COST OPTIMIZATION OF OIL TYPE DISTRIBUTION TRANSFORMER USING MULTI-OBJECTIVE GENETIC ALGORITHM

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ABSTRACT

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M.Sc. in Electrical and Electronics Engineering

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As technology advances, the need for the energy sector and electrical machines has increased. The usage of transformer, which is one of the electrical machines that converts AC electrical energy to another AC electrical energy at a fixed frequency, by electromagnetic induction, has become widespread.

Transformers help transmit and distribute electrical energy from power plants to final consumers. During this transmission, power losses and voltage changes can occur in electrical energy. Therefore, by increasing the voltage, the current must be decreased. It is aimed to reduce the losses by keeping the current at a low level. Thus, the current is reduced to transmit power over long distances and the transformer is used to increase the voltage. To improve the operational performance of transformers, a lot of research and study have been done. Over time, more studies have been conducted using the optimization strategy.

Yzn connected transformers have gained importance day by day due to reasons such as effective power transmission, reduction of harmonics, protection of the components of the power system from overloading.

In this thesis, a 3-phase, 25 kVA, Yzn connected oil-type distribution transformer; It is aimed to reach the minimum cost by reducing the losses and weight.

For this purpose, the design parameters of the transformer will be optimized with the Multi-Objective Genetic Algorithm method using the MATLAB program. Increasing the design parameter to be optimized is important to evaluate many conditions simultaneously. Therefore, it was decided to optimize five parameters in this study. Transformer design will be done with the help of optimum parameters obtained by this method. Transformer design parameters that lead to optimum cost will be recorded. While designing the transformer, the boundary conditions specified in the specification were taken into account, so that no value was exceeded.

The transformer developed using the Multi-Objective Genetic Algorithm optimization approach yields the best results when compared to the results of the transformer designed using experimental methods with the same attributes.

The modeling of the transformer obtained as a result of the optimization was made with the ANSYS Maxwell program. The results obtained using Finite Element Method (FEM) analysis were also supported.

Keywords: Transformer Design, Loss, Multi-Objective Genetic Algorithm, Cost Optimization

ÖZET

YAĞLI TİP DAĞITIM TRANSFORMATÖRÜNÜN ÇOK AMAÇLI GENETİK ALGORİTMA İLE MALİYET OPTİMİZASYONU

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Teknoloji ilerledikçe enerji sektörüne ve elektrik makinelerine duyulan ihtiyaç artmıştır. AC elektrik enerjisini, başka bir AC elektrik enerjisine sabit bir frekans değerinde elektromanyetik indüksiyon yolu ile dönüştüren elektrik makinelerinden olan transformatörün kullanımı yaygınlaşmıştır.

Transformatörler, elektrik enerjisinin santrallerden nihai tüketicilere iletilmesine ve dağıtılmasına yardımcı olur. Bu aktarım boyunca elektrik enerjisinde güç kayıpları, gerilim değişimleri meydana gelebilmektedir. Bu nedenle voltajın yükseltilerek akımın azaltılması gerekir. Akım düşük bir seviyede tutularak kayıpların azaltılması amaçlanır. Böylelikle, uzun mesafelere güç iletimi için akım düşürülür ve voltajı yükseltmek için de transformatör kullanılır. Transformatörlerin çalışma performansını iyileştirmek için birçok araştırma ve çalışma yapılmıştır. Zamanla, optimizasyon stratejisi kullanılarak daha fazla çalışma yapılmıştır.

Güç aktarımının etkin bir şekilde sağlanması, harmoniklerin azaltılması, güç sistemini oluşturan bileşenlerin aşırı yüklemeden korunması gibi sebeplerden dolayı Yzn bağlı transformatörler gün geçtikçe önem kazanmıştır.

Bu tezde, 3 fazlı, 25 kVA, Yzn bağıntılı yağlı tip bir dağıtım transformatörünün; kayıplarını ve ağırlığını azaltarak, minimum maliyete ulaştırılması amaçlanmaktadır. Bu amaç kapsamında MATLAB programı kullanılarak Çok Amaçlı

Genetik Algoritma yöntemi ile transformatörün tasarım parametreleri optimize edilecektir. Optimize edilecek tasarım parametresinin artması birçok koşulu aynı anda değerlendirmek için önemlidir. Bu yüzden bu çalışmada beş adet parametre optimize edilmesine karar verilmiştir. Bu yöntem ile elde edilen optimum parametreler yardımıyla transformatör tasarımı yapılacaktır. Optimum maliyete ulaştıran transformatör tasarım parametreleri kaydedilecektir. Transformatör tasarımı yapılırken şartnamede belirtilen sınır şartları dikkate alınmıştır ve böylece herhangi bir değerde aşım gözlenmemiştir.

Çok Amaçlı Genetik Algoritma optimizasyon yaklaşımı kullanılarak geliştirilen transformatör, aynı özniteliklere sahip deneysel yöntemler kullanılarak tasarlanan transformatörün sonuçlarına kıyasla en iyi sonuçları vermektedir.

Optimizasyon sonucu elde edilen transformatörün modellemesi ANSYS Maxwell programı ile yapılmıştır. Sonlu Elemanlar Yöntemi (SEY) analizi kullanarak da elde edilen sonuçlar desteklenmiştir.

Anahtar Kelimeler: Transformatör Tasarımı, Kayıplar, Çok Amaçlı Genetik Algoritma, Maliyet Optimizasyonu

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SYMBOLS

A_c : Core area

A_g : Gross core area in cm^2

A_p : Area of primary conductor

A_s : Area of secondary conductor

B_m : Magnetic flux density

B_{pk} : Density of peak values

cm : Centimeter

cm^2 : Square Centimeter

C_{core} : Circumference of core

$C_{LV\ avg}$: Mean circumference of the secondary winding

$C_{HV\ avg}$: Mean circumference of the primary winding

d_{core} : Core diameter

$d_{HVinner}$: HV winding inner diameter

$d_{HVouter}$: HV winding outer diameter

$d_{LVinner}$: LV winding inner diameter

$d_{LVouter}$: LV winding outer diameter

D_m : Mean diameter of leakage flux density distribution

$D_{HV\ avg}$: Average diameter of the primary winding

$D_{LV\ avg}$: Average diameter of the secondary winding

E : Window width of core

$^{E}/_{T}$: Volt per turn

ε_1 : Electromotive force for primary winding (Volts)

ε_2 : Electromotive force for secondary winding (Volts)

ε_{rms} : rms value of induced voltage

f : Frequency as 50 Hz

f_{obj}	: Objective function
h_1	: Electrical axial height of LV
h_2	: Electrical axial height of HV
H	: Magnetic field strength
Hz	: Hertz
$HV_{conductordiameter}$	: Conductor diameter of primary winding
I_{ll}	: Line to line current
I_{ph}	: Phase current
I_{HVll}	: Transformer HV line to line current
I_{HVph}	: Transformer HV phase current
I_{LVll}	: Transformer LV line to line current
I_{LVph}	: Transformer LV phase current
I_1	: Current of primary winding
I_2	: Current of secondary winding
j	: Current density
j_{AL}	: Current density of aluminum conductor
j_{core}	: Specific weight of core
j_{oil}	: Specific weight of oil
j_1	: Current density of primary conductor
j_2	: Current density of secondary conductor
kV	: Kilovolts
kVA	: Kilo volts ampere
k_1	: 1.04 (factor based on actual measured results)
k_2	: f/50 (frequency factor)
K	: K constant number
K_{AL}	: Constant number of Aluminum as 12.61
K_R	: Rogowski’s factor
K_1	: Core stack for step 1
K_2	: Core stack for step 2
K_3	: Core stack for step 3
K_4	: Core stack for step 4
L	: Window length of core

$LV_{conductorlength}$: Conductor length of secondary winding

$LV_{conductorwidth}$: Conductor width of secondary winding

L_1 : Width of step 1

L_2 : Width of step 2

L_3 : Width of step 3

L_4 : Width of step 4

m : Meter

mm : Millimeter

MVA : Mega volts ampere

N_{HV} : HV turn number

N_{LV} : LV turn number

N_1 : Number of primary turns

N_2 : Number of secondary turns

P_K : Load losses

P_0 : No-Load losses

S : Rated power of the transformer

S_1 : Rated power of primary winding

S_2 : Rated power of secondary winding

t_{HV} : Thickness of HV winding

t_{LV} : Thickness of LV winding

T : Tesla

U_K : Short circuit impedance

U_R : Resistive component

U_X : Reactive component

$V_{active\ part}$: Volume of transformer active part

$V_{active\ part\ oil}$: Volume of transformer active part oil

V_{core} : Volume of transformer core

$V_{corrugated\ wall\ oil}$: Volume of transformer corrugated wall oil

V_{ll} : Line to line voltage

V_{ph} : Phase voltage

V_{tank} : Volume of transformer tank

$V_{tank\ oil}$: Volume of transformer tank oil

$V_{transformer\ oil}$	: Volume of transformer oil
$V_{windings}$	: Volume of transformer windings
V_{HVll}	: Transformer HV line to line voltage
V_{HVph}	: Transformer HV phase voltage
V_{LVll}	: Transformer LV line to line voltage
V_{LVph}	: Transformer LV phase voltage
VA	: Volts ampere
V_1	: Voltage induced in the primary winding
V_2	: Voltage induced in the secondary winding
w/kg	: Watt per kilograms
W	: Watt
$Wire\ L_{HV}$	: Wire length of primary winding
$Wire\ L_{LV}$	: Wire length of secondary winding
W_{core}	: Total weight of core
W_g	: HV-LV insulation gap
$W_{total\ winding}$	: Total weight of winding
$W_{transformer\ oil}$	: Weight of transformer oil
$W_{HV\ winding}$	: Weight of HV winding
$W_{LV\ winding}$	: Weight of LV winding
$W_{Transformeroil}$	: Total weight of transformer oil
ω	: Angular velocity
Φ	: Magnetic flux in the core
Φ_{pk}	: Peak value of flux

