{vector_x (2)} - 3 * \text{vector_x (3)})/4 \quad (4.2)$$

$$\text{espace_left_y} = (\text{vector_x (4)} - \text{vector_x (5)})/2 \quad (4.3)$$

Hence, MATLAB code depends mainly on these nine parameters after adding above modifications. Though some independent variables need attention, considering the thesis problem, these nine should be regarded primarily, and discussed with the set of data in below Section 4.4.

4.4. Sensitivity analysis

In this thesis, sensitivity analysis determines how parameters affect the objectives, such as the weight of the core and iron loss. It is done to identify the range of failures and consequence when parameters have limits of (+/-) 10 percent, showing the trend maximum to minimum and relativity by doing analysis, for that we need set of data, means multiple numbers of FEM outputs, As mentioned in above Section 4.3, parameterization is done that means now limit and automate repetition of code until some number of cycles required, hence, to achieve this hypercube function is used.

Function *lhsdesign* is used to generate the design space, a Latin hypercube sample matrix of size designs by parameters. For each column of parameter, the n number of designs are performed with specified limit values of parameters are randomly distributed with one from each interval $(0,1/n)$, $(1/n,2/n)$, ..., $(1 - 1/n,1)$, then

randomly permuted then the results are saved in MATLAB, by replacing vector_x with X_{design_domain} .

Further, to obtain the data set, 200 designs in this problem are executed to run simultaneously to get the FEM output from Simcenter MAGNET, which took almost 1.5 hrs only in simulation. Finally, the results are saved in MATLAB. Hence data set of 200 designs is ready to analyze, below Figure 4.12 can be seen for the iron loss output range obtained from FEM model, whereas the minimum is 6.32 W/kg, maximum iron loss obtained is 9.39W/kg, by transient analysis at 20 ms.

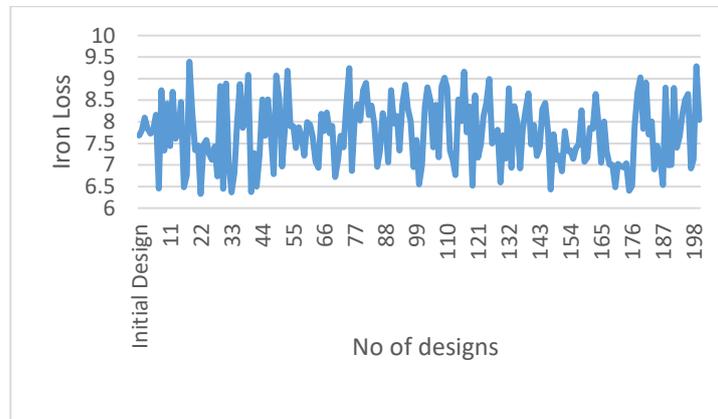


Figure 4.12 Plot Iron Loss vs No of designs

Hence, the range of iron losses can be determined as above Figure 4.12 in between 6 to 9.5 W/kg, Similarly, for the mass of the core, the minimum is 0.319 kg, and the maximum obtained is 0.455 kg, which is in the below Figure 4.13, whereas the range is between 0.5 kg to 0.3 kg, when deviation for the initial parameter is set at limit of (+/-) 10%,

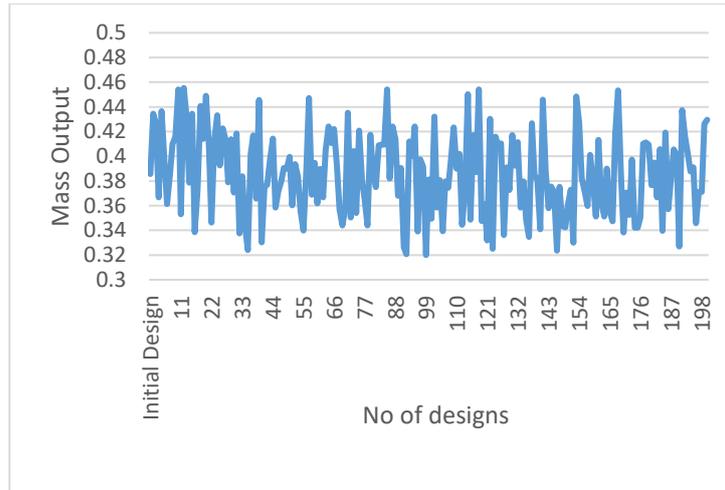


Figure 4.13 Plot Mass Output vs No of designs

Overall comparison trend between weight of core and iron loss can be seen below in Figure 4.14, To conclude, the sensitivity analysis deviation of (+/-) 20 percent can be seen in the iron loss output of the FEM model and mass output of mathematical expression according to Equation 2.11.