ABBREVIATIONS

ABC : Artificial Bee Colony
AC : Alternative current
BSA : Backtracking Search Algorithm
CFD : Computational Fluid Dynamics
CRGO : Cold-rolled grain oriented
CSA : Crow Search Algorithm
FEA : Finite Element Analysis
FPA : Flower Pollination Algorithm
GA : Genetic Algorithm
GWO : Gray Wolf Optimization
HV : High Voltage
LV : Low Voltage
MABC : Multi- Artificial Bee Colony
MOGA : Multi-Objective Genetic Algorithm
ONAN : Oil Natural Air Natural
PSO : Particle Swarm Optimization
SA : Simulated Annealing
TDO : Transformer Design Optimization
FEM : Finite Element Method

CHAPTER I

INTRODUCTION

1.1. AIM AND OBJECTIVES

Transformer design is the process of choosing a transformer's physical characteristics, material composition, and number of turns in order to achieve the necessary voltage and current ratings for a given application.

The design of a transformer involves a lot of specifics, including the choice of the transformer's components, the number of turns calculated, the size of the conductors, the size of the magnetic circuit, and the choice of the insulation material. During the design process, various factors such as efficiency, reliability, size, weight, cost, and suitability of operating conditions of the transformer are taken into consideration. Transformer design is an important engineering discipline used in power transmission and distribution systems, industrial power applications, medical devices, electronic devices, and many other fields. The transformer is designed with a focus on minimizing the copper and iron weights, short-circuit impedance, load and no-load losses, heat generated in the transformer, and transformer cost. Many methods have been developed for this purpose.

In this thesis, information about what the transformer is, it’s working principle, usage areas and accessories are given in the “Chapter II – Transformer” section.

The relevant formulas for the transformer's design are presented in "Chapter III - Electrical Design of Oil Type Distribution Transformer". These formulas have been used to study the transformer's mathematical modeling.

In the “Chapter IV – Numerical Methodology” section, the Multi-Objective Genetic Algorithm method, which is a type of optimization used in transformer design, is explained in detail. Finally, it has been shown that the results of the parameters and cost optimization, which is the main goal, are provided in the optimization used.

1.2. LITERATURE SURVEY

In the literature, many studies have been carried out to reach the optimal transformer design for different purposes. The parameters that will determine the transformer design, design purpose and results can be determined by optimization studies. Transformer design optimization has been developed by specifying many metaheuristic algorithm methods. In some studies, the optimization outputs were supported by the analysis results.

Tosun [1] conducted a study on weight optimization of a 1500 VA dry type transformer in 2012. The determining factor of the designed transformer in terms of cost is the weight of the transformer. Therefore, Taboo Search Algorithm has been used to reach the optimum weight without reducing the efficiency of the transformer. The iron cross section conformity factor and current density, which are transformer variables, are optimized using this approach, which also extracts the transformer's mathematical model. Accordingly, the weight of the transformer has been reduced by nearly 20%.

In 2017, Alhan [2] used five modern metaheuristic optimization algorithms as a solution to transformer design optimization (TDO) problems. Artificial Bee Colony (ABC), Competitive-Adaptive, Back-Tracking Search (BSA), Cuckoo Search (CS), and Flower Pollination Algorithm (FPA) are some examples of these algorithms. He categorized the algorithms for theoretical and practical TDO using these methods and compared them to one another. These optimization studies aim to maximize efficiency, maximize rated power, minimize total cost, minimize the weight and cost of the active component of the transformer, minimize the main material and production cost.

In 2022, Akdağ [3] used the Firefly Algorithm to optimize the current density (s) and iron cross section conformity factor (C) of the oil type, delta-star connected, 50 kVA, 34.5/0.4 kV transformer, lowering the transformer's weight and, in turn, its cost. As a result of the parameters he optimized using MATLAB, the weight of the transformer he designed decreased by 11%.

The volume of the oil-filled transformer is optimized using the Firefly Algorithm, one of the heuristic methods [4]. Parameters such as height, surface area width and length, depth of the transformer were optimized using genetic algorithm and firefly algorithms.

By utilizing the Tree Seed Algorithm, Simulation Annealing, and Particle Swarm Algorithm techniques, the transformer's efficiency is intended to be increased [5]. In order to maximize efficiency, the iron section conformity factor and the current densities of the 3-phase, 100 kVA dry type transformer were tuned within the study's parameters.

Çelebi used a genetic algorithm to conduct a study on the cost optimization of a 1.5 kVA dry type transformer. The weight and efficiency outcomes of the transformer were studied by optimizing two different mutation settings, random and limit mutation [6].

Smolka [7] enhanced the heat dissipation and losses of the transformer in 2011 by using a genetic algorithm to optimize the cooling channels and HV-LV coil widths. The results were supported using the CFD-EMAG model.

[8] employs the Direct Search, Differential Evolution, Heat Treatment Algorithm (Simulated Annealing-SA), and Random Search to reduce costs while taking into account variables like magnetic flux density, primary-secondary winding dimensions, secondary current density, and gap between primary-secondary winding of three-phase oil-type distribution transformer. An electromagnetic study for losses, short-circuit impedance, and forces based on finite elements was carried out in order to assess the design parameters established by the approaches used.

Cost optimization is done in [9] by taking into account the costs associated with purchasing, operating, maintaining, insuring, and depreciating distribution transformers as well as MV-LV lines. Comparisons were made between the outcomes of the Simulated Annealing (SA) and Genetic Algorithm (GA) optimization techniques.

Hernandez [10] researched Multi-Objective Optimization to determine the ideal core and winding parameters for a three-phase power transformer. It is aimed to minimize losses, copper and core weights by using NSGA-III. Results have been validated with FEA.

Multi-Objective Optimization problems fall under the category of global problems that are encountered in many different domains of industry, engineering, and science. In order to deal with these issues, multi-objective optimization techniques have been created. The Multi-Objective Artificial Bee Colony method (MOABC), which is used to solve engineering problems in [11], was used to choose the single-phase transformer configuration parameters. By doing this, the error rate between the expected and real parameters is decreased.

The GA, PSO, and ABC design methodologies were used in [12] to create a cast resin transformer. The outcomes of the various optimization techniques were compared. PSO has been shown to be the best method for cast resin dry-type transformer design.

In [13], Bozkurt optimization algorithm (Gray Wolf Optimization-GWO), which was applied for the first time as a transformer optimization method, was used. The goal is a power transformer's overall production costs and power loss expenses have to be kept to a minimum. In the study, four alternative techniques of design optimization were used. The GWO method was found to be successful when the results of the many applicable procedures were compared.

To reduce the weight of the 200 MVA oil type transformer to the minimum, Soldoozy [14] used the Tree Pruning Method. Considering the design variables determined by optimization, the transformer was simulated with FEM. Supported by test results, this method is presented for evaluation.

In addition to the optimization algorithms used in transformer design, the finite element method has also been added to the studies. The use of FEM in transformer design has become widespread. The maximum temperature points for various dry-type transformer winding types as well as the maximum temperature points for expressed dry-type transformers are described in [15].

[16] has studied the thermal response of a 10 kVA dry type transformer with H-class insulation at various temperatures. The maximum temperature point of the transformer was obtained and analyzed using its thermal model.

In [17], a Shell-type single-phase distribution transformer is optimized for total cost of ownership, low mass, minimal total losses, and minimal transformer material cost using transformer design software. Properties such as voltage levels, transformer connection types are given as input data. This study involved the design and testing of a 25 kVA, primary voltage is 13.200 Grd Y/7.620 V, secondary voltage is 240/120 V, oil-filled, single phase distribution transformer. Process measurements have been used to evaluate and validate the optimized outcomes in the transformer design.

In [18], he saw that the winding temperatures of a distribution transformer with the Finite Element method gave very close results to the real ones. It is possible to utilize this approach as a design tool for improving the performance and altering transformers.

The combined thermal, liquid flow, and electromagnetic numerical analysis of a medium power dry-type transformer was studied [19] in order to look at the losses in the coils and core. In this multidisciplinary work, a 3-dimensional dry-type transformer geometric model was produced with the use of CFD, taking the temperature constraints into consideration. Numerical analyses were conducted using a mathematical model that was generated in order to investigate the transformer's construction and operation. Based on the local distribution of wall heat fluxes, the average heat transfer coefficients of all transformer elements used throughout the study were computed. It can be employed in analyses that do not account for air flow because of this.

1.3. AIM OF THESIS

As seen in the studies in the literature, design variables are common in oil immersed or dry type transformers. The transformer was subsequently designed after five parameters, along from the iron cross section conformity factor and current density, were optimized using a Multi-Objective Genetic Algorithm in the MATLAB environment. It is aimed to reach the optimum level of cost without decreasing the efficiency of the designed oil-type transformer. Transformer weight, which is one of the most cost-determining factors, has also been minimized. In Ansys simulation studies, the parameters determined as a result of the optimization were checked and transformer losses and voltages were shown. While optimization studies were carried out with limited variables in previous studies, within the scope of this thesis, multiple parameters were examined simultaneously and the factors affecting the transformer design were determined. The significance of the transformer active, tank, oil weights, transformer losses, and magnetic flux value at which the transformer operates was also noted while attempting to lower the transformer's cost.

CHAPTER II

TRANSFORMERS

2.1. HISTORY OF TRANSFORMERS

Transformers are necessary electromagnetic device for the distribution and transmission of electrical energy. Transformers enable the conversion of electrical energy from high voltage levels to low voltage levels. It is a static tool that is used to move electrical power between circuits. In order to use electrical energy safely and effectively, transformers are crucial.

The history of the transformer is connected with the emergence of electromagnetic field theories and the widespread use of alternating current.

Michael Faraday's discovery of electromagnetic induction in the 1830s served as the foundation for the first transformers. However, these transformers are not like modern transformers used today.

In 1831, the first practical induction coil was invented by the American scientist Joseph Henry. An induction coil is a device based on the electromagnetic induction principle, used to demonstrate the inducing effect of electromagnetic fields. It was developed by many different people.

One of the devices that created the greatest electric current of the 1836 period was developed by Nicholas Callan. This device is known today as the “Callan Coil”. The Callan coil was used to convert low voltages to high voltages. Its working principle is explained by electromagnetic induction. In 1876, the American scientist Zénobe Théophile Gramme invented the first induction coil. These coils can be considered as the precursors of transformers. The work of Nicholas Callan and Zénobe Théophile Gramme set the stage for the transformer.

The first transformer was built in the middle of the 19th century for the generation and distribution of electrical power. The modern design and production of the transformer has been realized with the contribution of many different people and organizations. These include names such as Nikola Tesla, George Westinghouse and Lucien Gaulard.

In 1876, Nikola Tesla developed the first prototypes of the modern transformer. In 1885, Tesla invented the transformer that enables the conversion of magnetic fields into electrical energy and patented the AC (alternating current) transformer device. This patent made it possible to transmit electrical energy over longer distances and contributed to the spread of AC electrical systems. In addition to power transmission, great potential has been presented for many applications such as lighting and telecommunications. Transformers are a crucial component of AC power systems, which were developed in part because to Tesla.

The creation and adoption of AC electrical systems were significantly aided by George Westinghouse. By using Tesla's AC transformer device, Westinghouse has facilitated the distribution of electrical energy and created a more efficient system. Transformers developed by George Westinghouse were used in the first large-scale AC power system, opened in New York in 1882.

Lucien Gaulard, on the other hand, developed the first prototype of the AC transformer device in 1881. Gaulard's design made possible the production of high voltage transformers and made the distribution of electrical energy more efficient.

In 1891, Mikhail Dolivo-Dobrovolsky worked on the development of three-phase AC systems and designed the first three-phase AC generator.

As a result, the invention and development of the transformer device has been realized with the contribution of many different people and organizations. These contributions enabled him to achieve the modern design of the transformer, which is an indispensable electromagnetic device for the distribution and transmission of electrical energy.

2.2. STRUCTURE OF TRANSFORMERS

Due to the changing and developing technological advances, the need for the energy sector and electrical machines is increased. Electrical machines, which form the keystone of energy conversion, are divided into 3 among themselves. Electric machines known as generators transform mechanical energy into electrical energy. Motors are the machinery that transform electrical energy into mechanical energy. A transformer is an electrical device that changes one type of AC electrical energy into another type of AC electrical energy.

Transformers are static devices that use electromagnetic induction to transmit electrical energy between electrical circuits at a constant frequency. These electrical devices, which are used to adjust the desired voltage and current values at the chosen power, have no moving parts. Therefore, friction and wind losses are not mentioned in transformers.

Transformers are made up of two windings (coils) with a shared magnetic core and a mutual inductance that are isolated from one another. They are referred to as primary and secondary windings. The transformer's primary winding is the input winding. The alternating voltage source or the mains are connected to the primary winding. The transformer's secondary winding, which is connected to the load, serves as the transformer's output winding. In the low voltage area, loads are supplied by the secondary winding. The transformer's architecture is displayed in Figure 1.

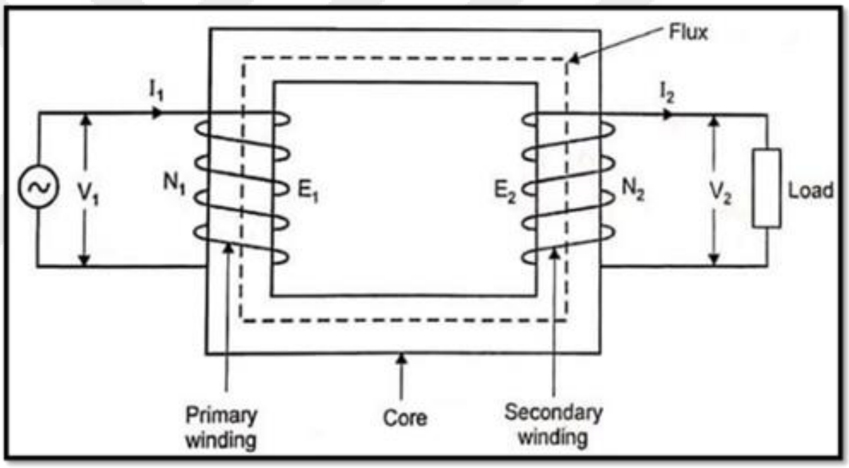


Figure 1: Structure of Transformer

2.2.1. Core of Transformers

The core of a transformer is a fundamental part that stores and transmits magnetic energy.

The material of the cores affects the characteristics of the transformer such as efficiency, dimensions, power capacity and operating frequency.

In the cores of the first transformers, iron cores or steel plates were used to direct the magnetic field. However, these materials caused magnetic losses and reduced the efficiency of the transformer.

In the 1890s, nickel-iron alloys were discovered as a more efficient material for transformer cores. These alloys allowed the production of transformers with higher efficiency as they minimized magnetic losses.

The use of silicon materials with a structure that enhances the material resistance and lowers the eddy currents created in the transformer started in the 1930s with the development of ferromagnetic materials [20]. These materials allow better orientation of the magnetic flux and reduce magnetic losses. In particular, silicon steel sheets have become one of the most widely used materials in transformer cores.

The following list of silicon steel varieties is presented to the market in chronological order:

- Hi-B
- Mechanically scribed
- Laser scribed
- Non-oriented
- Cold-rolled grain oriented (CRGO)
- Hot-rolled grain oriented (HRGO)

The first three kinds of materials are enhanced versions of the CRGO class. For the CRGO grades, the saturation flux density has largely remained constant at or near 2.0 Tesla, but the more advanced manufacturing techniques and technologies have led to appreciable advancements in the watts/kg and volt-amperes/kg characteristics in the rolling direction [21].

In the 1970s, amorphous metals were discovered as magnetic core materials. Amorphous metals operate with less magnetic loss than conventional nickel-iron alloys. Thus, amorphous metals provide higher efficiency. When compared to CRGO grades, the usage of amorphous steel materials significantly reduces core loss, by a factor of 60–70%. Its usage is restricted to transformers with lower ratings since handling this brittle material requires highly advanced production methods [21]. Since CRGO is a more easily shaped and cut material, it allows transformers to be produced in different sizes and shapes. CRGO is considered an important material for transformer cores. Today, it is utilized extensively in the transmission and distribution of power.

To control the course of the magnetic flux in transformers, the geometry of the core is crucial. The transformer's core creates a loop when the magnetic flux flows through it, and this magnetic flux induces voltage in the secondary winding of the transformer.

The distribution of the magnetic field as it is created is influenced by the transformer's core, which is a crucial structural component. Thus, it can reduce or increase the magnetic losses. An ideal core geometry is optimized to maximize magnetic flux and minimize magnetic losses.

Round cores in transformer are a type of core designed to best direct the magnetic flux and reduce magnetic losses. The round core offers high efficiency, less vibration and less noise.

2.2.2. Winding of Transformers

Another fundamental part of transformer design is the windings. The transformer windings are an important component that carries the main current where energy conversion takes place. Depending on the transformer connection group, the number of windings in a phase may vary. A transformer can have two or more windings. Electrical energy can be converted using these windings from one voltage or current level to another.

The primary and secondary windings of the transformer are separated. The transformer receives energy through its input windings, or primary windings. The transformer's output windings, where the energy exits, are called secondary windings.

Insulating materials are often used to insulate the magnetic field between transformer windings. These materials may include rigid insulators such as plastic or fiberglass, and flexible insulators such as paper or plastic film. Also, in some cases, an insulating material can be placed between the windings to isolate them from each other. The most common conductors used in transformers are copper and aluminum. The differences between copper and aluminum can be evaluated under the headings of conductivity, strength, density and cost.

1. Conductivity: Copper is a conductor with higher conductivity than aluminum. By using a thinner copper wire, the same current carried by the aluminum wire can be carried in this way. Thus, transformer windings are more compact and less material is used.

2. Strength: It is the resistance of a material to deformation or breakage. Depending on the material's properties, composition, and temperature. Aluminum has a lower strength than copper. This requires thicker aluminum wires in a transformer of the same power level.