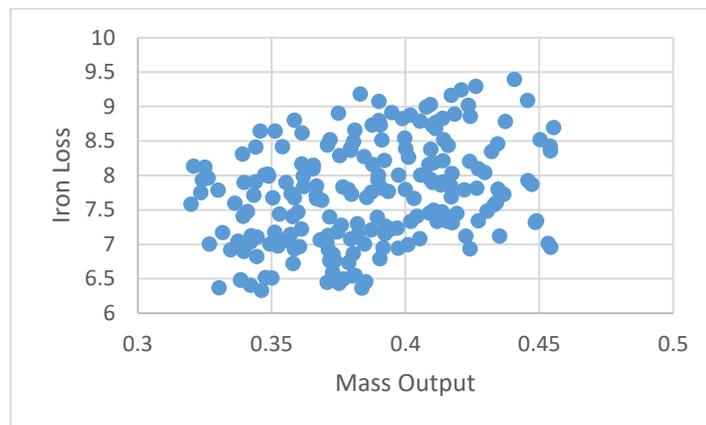


Figure 4.14 Plot between mass and iron loss output

To analyse the model plot range is added to compare each parameter with iron loss. below are Figures 4.15 - 4.23

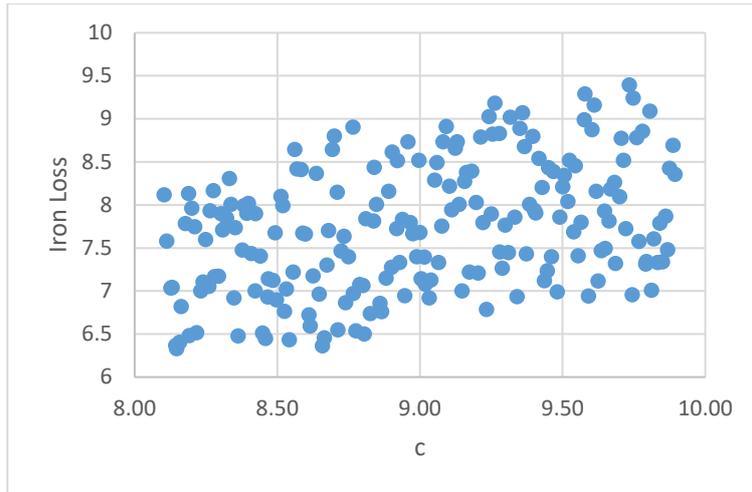


Figure 4.15 Plot between c and Iron Loss

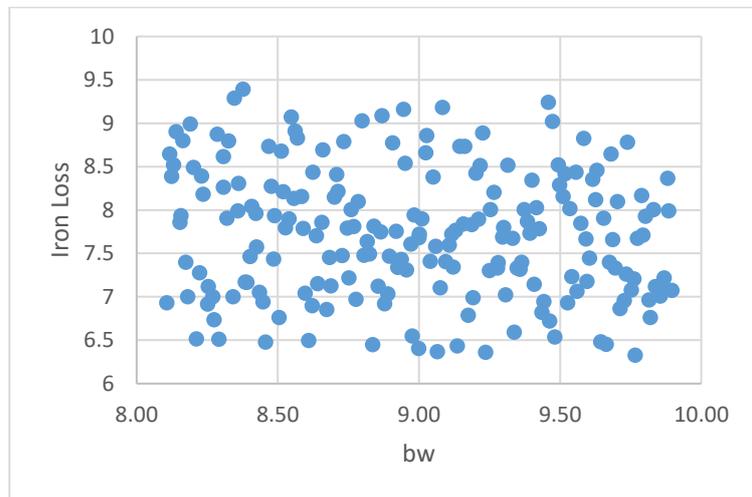


Figure 4.16 Plot between bw and Iron Loss

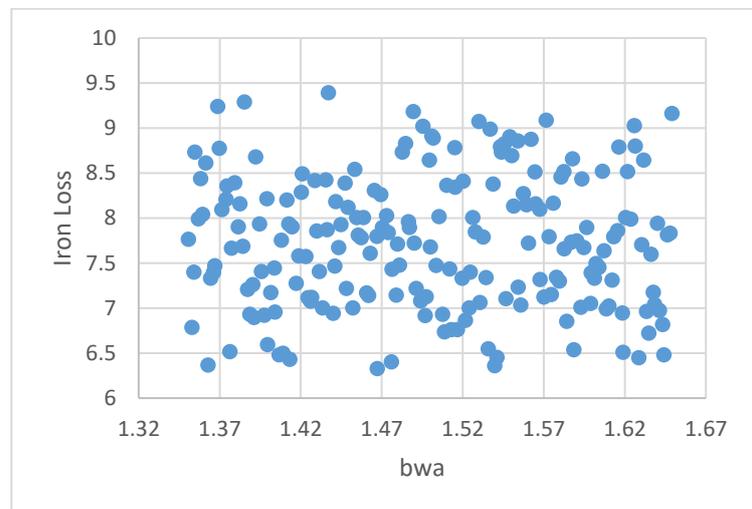


Figure 4.17 Plot between bwa and Iron Loss

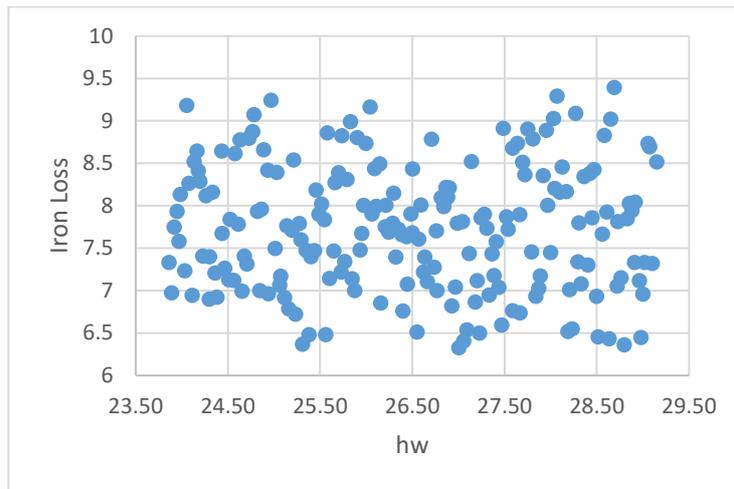


Figure 4.18 Plot between hw and Iron Loss

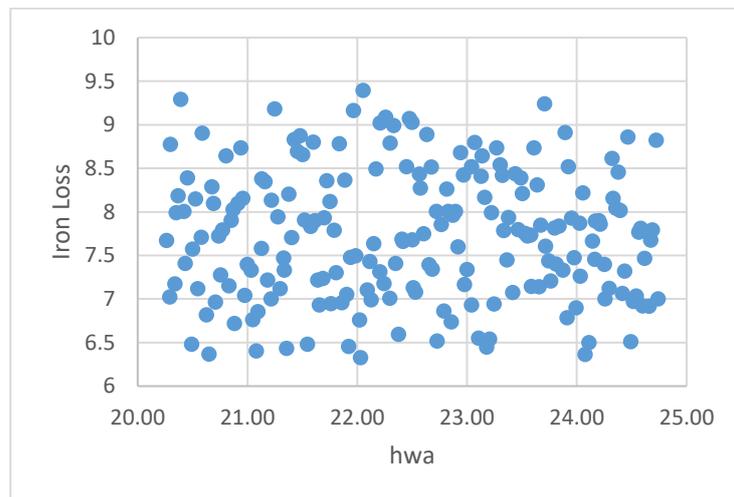


Figure 4.19 Plot between hwa and Iron Loss

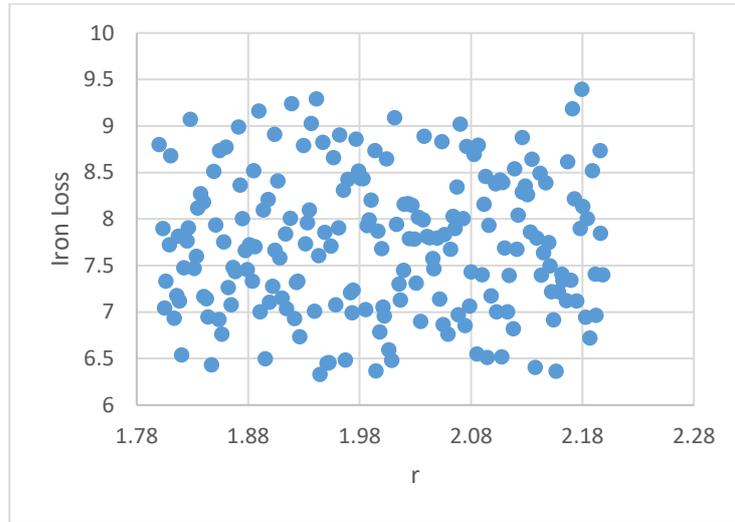


Figure 4.20 Plot between r and Iron Loss

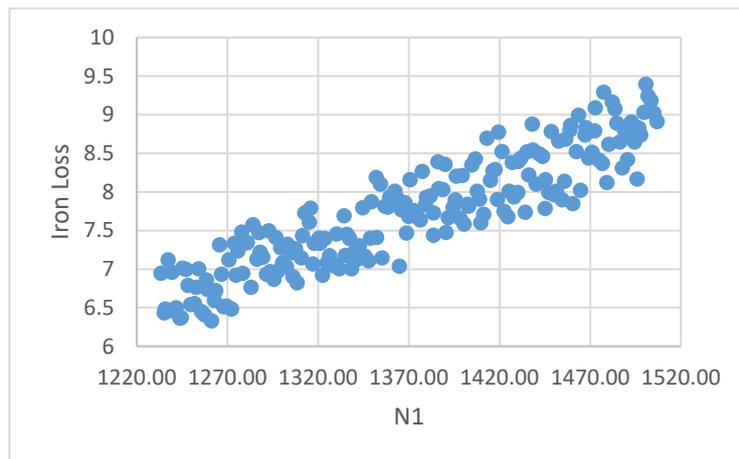


Figure 4.21 Plot between N1 and Iron Loss

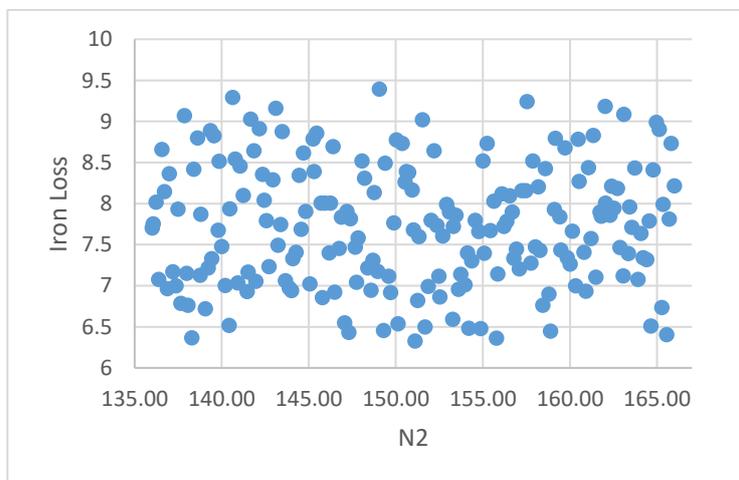


Figure 4.22 Plot between N2 and Iron Loss

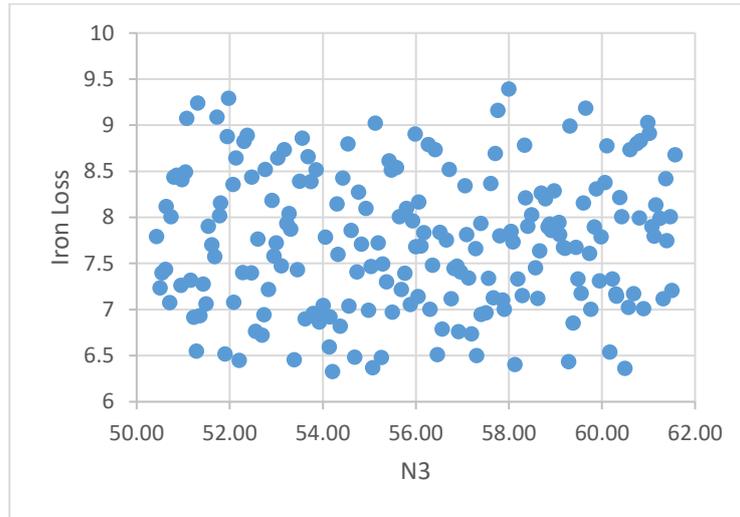


Figure 4.23 Plot between N3 and Iron Loss

Hence, it can be seen above in Figures 4.15 and 4.21 that parameters c and $N1$ have an undeniable influence on the iron loss. At the same time, other parameters such as in Figures 4.16, 4.17, 4.18, 4.19, 4.20, 4.22, 4.23 have a minimal impact to iron loss because they are diversified.

4.5. Optimization of the transformer using DOM, where a FEM model is used along with GA

4.5.1. Genetic Algorithm

To obtain a multi-objective optimization, an optimization model should be developed as Equation 3.2

$$\begin{aligned}
 &\text{Minimize } f(x) = \{f_1(x), f_2(x), \dots, f_p(x)\}, & (4.4) \\
 &\text{Subject to } g_i(x) \leq 0, \{i = 1, 2, \dots, m\}, \\
 &\quad h_j(x) \leq 0, \{j = 1, 2, \dots, p\},