3. Density: Copper has a higher density than aluminum. This allows copper wires of the same weight to be shorter and more winding to be wound.

4. Cost: Aluminum is a cheaper conductor than copper. Therefore, transformers made using aluminum wires are less costly than transformers designed using copper wires.

As a result, when choosing between copper and aluminum conductors, factors such as current density, number of windings, power requirement and cost should be considered. Copper wires provide higher performance. However, the disadvantage of using copper conductor; It makes transformers heavier and makes transformer costs more expensive. Aluminum wires are associated with lower cost and lighter weight.

2.2.3. Losses of Transformers

Transformers are static electricity machines. Therefore, friction and wind losses are not mentioned in transformers.

Transformer losses affect the efficiency of the transformer and cause increased cost. Therefore, while designing the transformer, optimization processes are carried out to minimize losses. No-load losses and load losses are two different ways that transformer losses can happen.

2.2.3.1. Load Losses

They are the losses caused by the current in the windings of the transformer. Also known as I2R Losses or Copper Losses. These losses happen in the transformer's high current-passing areas. Copper losses may differ depending on the transformer's nominal power.

2.2.3.2. No-Load Losses

In the transformer's magnetic circuits, these losses take place. Iron loss or core loss are other names for it. It occurs when a change in magnetic flux occurs. Core losses; Also known as additional losses, they consist of leakage and dielectric losses as well as hysteresis caused by the material, eddy current loss caused by the core's structure, and hysteresis due to the material [22]. These losses vary depending on the material and design choices of the transformer.

2.2.3.2.1. Hysteresis Losses

It is the energy loss that occurs as a result of the magnetic core material being exposed to magnetic field changes caused by frictional motion. When a magnetic field is applied, the magnetic core material becomes magnetically saturated. Because of this, it takes the material some time to regain magnetic saturation after a change in the magnetic field. During this process, losses occur in the core and this is called hysteresis loss. In ferromagnetic materials like iron or steel, the hysteresis losses are proportional to the region that the B-H curve encloses [22].

The magnetic characteristics of the magnetic core material are described by the B-H curve. The material is subjected to variations in the magnetic field, and the relationship between magnetic flux and magnetic field is measured in order to understand these qualities. These measurements lead to the appearance of the B-H curve. In Figure 2, it is displayed.

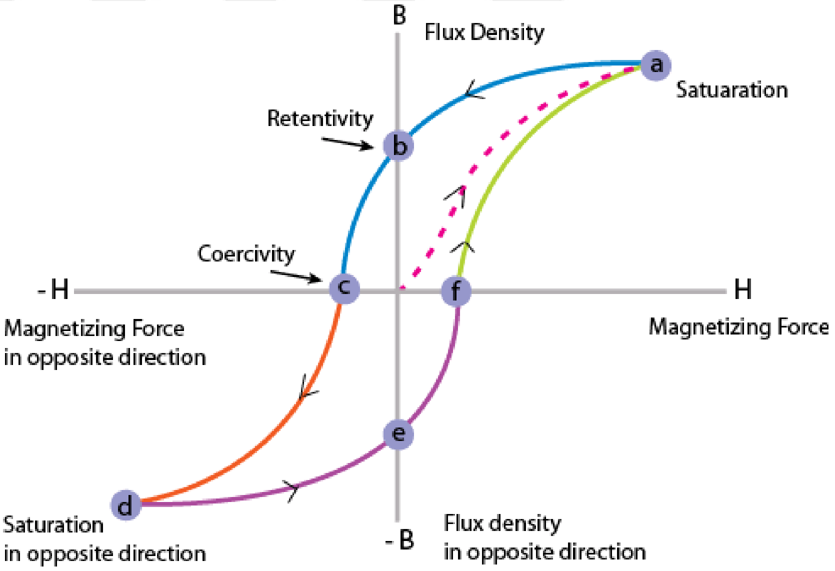


Figure 2: B-H Curve

H denotes the magnetic field intensity, while B represents the magnetic flux density. It is not possible to completely eliminate the loss of hysteresis. However, to reduce it, the volume and temperature of the core material can be reduced.

2.2.3.2.2. Eddy-Current Losses

Eddy currents are circular magnetic currents that cause energy loss in the magnetic core. Faraday's law of induction explains that an electric current forms inside conductors as a result of a changing magnetic field.

The energy loss that results from the magnetic flux's varied route as it passes between the air gaps in the magnetic core and the core's material. It happens as a result of shifting magnetic flux and field. Eddy current causes heat or kinetic energy losses due to resistance. Thin plates are used in transformers to prevent heat that will occur due to eddy losses. It is shown in Figure 3.

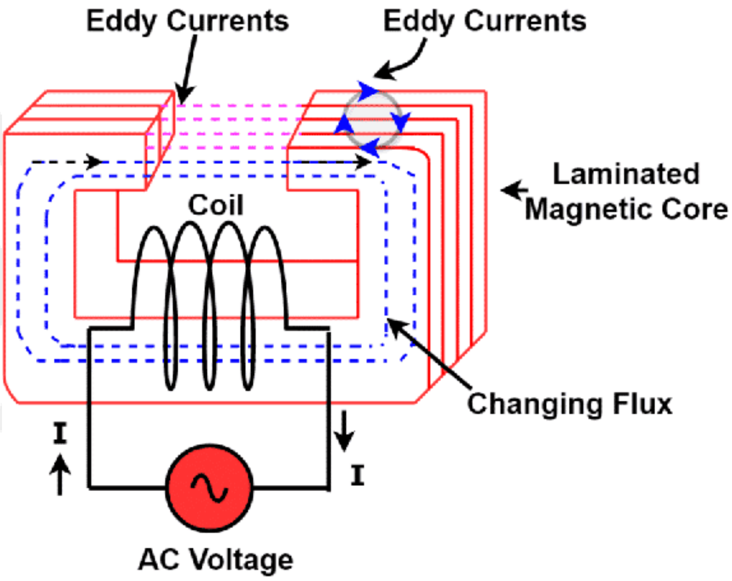


Figure 3: Eddy Current Diagram

The following factors affect the eddy current's size:

- Frequency of supply source
- The flux density
- The thickness of the lamination
- The resistance of current route
- The magnitude of the Eddy Current

2.2.3.2.3. Leakage and Dielectric Losses

When creating the transformer core, further losses take place. Mechanical tensions, flux density harmonics, the presence of connections, air gaps, and mechanical stressors all contribute to these losses [22]. The leakage currents between the coils and in the transformer's insulating materials are to blame for the stray losses. Dielectric losses, on the other hand, are the polarization-induced energy loss of the insulating materials of the transformer. These losses can reduce efficiency especially in high frequency transformers.

2.2.4. Transformers Connection Types

In three-phase transformers, winding connection groups can be grouped as star, delta and zigzag connections.

2.2.4.1. Star Connection

The most commonly used connection type in three-phase power systems is Star connection. It can be applied to both primary and secondary winding of transformer. The input ends of the windings, U, V, and W, are subjected to a 3-phase voltage, while the output ends, X, Y, and Z, are short-circuited. Totally in reverse; Star connections can be made by short-circuiting the U, V, and W terminals and applying voltage to the X, Y, and Z terminals. The neutral or star point is the name for the joining point. This type of connection can be used to control the power factor and voltage regulation of the transformer.

Due to the 120-degree phase difference between the windings, the line voltage in a star connection is three times the phase voltage. Phase current and line current are equivalent. Figure 4 displays a diagram of a star's connections.

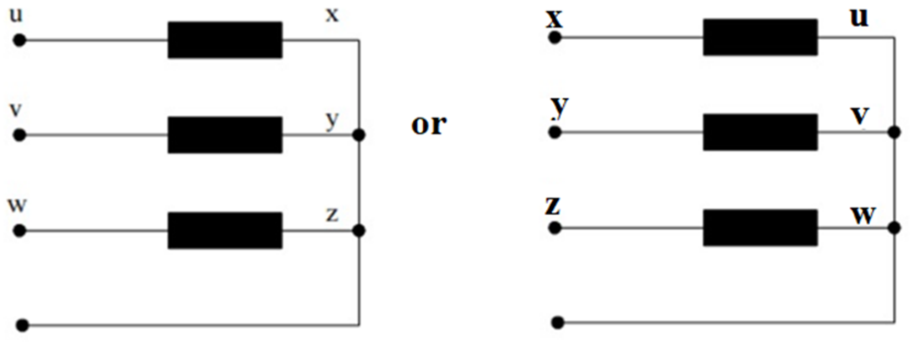


Figure 4: Phasor Diagram of Star Connection

2.2.4.2. Delta Connection

In order to make a delta connection in the transformer, the input end of each phase winding is combined with the output end of the other winding. Both the transformer's primary winding and secondary winding go through the same process. The phase windings are connected to one another in a closed circuit. There is no neutral line in the delta connection. Therefore, the neutral line is used in undesirable places.

A greater voltage difference between the phases occurs than with a star connection because the primary and secondary windings are connected in a delta. Therefore, delta connection is generally preferred in high voltage applications.

The delta connection shape is shown in Figure 5. The line current is three times the phase current in a delta connection. Phase and line voltage are same.