 \end{aligned}$$

The vector $f(x)$ is created in above Equation 4.4 from objective functions, and the vector x gives a set of n parameters. whereas the functions $g_i(x)$ and $h_j(x)$ are constraint functions, following are the functions or the goals of solving multi-objective problems,

The primary goal of solving multi-objective problems is to find good compromises between the objective functions. Traditionally, this objective is accomplished using the concept of Pareto Optimality, which means, for example, the design has the mass $m = x$ and iron loss $p=y$, and for the next iteration, the solution changes to the mass $m = x-h$. In contrast, $h < x$, and $p=y$, then $m=x$, $p=y$ is not Pareto optimum. To summarize the idea of the Pareto Optimality, several characterizations are discussed below [4].

Pareto Optimal Solution - A resolution $x \in \Omega$ is called a Pareto Optimal Solution if there is no $x' \in \Omega$ for which the objective vector $f_A(x')$ overlooks $f_A(x)$. Here, Ω implies the feasible area of the optimization problem. The feasible area is an area where all constraints are satisfied.

Pareto Dominance - A vector $f_A(x)$ is expressed to dominate another vector $f_A(x')$ only if $f_A(x)$ is partially less than $f_A(x')$. Essentially, the multi-objective genetic algorithm obtains a set of Pareto Optimal Solutions. This set is a set of optimal values of the optimization parameters. Mathematically, the Pareto Optimal Set (P^*) can be described as follows

$$P^* := \{x \in \Omega \mid \neg \exists x' \in \Omega \mid f(x') \leq f(x)\}, \quad (4.5)$$

The second function of the multi-objective optimization is to construct the Pareto Front. At first, numerous points within the feasible region in the Figure 4.24 below should be estimated. If the points are high enough, the GA finds the non-dominated points as shown in the red dots below in Figure 4.15 and identifies Pareto Front (PF*) [41].

$$PF^* := \{u = f(x) \mid x \in P^*\} \quad (4.6)$$

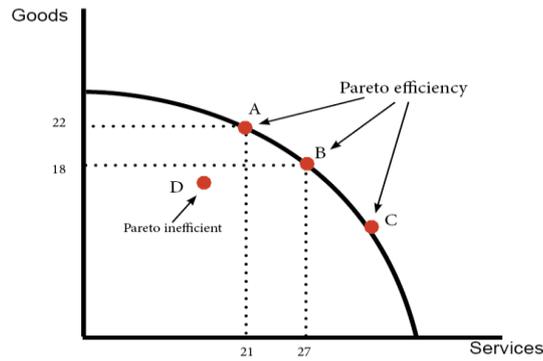


Figure 4.24 Pareto front example

The technique that allows the multi-objective genetic algorithm to study the solution space is presented in Algorithm 1 [41]. The precise terms used within the MOGA procedure are the following:

- The term "gene" means an optimization parameter.
- The term "individual" represents a set of optimizations parameters.
- The term "population" shows a group of different parameter sets.

The principal steps in the MOGA stand to generate the initial population and compute the optimization objectives' values. The next phase involves ranking depending on the Pareto Dominance and allocating the niching technique's fitness values. Fitness value expresses how "fair" an individual is. The evolutionary search process begins with the subsequent operators: selection, crossover, and mutation using the developed fitness values.

The general functions for these operators are below:

- The selection operator chooses individuals from the existing population based on their fitness values; these selected individuals are called "parents".
- The crossover operator is applied to the "parents" to create unique individuals called "offspring".
- The mutation operator broadens the search space by changing the current population; then, the "offspring" and mutated individuals form a new generation.