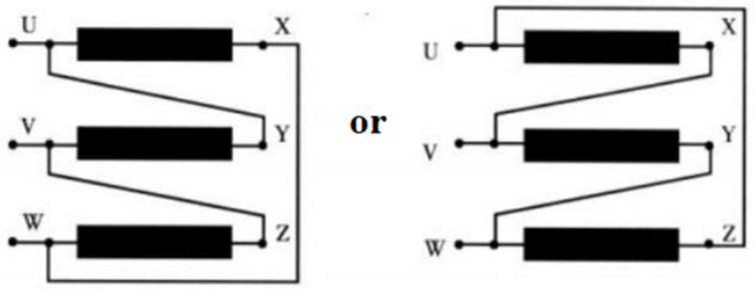


Figure 5: Phasor Diagram of Delta Connection

2.2.4.3. Zig-Zag Connection

A Zig-Zag transformer is a special purpose three-phase transformer with a zigzag or "star connection" winding connection. The Zig-Zag transformer's primary function is to offer a low leakage reactance that will allow the zero components to take over in the event of a failure [23]. Unbalanced loads and ground faults in the power system are the main causes of zero-sequence currents. In order to enhance the flow of zero sequence currents and triplet harmonics, Zig-Zag transformers also reduce leakage reactance. Leakage reactance is one of the Zig-Zag transformer's most crucial variables as a result.

There are two coils in each phase of the Zig-Zag connection. However, in order to eliminate the mismatched voltages, they are coiled in the opposite directions. 3-phase transformers have 3 primary windings with Zig-Zag connection and 6 identical secondary windings. Zig-Zag connection of transformer phasor diagram is indicated in Figure 6.

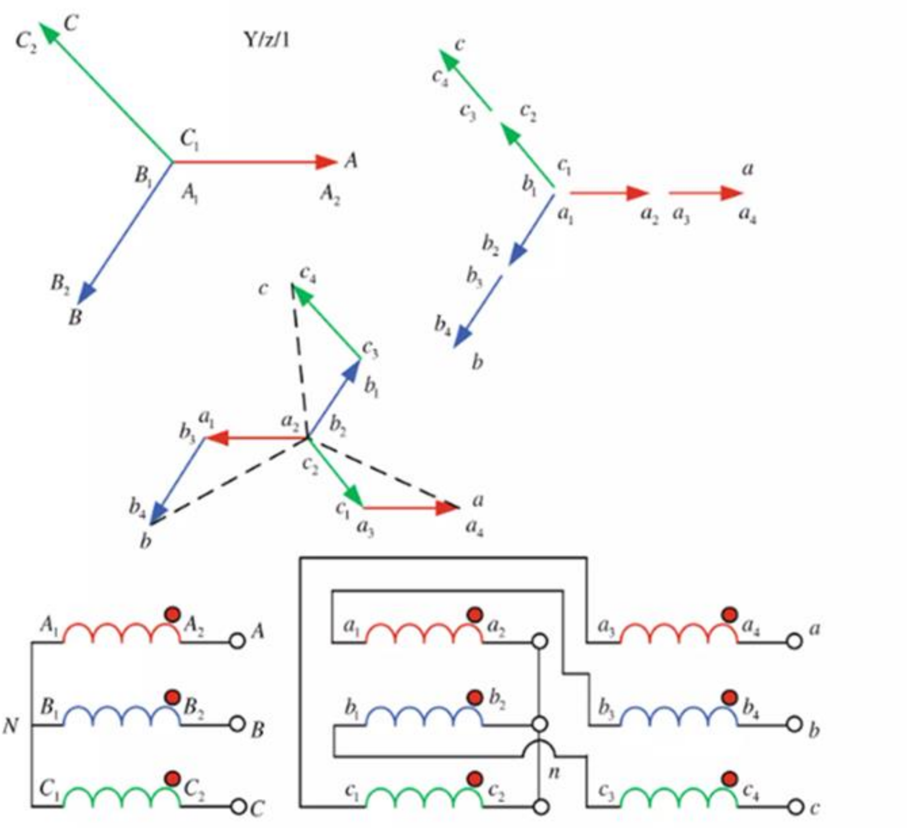


Figure 6: Phasor Diagram of Yzn Connection

2.2.4.3.1. Zig-Zag Connection Advantages

The Zig-Zag transformer contains certain characteristics of both delta and star connections, as well as both connections' benefits. The main advantages of the Zig-Zag connection can be listed as follows

- Harmonics are attenuated and eliminated by the Zig-Zag transformer [36]. Due to the reverse connection of the winding coils in Zig-Zag windings, the harmonic voltages existing in the system can be cancelled to some extent.

- In a power system, the third, ninth, fifteenth, and twenty-first harmonic currents can be captured using a Zig-Zag transformer. In order to reduce the negative impacts of triple harmonic, Zig-Zag transformers are placed close to loads that produce larger triple harmonic currents [37].

- The Zig-Zag transformer also prevents the voltage growth in faultless phases. It prevents voltage increase by preventing one phase from being overloaded in case of unbalanced load.

- Zig-Zag transformers provide a practical way to ground the electrical system. [38]

Zig-Zag transformers have low internal winding impedance, which makes grounding more efficient.

2.2.4.3.2. Zig-Zag Connection Disadvantages

- Since the structure of Zig-Zag connection is more complex than star and delta connections, it may be over costing.
- Zig-Zag connection has lower voltage regulation. Voltage regulation is less effective than star and delta connections.

2.3. WORKING PRINCIPLE OF TRANSFORMERS

The electromagnetic induction theory, provided an explanation by Faraday's law of electromagnetic induction, underlies the operation of transformers. The transformer's primary winding is linked to the AC power source. A magnetic field is produced by the alternating current flowing through the transformer's primary winding when an AC voltage is supplied to it. The transformer core, which is made of a magnetic substance, is traversed by this magnetic field. The secondary winding is included in the circuit that the generated magnetic field completes in the iron core. An emf is produced by the change in the magnetic field when the secondary winding is exposed to it. This induction voltage induces a secondary winding current that travels to the transformer's output. To transmit power to the load attached to the secondary, a voltage is induced in the secondary winding. As a result, the power is moved via electromagnetic induction from the primary circuit to the secondary circuit.

There is no energy loss in ideal transformers. Input power and output power are equal. The ratio of the voltage induced in the transformer's primary winding (V_1) to the voltage induced in its secondary winding (V_2) is equal to the ratio of the number of windings because the magnetic flux cross section in transformers is constant. In Equation 2.1 gives the definition of this:

$$\frac{V_1}{V_2} = \frac{N_1}{N_2} \tag{2.1}$$

N_1 and N_2 are the primary and secondary winding numbers, respectively, in the formula. The Equation that is 2.2 below illustrates the link between the amount of current flowing through the transformer's primary and secondary windings and the number of windings.

$$\frac{I_2}{I_1} = \frac{N_1}{N_2} \tag{2.2}$$

The primary winding's current is denoted by I_1in the formula, whereas the secondary winding's current is denoted by I_2.

$$\frac{V_1}{V_2} = \frac{N_1}{N_2} = \frac{I_2}{I_1} \tag{2.3}$$

$$V_1 I_1 = V_2 I_2 \tag{2.4}$$

$$S_1 = S_2 \tag{2.5}$$

When the Equation 2.3 and Equation 2.4 mentioned above are combined, an ideal transformer with no power loss is achieved. This situation is shown in Equation 2.5. Faraday's law states Equation 2.6;

$$\varepsilon_1 = N_1 \frac{d\Phi}{dt} \tag{2.6}$$

A magnetic field is produced when an AC voltage is applied to the transformer's primary winding. The magnetic flux (Φ) in the core and the quantity of primary windings both affect the electromotive force (ε_1) induced in the primary winding. The magnetic field that will be produced by the current brought on by the change in magnetic flux will be balanced by the magnetic field that the current induces in the opposite direction. This situation is explained by Lenz's Law.

According to the Equation 2.7, a perfect transformer core has no leakage flux, thus the flux Φ there connects all of the secondary windings and generates an e.m.f. [24].

$$\varepsilon_2 = N_2 \frac{d\Phi}{dt} \tag{2.7}$$

The flux as a function of time is described by the Equation 2.8, if the waveforms of the applied voltage and flux are sinusoidal [25]. Equation 2.9 shows the angular velocity equation. The scalar measure of the temporal rate of change of a sinusoidal wave is known as angular velocity, also called as angular frequency.

$$\Phi(t) = \Phi_{pk} \sin \omega t \tag{2.8}$$

$$\omega = 2\pi f \tag{2.9}$$

The flux's peak value is denoted by Φ_{pk} . The voltage induced in the secondary winding of the transformer is found as shown in Equation 2.10. The rms value of this voltage is given in Equation 2.11.

$$\varepsilon_2(t) = N_2 \frac{d\Phi(t)}{dt} = N_2 \omega \Phi_{pk} \cos \omega t = N_2 2\pi f \Phi_{pk} \cos \omega t \tag{2.10}$$

$$\varepsilon_{rms} = N_2 \frac{d\Phi(t)}{dt} = \frac{2\pi}{\sqrt{2}} f N_2 \Phi_{pk} = 4.44 f N_2 \Phi_{pk} \tag{2.11}$$

A_c, specified in Equation 2.12 shows the core area. The following values are found for the core's peak flux density:

$$B_{pk} = \frac{\Phi_{pk}}{A_c} \tag{2.12}$$

As a result, Equation 2.13 represents the final form of the secondary winding's rms value formula.

$$\varepsilon_{rms} = \frac{2\pi}{\sqrt{2}} f N_2 \mathrm{B}_{pk} A_c = 4.44 f N_2 \mathrm{B}_{pk} A_c \tag{2.13}$$

2.4. USAGE AREAS OF TRANSFORMERS

The use of transformers is critical for electrical power distribution. The development of transformers is an important milestone for electric power distribution and industrial production. Today, transformers transport electrical energy from high-voltage lines to homes and are used as power supplies for electronic devices. By minimizing the energy loss between the electrical energy producing point and the utilization point, transformers aid in the transmission and distribution of energy [26].