There are many types of selection, crossover, and mutation operators. The tournament selection, crossover intermediate, and mutation adapt feasible were used in this optimization problem.

4.5.2. Optimization method

The optimization was performed using the flow represented in the below Figure 4.25. The connection between MATLAB and Simcenter MAGNET software program was organized. The optimization cycle started with parameters defined by the GA within the MATLAB optimizer. Then, these parameters were used to build a 2D model using Simcenter MAGNET. Once it was complete, Simcenter MAGNET calculated the iron loss and directed the mass of the core to the MATLAB optimizer. Using the obtained values of the objectives, the MATLAB optimizer refined the parameters, and the same cycle was executed until the stop criterion had been satisfied. The population size and number of generations defined the stop criterion. Mainly, the optimization was performed for seven hours the optimized result was obtained by defining stop criterion as population size to 50 individuals and max generations to 10 that means total 500 cycles were executed to minimize the mass using mathematical Equation 2.11 and iron loss using FEM model in Simcenter MAGNET for the assumed initial model design.

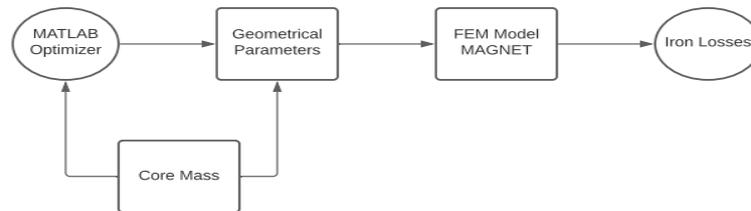


Figure 4.25 Optimization flowchart for thesis problem

Hence, eighteen outputs were obtained by solving the FEM model through MOGA. From all these outputs, the maximum and minimum iron losses were analysed, checked, and compared by manually adding each parameter obtained to code, and below is the matching result. It can be seen in the presentation of genetic results in the above Table 4.8.

Table 4.8 Comparison between Initial and GA solution

Parameters	Initial Design	Genetic result
c	9mm	8.1mm
bw	9mm	8.1mm
bwa	1.5mm	1.35mm
hw	26mm	23.9mm
hwa	22mm	21.2mm
r	2mm	2.04mm
N1	1370	1233
N2	151	148
N3	56	56
Mass	0.385kg	0.312kg
Iron Loss	7.71W/Kg	6.308W/kg

Whereas, in below Figure 4.26, the optimized design flux distribution area is similar to the initial design flux distribution in Figure 4.8

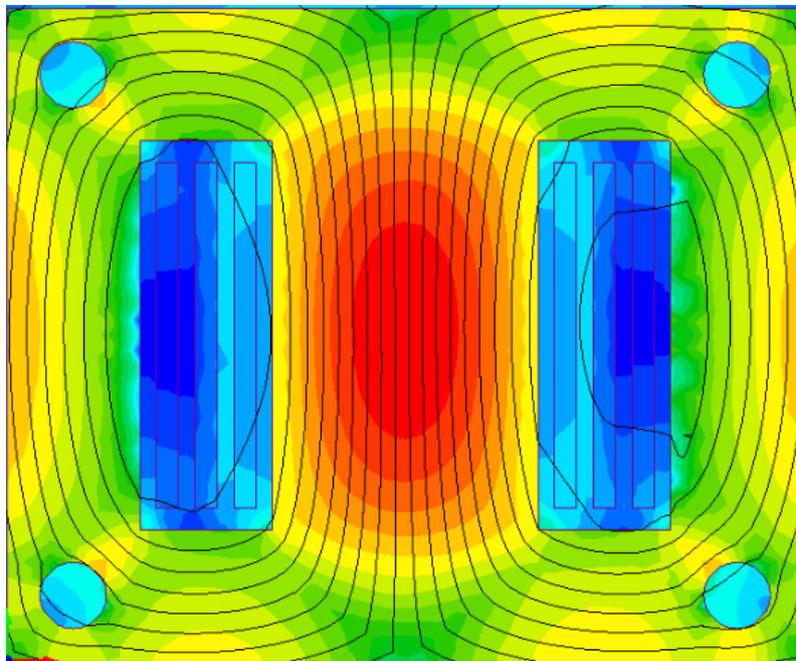


Figure 4.26 Flux distribution for optimized design

The trend for Pareto front can be seen below in Figure 4.27, however the iron loss at its peak is the optimal solution because it matches with the FEM model output, whereas

mass and iron loss in general decreases by 20 percent, when we limit Equation 4.1 to (+/-) 10 percent.

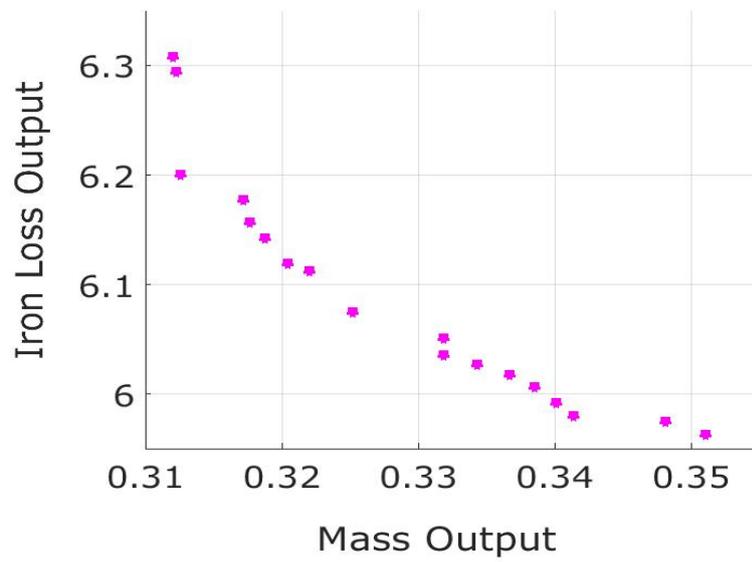


Figure 4.27 Pareto front

5. CONCLUSION

Transformers help to improve power systems' safety and efficiency by raising and lowering voltage levels when needed. They are used in many residential and industrial applications. Primarily and most notably, transformers are utilized for distributing and regulating power across long distances. There are many aspects a design review of the transformer helps advance the procurement procedure by bringing two parties together. First, discussion of the transformer design's technical details. Second aspect can be an adequately conducted design review which can establish a strategy agreed upon by both the purchaser and manufacturer. Hence design review verifies the purchaser that the manufacturer meets their specification's fit, function, performance, materials, and other requirements. Lastly, design reviews help prevent and minimize project schedule delays and cost overruns. The optimization of any machine is worth it as it provides the optimal solution or series of the optimal solutions. The complexity of the optimization depends on the type of machine, its structure, and the type of result required. Transformer design consists of many variables, and it's co-related to each other that impact the performance. Following the proper optimization method, it can be easy to define and track all the parameters and analyze them according to a particular need.

At the beginning thesis, mathematical expressions of the design of the transformer were reviewed. According to the initial dimension's assumptions and calculations, modelling of the geometry was carried out. The thesis proceeded with Simcenter MAGNET interface and VB scripting to build the FEM model. At the next stage of this study, the model required parameterization. The software MATLAB helped to create the parameterization of the transformer's FEM model. Then, the sensitivity analysis was carried out in order to assess the influence of the optimization parameters on the objective functions. The next step was to formulate the optimization model and move to the optimization phase using the GA insured by the MATLAB optimizer. As a result, the optimal FEM model solution was obtained. The optimization was carried out within seven hours.

This thesis has some potential benefits and limitations which are discussed below. This thesis uses the MATLAB and Simcenter MAGNET environment for transformer design optimization, which is one of the primary benefits and multiple simulations can be performed by adjusting nine parameters, and results are obtained according to the standard settings of Simcenter MAGNET. Secondly, this model can be saved and

analysis can be done by minding other problems to the transformer such as window area evaluation, ohmic loss calculation, coil area evaluation, circuit up-gradation, and much more just by changing the component's properties, materials can also be tested within minutes. Lastly, the optimal solution can be achieved using a primary or default setting of MATLAB optimizer.

Limitations of this thesis are that the model built in this work was 2D, hence eddy current losses were not considered in this problem. Instead, it only finds the core's iron losses and mass output. The transformer optimization is broad because it consists of many parts. As in this study, only core and windings have been given importance. Normally, transformers have other variables such as cooling, type of insulation, and much more. As far as thesis difficulties are concerned, there were numerous hurdles while obtaining the solution. They are related and diversified in all stages, such as initial design assumptions. Firstly, the design from the paper was considered. Still, it was not suitable to parameterize, and changes were made to the initial setup to obtain the results. Following the MATLAB and Simcenter MAGNET environment, parameterization and optimization, error in the function name, simulation integration, storing results, and running simulation for more than seven hours were some of the major difficulties faced.

6. BRIEFING IN ENGLISH AND ESTONIAN

6.1. Summary

This thesis followed the structure by investigating and assuming the initial design consideration mainly by referring [3], [4], [17]. First, the transformer design plan was executed. Then, the initial design was created, where the weight of the core was identified, coordinates of geometry were described, materials were assigned for all transformer parts, coils were characterized. Secondly, the FEM model was made in Simcenter MAGNET software by following the initially assumed parameters to obtain time-averaged iron losses. Thirdly, using the script generated in Simcenter MAGNET software, the FEM model was parametrized in MATLAB environment through command API. All parameters are converted to one vector_x (1:9) to develop a VB script as an output in MATLAB. Fourthly, sensitivity analysis of the FEM model was carried out using the hypercube function to get 200 designs and output following the resulting trend was discussed. Lastly, optimization of mass and iron loss was made using genetic algorithm, whereas the mass was referred from the Equation 2.11 as mathematical expression and iron losses from FEM model in Simcenter MAGNET. The optimal solution was obtained using multi-objective optimization with default MATLAB optimizer settings. The resulting Pareto front and Pareto optimality solution were discussed to conclude the work.

6.2. Kokkuvõte

See lõputöö järgis ülesehitust, uurides ja eeldades esialgset disainilahendust peamiselt viidates [3], [4], [17]. Kõigepealt viidi läbi trafo projekteerimisplaan. Seejärel kõik esialgsed parameetrid, nagu südamiku massi tuvastamine, geomeetria koordinaatide kirjeldus, materjalide määramine trafo kõigi osade jaoks, mähise omadused ja simulatsioonirežiim. Teiseks tehti Simcenter MAGNET tarkvaras FEM-mudel, järgides algelt oodatud parameetreid, et saada ajakeskmiste rauakaod. Kolmandaks parameetriseeris Simcenter MAGNET tarkvarast genereeritud skript FEM mudeli disaini MATLABis käsu API abil. Kõik parameetrid teisendatakse üheks vektoriks_x (1:9), et arendada VB-skripti MATLAB-i väljundina. Neljandaks järgiti FEM-mudeli tundlikkuse analüüsi, kasutades hüperkuubi funktsiooni, et saada 200 kujundust ja väljundit, järgides sellest tulenevat suundumust. Lõpuks massi- ja rauakao optimeerimine geneetilise algoritmi abil, samas kui massile viidati võrrandis 2.11 kui Simcenter

MAGNETi FEM-mudeli matemaatilisele avaldisele ja rauakadudele, et alustada simulatsiooni ja saada optimaalne lahendus kõigi esialgsete parameetrite jaoks. MATLAB optimeerija vaikesätetega, Pareto front ja Pareto optimeerimislahendus töö lõpetamiseks.