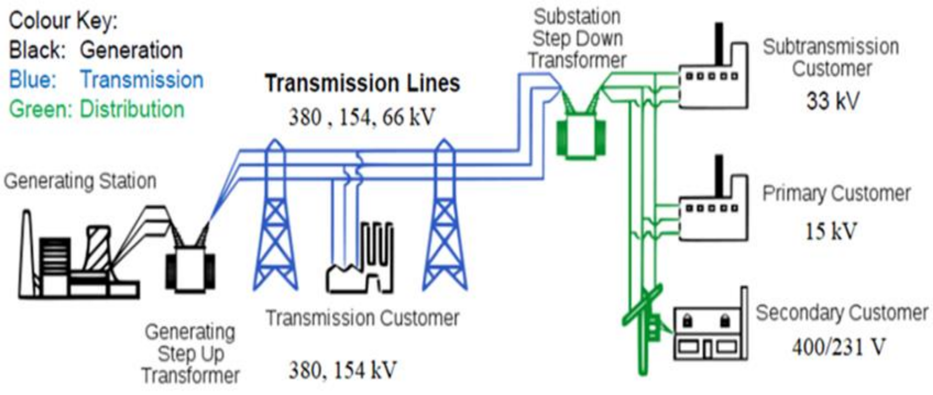


Figure 7: Transmission lines

Transmission lines are essential for the effective and dependable delivery of electricity to customers because they allow for the distribution of power across great distances and the satisfaction of regional energy needs. The steps of production, distribution and transmission of electrical energy can be seen in Figure 7.

Step-up transformers are used to boost the electrical energy generated in power plants so that it may travel further down transmission lines. In Turkey, high voltage levels are determined to be 380 kV, 154 kV, and 66 kV, whereas medium voltage levels are 6.3 kV, 15 kV, and 33 kV. However, due to significant power losses, 66 kV at high voltage, 6.3 kV, and 15 kV at medium voltage have been eliminated. Energy transmission lines are connected to substations. The voltage level is changed to 33 kV and connected to the load points in the city's electricity distribution network with the use of step-down transformers in the substations.

In distribution networks, the 33kV voltage level is reduced to 0.4 or 0.231 kV low voltage level in order for the energy to reach the consumers. Therefore, power loss and voltage change occur in electrical energy from power plants to the end user. While the voltage is increasing in order to keep the power of the system constant; As the current decreases, or as the current increases, the voltage must decrease. In order to ensure a healthy energy transfer, the voltage must be increased and the current must be reduced. The purpose of keeping the current at a low level; is to reduce losses. To transmit power over long distances, the current is reduced and a transformer is used to increase the voltage. While electrical energy is transmitted with high voltage in the most efficient way, it is used and produced at low voltages.

2.5. CLASSIFICATION OF TRANSFORMERS

Transformers can be classified differently according to various characteristics. They are differentiated according to their function, structural features, intended use, or various other factors. This classification can be done as follows.

2.5.1. According to Usage Purposes

According to their intended use, transformers can be listed as follows:

- *Power Transformers:* These are high voltage transformers. They convert high-voltage electrical energy from large power plants into lower-voltage electrical energy and give it to distribution lines in cities. They are also used to operate large machinery and equipment used in industrial facilities.
- *Distribution Transformers:* These are transformers operating at lower voltages. They are especially used in electricity distribution systems in cities. These transformers convert electrical energy to lower voltages, making it usable in industrial

facilities and homes. They usually have a medium voltage or low voltage classification.

- *Measurement transformers:* They are used for current and voltage measurements.
- *Auto Transformers:* Auto transformers are adjusting to the secondary voltage level.

2.5.2. According to Cooling Types

A four-letter code is used to identify oil-immersed transformers in accordance with the cooling method. The internal cooling medium in contact with the windings is expressed by the first letter. The internal cooling medium's circulation system is designated by the second letter. The external cooling medium is designated by the third letter. The circulation system for an external cooling medium is designated by the fourth letter. For instance, this cooling method would be coded as ONAN (Oil Natural Air Natural) if the internal cooling medium were mineral oil, which circulates by natural flow, and the external cooling medium were air, which circulates by natural convection. Naturally air-cooled transformers are more commonly used due to their low cost and simple design. However, their efficiency may decrease in hot weather. While oil-cooled transformers are preferred because of their high reliability, they can be more expensive because they require maintenance. Each of this classification offers advantages and disadvantages for different application areas and requirements. Different cooling techniques are employed in power transformers, such as forced air circulation with fans, oil circulation with pumps, or a combination of the two. Consequently, the following cooling techniques are available: [39]

- ONAN Oil Natural Air Natural
- ONAF Oil Natural Air Forced
- OFAN Oil Forced Air Natural
- OFAF Oil Forced Air Forced

In natural air cooled transformers, natural air is used for cooling. By providing sufficient air circulation around the transformer, it is aimed to dissipate and cool the heat. In oil cooled transformers, a specially designed oil is used for heat dissipation. Transformers are housed in an oil-filled tank. The oil absorbs and cools the high temperature coming to the windings of the transformer. The large heat capacity of the oil helps to regulate the transformer's temperature.

2.5.3. According to Isolation Types

- *Dry Type Transformers:* It is a kind of transformer used in high voltage and power transmission by using the natural insulation property of air without using liquid insulation. They can be preferred in industrial facilities, hospitals, shopping malls, office buildings, subway lines. High-strength insulating materials are used to cover the windings of the dry-type transformer. These materials protect the high voltage windings inside the transformer against external influences and increase their insulating properties. No oil or other liquid is used as the transformer is cooled by natural ventilation. It has advantageous compared to oil type transformers in terms of environmental friendliness, no risk of oil leakage, less maintenance, and high safety. However, they are larger in size than liquid insulated transformer. Consequently, the area where they will be located needs to be larger.
- *Oil Immersed Transformers:* This types of transformers are widely used in high voltage and power applications. The oil immersion method provides isolation and cooling of the transformer windings. The transformer windings are immersed in oil and the oil covers the windings. This duty of oil increases the insulation of the windings and acts as cooling by absorbing the heat of the windings.

Oil-immersed transformers are reliably used in power systems where high voltages and currents are handled. This type of transformer is used in power stations and industrial plants. However, the fact that oil is a dangerous substance that can cause environmental pollution creates a disadvantage for this type of transformer. Therefore, the use of oil-immersed transformers should be done by considering environmental risks and safety precautions.

Oil immersed type transformers are also divided into two categories as distribution and power transformers. In higher voltage transmission networks, power transformers are utilized for step-up or step-down applications [27]. Power transformers are rated above 200MVA. As explained under 2.5.3, distribution transformers operate at lower voltages compared to power transformers. Therefore, it is used for the final connection in low voltage distribution networks. There are some advantages to use oil immersed type transformers.

- *High Efficiency:* Since oil is an excellent insulator and coolant, it enables the transformer to operate with high efficiency. Oil improves performance by dissipating the heat generated by the transformer.
- *Low Maintenance:* Oil immersed transformers do not require much maintenance. Therefore, it is the most suitable option for remote locations or hard-to-reach areas. At the same time, oil helps protect the transformer from moisture and dust. Thus, the need for maintenance is reduced.
- *Long life:* The oil in oil-immersed transformers can extend the life of the transformer as it helps to prevent the transformer's insulator from deteriorating. Therefore, oil-immersed transformers can be used for many years, even in harsh environments.
- *High Reliability:* Oil immersed transformers are very safe. Because oil protects the transformer from damage and overheating. This makes it an ideal option for critical applications that require uninterrupted operation.
- *Low Noise Levels:* Oil-immersed transformers produce less noise than dry-type transformers. This is an important factor in applications where noise levels must be kept to a minimum.
- *High Voltage Levels:* Oil immersed transformers can handle higher voltage levels than other transformers. It is therefore suitable for high voltage applications such as power transmission and distribution.

Transformer cooling systems are crucial to the effective operation of the transformer. Because transformers operate at high power and this causes heating. The cooling systems of the transformer are divided into two as radiator and wave wall. The main difference between the two systems is the design of the cooling surfaces.

In distribution transformers, corrugated walls are often used up to 4000 kVA (the transformer's power). Due to their elastic structure, which expands as the temperature rises, corrugated walls are employed for both heat transfer and oil absorption [27]. The corrugated wall system consists of a series of corrugated metal sheets placed around the transformer. These corrugates allow air to circulate freely around the transformer and allow heat to be dissipated more quickly. The corrugated walls increase the surface area of the transformer, providing more cooling and helping to achieve higher efficiency. Figure 8 shows the corrugated structure of the transformer.

Figure 8: Tank with Corrugated Wall

The radiator system, on the other hand, consists of a series of metal plates to which pipes are attached to the side or above the transformer. These pipes allow the coolant to circulate and carry the heat of the transformer outside. The radiator system is designed to increase the cooling performance of the transformer. The size of the radiators varies according to the power of the transformers and the cooling requirement. Larger transformers usually have larger radiators. Fans are used to cool the radiators in cases where even the radiators are insufficient. Tank with Radiator is shown in Figure 9.

Figure 9: Tank with Radiator

2.6. TRANSFORMER ACCESSORIES

There are many equipment that will enable the transformer to work. These equipment are shown in Figure 10.

High Voltage Bushings prevent the electric current from high voltage lines from entering the transformer by overcoming the protection shield of the transformer. The most crucial transformer accessories are bushings and the tap changer (off-circuit or on-load) [21].

Transformer tap changers are a mechanism used to adjust the output voltage of transformers to different voltage levels. It provides an output voltage suitable for variable load conditions by adjusting the output voltage on the main coils of the transformer to different stages. On the high voltage side of the transformer, it is often installed in the main coils.

Grounding points in transformers; It is used to ground the electrostatic charge on the surface of transformers.

The pressure valve controls the internal pressure of the transformer and releases high pressures. When a predetermined pressure level is reached, the pressure valve opens and helps to control the pressure. It can also be used as a discharge point for gases and vapors that may occur due to temperature changes in the transformer. As a result, it stops the liquid oil inside the transformer from oxidizing and getting dirty.

An accessory that enables controlling the oil level in transformers is the oil level indicator. Typically, the transformer's side or bottom will host the indicator for the transformer's oil level. There are minimum and maximum level markings to check if the oil is at the correct level. In this way, the oil level of the transformer is controlled and oil is added when necessary, ensuring that the transformer operates in a healthy way.

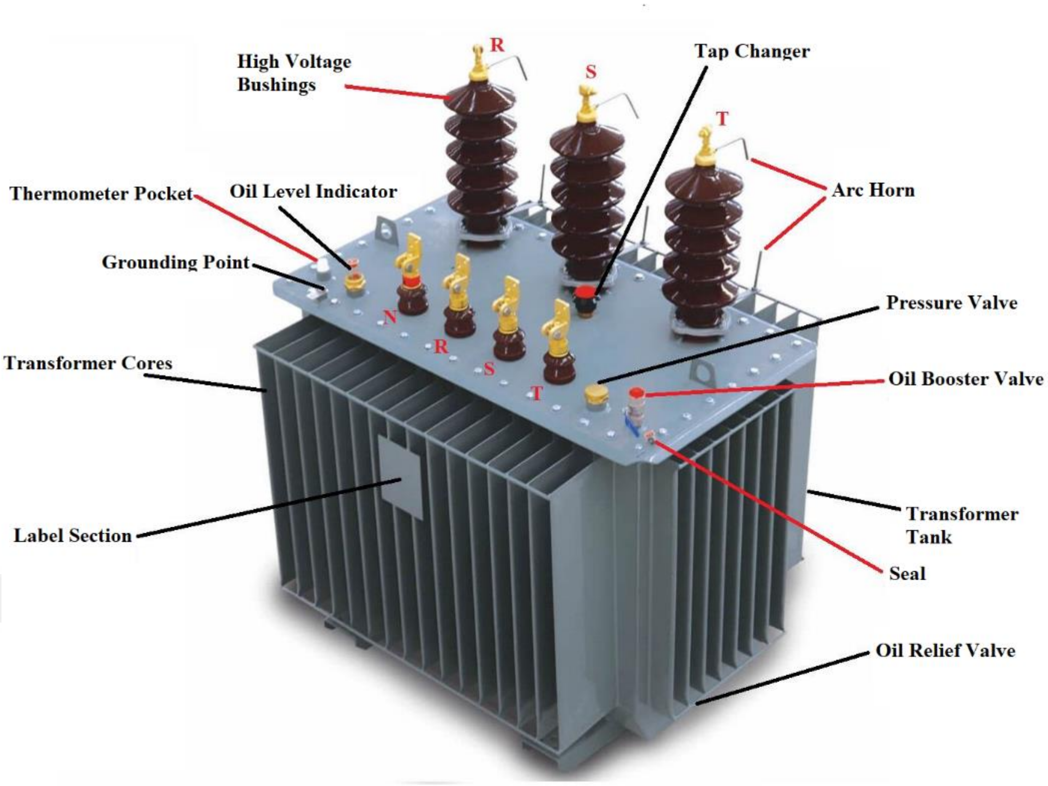


Figure 10: Transformer Accessories

CHAPTER III

ELECTRICAL DESIGN OF OIL TYPE DISTRIBUTION TRANSFORMERS

Electrical power distribution networks frequently employ oil-type distribution transformers. The primary and secondary windings, as well as the magnetic core, make up the structure of these transformers. Due to its high permeability, the magnetic core concentrates the magnetic flux. As a result, the magnetic field inside the winding is increased. The windings modify the voltage while converting the magnetic flux. Transformer oil insulates the magnetic core and winding structure and acts as a cooling agent. Oil-type transformers have advantages such as high efficiency, low losses, long life, reliability, easy maintenance and low cost, as well as some disadvantages. As an example of these disadvantages; oil leakage and high temperatures may present a risk of burns. For this reason, oil-free or less oily transformer designs have been directed. The electrical design of oil-filled distribution transformers depends on factors such as transformer capacity, voltage ratio, current density, losses and insulation properties. The capacity of the transformer is usually expressed in volt-ampere (VA) or kilovolt-ampere (kVA) units. The transformer's primary and secondary coil voltage and current levels determine its capacity. The ratio between primary and secondary voltage is known as the transformer's voltage ratio. This voltage ratio carries out the voltage conversion process and establishes the transformer's working voltage. One element that affects the transformer's primary current carrying capacity is the current density. The size, shape, and height of the transformer are all impacted by the current density. The losses of the transformer have an important place in terms of the efficiency and performance of the transformer. It is collected under two headings as copper and iron losses. Copper losses are due to their resistance in the windings inside the transformer. The movement of the magnetic flux in the magnetic core is what causes iron losses. The transformer’s dependability and endurance depend heavily on its insulating qualities. Insulation materials protect against insulation voltages and isolate the transformer’s magnetic core, windings and oil.

The electrical design of oil-type distribution transformers should meet the objectives such as high efficiency, low loss, optimum weight, minimum cost, long life. In order to achieve these goals, many factors such as sizing of the transformer, selection of materials, winding shape, cooling method, insulation systems must be considered. Transformers must be built to specific load specifications, including high efficiency, vector group and phase displacement for power systems, operating voltages, temperature conditions, and VA rating [28]. With respect to the transformer kinds that the designers have created, the economic cost should be taken into account. Without compromising the quality of the transformer, it is expected that the transformer cost will be minimized to meet the desired specifications. Additionally, the following factors should be taken into account when designing:

- Reduce the transformer's load and no-load losses as much as possible.
- Take into account the transformer's regular operating temperature to prevent overheating, which could shorten the transformer's lifespan [28].
- To prevent saturation, take into account the operating flux density [28].
- Pay closer attention to the operating frequency, particularly with high frequency transformers [28].

Input parameters determined for the emergence of electrical and mechanical properties in transformer design can be listed as follows:

- Power
- Voltage level
  - High voltage
  - Low voltage
- Conductor type
- Connection group
- Tank type
- Short circuit voltage impedance
- Maximum ambient temperature
- Transformer losses
  - No Load loss
  - Load loss
- Transformer weight
  - Primary and secondary winding weights

- Core weight
- Tank weight
- Weight of oil used

An equation set that describes the properties of the transformer makes up the mathematical model of an oil-filled distribution transformer. These equations explain various properties of the transformer such as voltage, current, power loss, magnetic flux, number of turns. The electrical design of the transformer's active component, which accounts for the needs stated in the specification, comes first in the design process. Tank design is made by taking into consideration losses of the transformer.

This study consists of a 3-phase, Yzn11, 25 kVA, 33/0.4 kV two-winding, oil-filled distribution transformer design. The transformer design starts with the design of the active part consisting of the core diameter, area, step widths and thicknesses of the transformer, the low voltage and high voltage windings' total number of turns, the low and high voltage winding section, the current densities of the conductors used. In this study, transformer heating is neglected. The transformer tank design is completed according to the results obtained in the active part and transformer losses.

The design specification of the subjected transformer is shown in Table 1.

Table 1: Transformer requirements

Technical Specifications	Values
Power (KVA)	25
Frequency (Hz)	50
Cooling System	ONAN
Primary Voltage (V)	33000
Secondary Voltage (V)	400
Vector Group	Yzn11
Off circuit taps on HV	+2,-3 x 4.54 % steps
Ambient Temperature (°C)	40
Top Oil Temperature Rise (°C)	60
Average Winding Temperature Rise (°C)	65
HV BIL (Basic Insulation Level) (kV)	170
AC Test Voltage (kV)	70
No Load Loss Max (W)	81
Load Loss Max (W)	660
Short Circuit Impedance	4.5% ± 10%

3.1. MATHEMATICAL MODELING OF TRANSFORMERS CONNECTION

Based on the transformer's current and voltage values at a specific power level, the transformer design stage is chosen. Calculations are made based on the transformer's connection type to determine the current and voltage values in the primary and secondary windings. The transformer that is the subject of this thesis has a Yzn-shaped connecting group. With the aid of the following calculations and in accordance with the phasor diagram in Figure 11, the phase and line currents and voltages of the 25 kVA, Yzn connected distribution transformer studied within the scope of the thesis were determined. The voltage and current values found are filled as shown in Table 2.