7. REFERENCES

- [1] P. Georgilakis, N. Hatzargyriou, and D. Papparigas, "AI helps reduce transformer iron losses," *IEEE Comput. Appl. Power*, vol. 12, no. 4, pp. 41–46, 1999, doi: 10.1109/67.795137.
- [2] R. Darwante, D. Nikam, R. Sonawane, and R. Sonawane, "Design and Analysis of Heat Transformer through FINS," vol. 6, no. 02, pp. 735–738, 2018.
- [3] L. D. S. Coelho, V. C. Mariani, F. A. Guerra, M. V. F. Da Luz, and J. V. Leite, "Multiobjective optimization of transformer design using a chaotic evolutionary approach," *IEEE Trans. Magn.*, vol. 50, no. 2, pp. 669–672, 2014, doi: 10.1109/TMAG.2013.2285704.
- [4] E. Andriushchenko *et al.*, "Optimization of a 3d-printed permanent magnet coupling using genetic algorithm and taguchi method," *Electron.*, vol. 10, no. 4, pp. 1–16, 2021, doi: 10.3390/electronics10040494.
- [5] D. Transformers, *IEEE standards*, vol. 12, no. 4. 2012.
- [6] S. Edition, *Transformer Design Principles*. 2001.
- [7] V. Lebedev, "Transformer basics," *2007 Electr. Insul. Conf. Electr. Manuf. Expo, EEIC 2007*, pp. 356–359, 2007, doi: 10.1109/EEIC.2007.4562642.
- [8] A. D. T. J. M. T. Zacharias, "Single-phase transformer model including magnetic hysteresis and eddy currents Single-phase transformer model including magnetic hysteresis and eddy currents," no. June, 2015, doi: 10.1007/s00202-007-0071-5.
- [9] A. M. T. I. Al-naib, "Open Circuit Test (O . C . T .) of Single-Phase Transformer," no. October, 2019, doi: 10.13140/RG.2.2.19891.58401.
- [10] E. I. Amoiralis, M. A. Tsili, and A. G. Kladas, "Transformer design and optimization: A literature survey," *IEEE Trans. Power Deliv.*, vol. 24, no. 4, pp. 1999–2024, 2009, doi: 10.1109/TPWRD.2009.2028763.
- [11] V. Jagota, A. P. S. Sethi, and K. Kumar, "Finite element method: An overview," *Walailak J. Sci. Technol.*, vol. 10, no. 1, pp. 1–8, 2013, doi: 10.2004/wjst.v10i1.499.
- [12] C. Society, "PowerCon 2002 - 2002 International Conference on Power System Technology, Proceedings," *PowerCon 2002 - 2002 Int. Conf. Power Syst. Technol. Proc.*, vol. 4, 2002.

- [13] Y. Li, S. L. Ho, N. Wang, and R. Y. Tang, "Numerical analysis of eddy current field in the ascending flange for the bushings and tank wall of a large transformer," *2008 Jt. Int. Conf. Power Syst. Technol. POWERCON IEEE Power India Conf. POWERCON 2008*, vol. 44, no. 6, pp. 1522–1525, 2008, doi: 10.1109/ICPST.2008.4745377.
- [14] X. M. Lopez-fernandez, "Stray Losses Control in Core and Shell Type Transformers Part I: UPGRADING OF ENERGY-SAVING AND RELIABILITY OF LARGE TRANSFORMERS Stray Losses Control In Core- And Shell Type Transformers," no. December, 2020.
- [15] L. Susnjic, Z. Haznadar, and Z. Valkovic, "Electromagnetic Analysis Applied to the Prediction of Stray Losses in Power Transformer," *Int. Conf. Electr. Mach.*, no. January 2004, pp. 2–6, 2004.
- [16] M. Vitelli, "Numerical evaluation of 2-D proximity effect conductor losses," *IEEE Trans. Power Deliv.*, vol. 19, no. 3, pp. 1291–1298, 2004, doi: 10.1109/TPWRD.2004.829875.
- [17] H. Tiismus, A. Kallaste, A. Belahcen, A. Rassõlkin, T. Vaimann, and P. S. Ghahfarokhi, "Additive manufacturing and performance of E-Type transformer core," *Energies*, vol. 14, no. 11, 2021, doi: 10.3390/en14113278.
- [18] M. Mehrpouya, A. Vosooghnia, A. Dehghanghadikolaei, and B. Fotovvati, *The benefits of additive manufacturing for sustainable design and production*, no. April. 2021.
- [19] A. A. Zadpoor, "Mechanical performance of additively manufactured meta-biomaterials," *Acta Biomater.*, vol. 85, pp. 41–59, 2019, doi: 10.1016/j.actbio.2018.12.038.
- [20] W. Chen *et al.*, "Fatigue behaviour and biocompatibility of additively manufactured bioactive tantalum graded lattice structures for load-bearing orthopaedic applications," *Mater. Sci. Eng. C*, vol. 130, no. August, p. 112461, 2021, doi: 10.1016/j.msec.2021.112461.
- [21] T. Maconachie *et al.*, "SLM lattice structures: Properties, performance, applications and challenges," *Mater. Des.*, vol. 183, p. 108137, 2019, doi: 10.1016/j.matdes.2019.108137.
- [22] E. I. Amoiralis, P. S. Georgilakis, and E. Litsos, "Methodology for the Optimum Design of Power Transformers Using Minimum Number of Input Parameters," *Power*, no. 470, pp. 1–6, 2006.

- [23] Y. Sun, J. Li, X. Fu, H. Wang, and H. Li, "Application research based on improved genetic algorithm in cloud task scheduling," *J. Intell. Fuzzy Syst.*, vol. 38, no. 1, pp. 239–246, 2020, doi: 10.3233/JIFS-179398.
- [24] E. I. Amoiralis, M. A. Tsili, S. Profile, A. Kladas, and A. G. Kladas, "Development of power transformer design and simulation methodology integrated in a software platform European Smart Grid projects View project AC Magnetic measurement systems View project Development of power transformer design and simulation methodology ," *Adv. Res. Work.*, no. October, 2010, [Online]. Available: <https://www.researchgate.net/publication/260553013>.
- [25] W. G. Hurley, W. H. Wölfle, and J. G. Breslin, "Optimized transformer design: Inclusive of high-frequency effects," *IEEE Trans. Power Electron.*, vol. 13, no. 4, pp. 651–659, 1998, doi: 10.1109/63.704133.
- [26] M. Poloujadoff and S. Martin, "Optimal Transformer Design," no. 4, pp. 202–205, 1986.
- [27] W. T. Jewell, "TRANSFORMER DESIGN IN THE UNDERGRADUATE POWER ENGINEERING LABORATORY," vol. 5, no. 2, pp. 499–505, 1990.
- [28] P. S. Georgilakis, "Decision support system for evaluating transformer investments in the industrial sector," *J. Mater. Process. Technol.*, vol. 181, no. 1-3 SPEC. ISS., pp. 307–312, 2007, doi: 10.1016/j.jmatprotec.2006.03.040.
- [29] Y. Duan and D. M. Ionel, "A review of recent developments in electrical machine design optimization methods with a permanent-magnet synchronous motor benchmark study," *IEEE Trans. Ind. Appl.*, vol. 49, no. 3, pp. 1268–1275, 2013, doi: 10.1109/TIA.2013.2252597.
- [30] S. S. Rao, *Engineering optimization: Theory and practice*. 2019.
- [31] G. Lei, J. Zhu, Y. Guo, C. Liu, and B. Ma, "A review of design optimization methods for electrical machines," *Energies*, vol. 10, no. 12, pp. 1–31, 2017, doi: 10.3390/en10121962.
- [32] M. A. Khan, I. Husain, M. R. Islam, and J. T. Klass, "Design of experiments to address manufacturing tolerances and process variations influencing cogging torque and back emf in the mass production of the permanent-magnet synchronous motors," *IEEE Trans. Ind. Appl.*, vol. 50, no. 1, pp. 346–355, 2014, doi: 10.1109/TIA.2013.2271473.
- [33] M. Degano, E. Carraro, and N. Bianchi, "Selection criteria and robust optimization of a traction PM-assisted synchronous reluctance motor," *IEEE*

- Trans. Ind. Appl.*, vol. 51, no. 6, pp. 4383–4391, 2015, doi: 10.1109/TIA.2015.2443091.
- [34] P. N. Koch, R. J. Yang, and L. Gu, "Design for six sigma through robust optimization," *Struct. Multidiscip. Optim.*, vol. 26, no. 3–4, pp. 235–248, 2004, doi: 10.1007/s00158-003-0337-0.
- [35] W. W. Ii and A. Battle, "Introduction to Optimization CO."
- [36] G. Lei, C. Liu, J. Zhu, and Y. Guo, "Techniques for Multilevel Design Optimization of Permanent Magnet Motors," *IEEE Trans. Energy Convers.*, vol. 30, no. 4, pp. 1574–1584, 2015, doi: 10.1109/TEC.2015.2444434.
- [37] J. Gong, F. Gillon, J. T. Canh, and Y. Xu, "Proposal of a Kriging Output Space Mapping Technique for Electromagnetic Design Optimization," *IEEE Trans. Magn.*, vol. 53, no. 6, pp. 1–4, 2017, doi: 10.1109/TMAG.2017.2666263.
- [38] M. E. Beniakar, P. E. Kakosimos, and A. G. Kladas, "Strength Pareto Evolutionary Optimization of an In-Wheel PM Motor With Unequal Teeth for Electric Traction," *IEEE Trans. Magn.*, vol. 51, no. 3, pp. 1–4, 2015, doi: 10.1109/TMAG.2014.2347963.
- [39] A. Dutt, "Effect of Mesh Size on Finite Element Analysis of Beam," *Int. J. Mech. Eng.*, vol. 2, no. 12, pp. 8–10, 2015, doi: 10.14445/23488360/ijme-v2i12p102.
- [40] S. Version, "Simcenter MAGNET™ Software VBScripting Manual," no. November, 2019.
- [41] C. A. C. Coello, G. B. Lamont, and D. A. Van Veldhuizen, *Evolutionary Algorithms for Solving Multi-Objective Problems*. 2007.