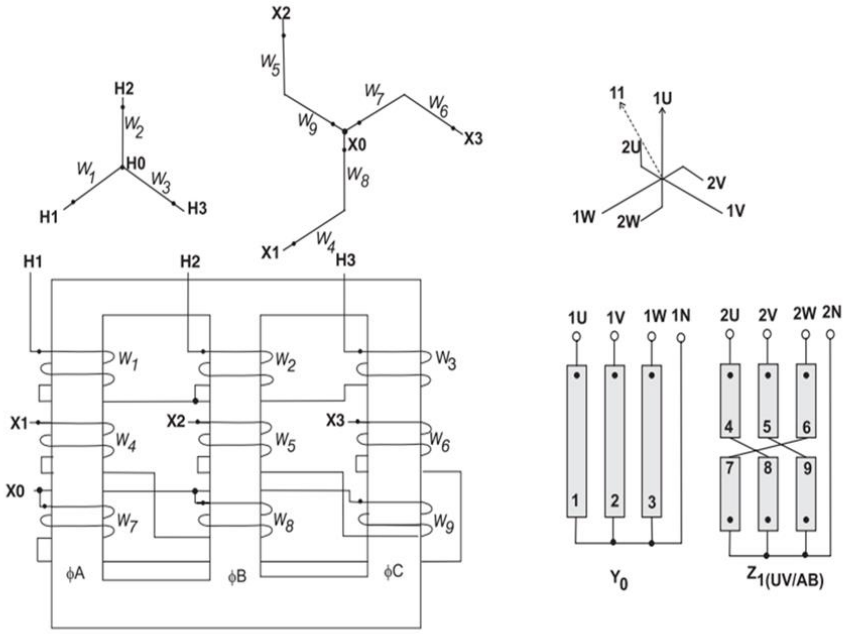


Figure 11: Vector Diagram of Yzn Connection

The transformer created for the thesis has a star-connected HV side. The power value is calculated in kVA and the voltage value is calculated in kV. In star connection, the line voltage is root three times the phase voltage. In other words, as in Equation 3.1, phase voltage is the line voltage divided by root three.

$$V_{HVph} = \frac{V_{HVll}}{\sqrt{3}} \tag{3.1}$$

Line current is found as in Equation 3.2

$$I_{HVll} = \frac{S \times 1000}{\sqrt{3} \times V_{HVll}} \tag{3.2}$$

In star connections, line current and phase current are equal to each other as expressed in Equation 3.3.

$$I_{HVph} = I_{HVll} \tag{3.3}$$

The LV side of the transformer is Zig-Zag connected. The formulas for Zig-Zag relations are as following equations. First of all, the line current of secondary side is found as Equation 3.4.

$$I_{LVll} = \frac{S \times 1000}{\sqrt{3} \times V_{LVll}} \tag{3.4}$$

Phase current and line current are equal each other just like in star connection. This is shown in Equation 3.5.

$$I_{LVph} = I_{LVll} \tag{3.5}$$

Line voltage in Zig-Zag connection is the vector sum of the two voltages which are 120° out of phase. Line voltage found as Equation 3.6. The zig and zag voltages specified in Equation 3.7 are found as in Equation 3.8 and Equation 3.9.

$$V_{LVll} = \sqrt{3} \times V_{LVph} \tag{3.6}$$

$$V_{LVph} = \sqrt{3} \times zig\ voltage = \sqrt{3} \times zag\ voltage \tag{3.7}$$

$$Zig\ winding\ voltage = \frac{V_{LVll}}{3} \tag{3.8}$$

$$Zag\ winding\ voltage = \frac{V_{LVll}}{3} \tag{3.9}$$

Table 2: Line, Phase Voltage and Current of Transformer

Description	LV	HV min.	HV rated	HV max.
Line Voltage V_{ll}	400 V	28500	33000	36000
Phase Voltage V_{ph}	230.94 V	16454	19052	20784
Line Current I_{ll}	36.08 A	0.506A	0.437A	0.400A
Phase Current I_{ph}	36.08 A	0.506A	0.437A	0.400A

3.2. MATHEMATICAL MODELING OF TRANSFORMERS CORE

One of the most crucial design processes that affects a transformer's electrical characteristics is the core design. Figure 12 illustrates the round core geometry of the transformer under study for the purpose of this thesis. The round core in transformers can distribute the magnetic field more homogeneously due to the minimization of air gaps. Thanks to this homogeneous distribution, transformer losses can be reduced. Another advantage is that round cores can be designed to allow higher flux density, so transformers of smaller sizes can be produced. Because of these features of the round core, it is preferred in high frequency applications and some special designs.

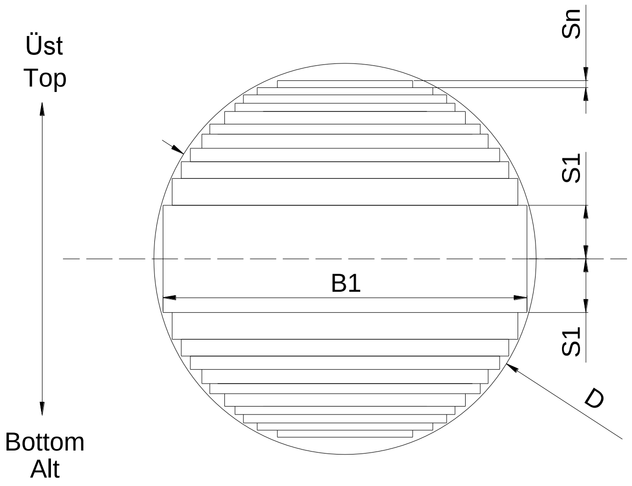


Figure 12: Transformer Core Geometry

For the transformer core design, firstly, it starts with finding ${}^{E}\!/_{T}$, which is the initial voltage value of the transformer in each turn. ${}^{E}\!/_{T}$ found with the help of the Equation 3.10. The K value, which is taken as a variable value within the scope of the thesis, takes a value between 0.25 and 0.55.

The value of "K" should be carefully chosen because the improper choice could have an impact on performance characteristics like impedance, efficiency, regulation, and no-load and full-load loss. A wrong estimate of the value of "K" may also have an impact on the cost of constructing the transformer [23].

$$ {}^{E}\!/_{T} = K \times \sqrt{S} \tag{3.10} $$

The primary and secondary transformer windings' total number of turns is one of the elements influencing the dimensions of the transformer core. The ratio of primary to secondary voltages, as well as the magnetic characteristics of the core material, both affect the number of turns. The Equation 3.11 is used to determine the initial LV turns:

$$ N_{LV} = \frac{2}{3} \times \frac{V_{LVll}}{{}^{E}\!/_{T}} \tag{3.11} $$

The Equation 3.12 is used to determine the number of turns on the HV side.

$$ N_{HV} = \frac{V_{HVph}}{V_{LVph}} \times N_{LV} \tag{3.12} $$

The results that applying the Multi-Objective Genetic Algorithm optimization will be explained in detail under the title of “Optimization Results”. The choice of core material in transformers greatly affects the electrical properties and performance of the transformer. MOH sheet is a common choice for transformer core because of its magnetic properties. MOH sheet is a cold rolled electro-galvanized steel sheet material with 3% silicon content. It is ideal for transformers due to its low magnetic loss and high saturation current. The high electrical resistance of the MOH sheet not only extends the life of the transformer, but also reduces the risk of failure. It can also be produced in thin thicknesses since it has high rolling properties. This feature makes it possible to manufacture transformers in smaller sizes. The MOH core with specifications of 0.225 mm thickness and 0.79 w/kg at 1.7 T is chosen for the intended transformer. A magnetic flux density of 1.72 T with 0.82 w/kg is used in the design process.

The following Equation 3.13 is used to obtain the core cross-sectional area. The stacking factor for Cold Rolled Grain Oriented (CRGO) steel is 0.97.

$$A_g = \frac{{}^{E}\!/_{T} \times\ 10^2}{2.22 \times B_m \times\ 0.97} \tag{3.13}$$

Equation 3.10 mentioned above becomes Equation 3.14 when rearranged according to Equation 3.13.

$${}^{E}\!/_{T} = 4.44\ \times f\ \times\ B_m \times A_g \times 0.97 \times 10^{-4} \tag{3.14}$$

It is important to compute the core area based on ${}^{E}\!/_{T}$, magnetic flux density (B_m) and operating frequency (f) in order to determine the diameter of the transformer core. The following Equation 3.14 is used to obtain the core cross-sectional area. The stacking factor for Cold Rolled Grain Oriented (CRGO) steel is 0.97.

Accordingly, transformer core steps are placed in four stage with a minimum core steps of 50 mm. The transformer core diameter was found by taking the rounding factor of 0.94 as shown in the Equation 3.15 below.

$$d_{core} = \sqrt{\frac{A_g \times 4}{\pi \times\ 0.94}} \tag{3.15}$$

The maximum allowed width of laminations must be determined for any given core diameter in order to fill the maximum amount of the core circle. There will need to be N different lamination widths chosen in order to construct the circular cross section of the core in N phases. This is true for constructions that use stacked cores of the core type. By choosing the best step widths, the core area can be increased for a specific number of steps. If there are infinitely many steps, the core cross section turns into a circle [29].

L_1, shown as core step widths in the transformer, are stacked on top of each other starting from the diameter of the core indicated in Figure 13.

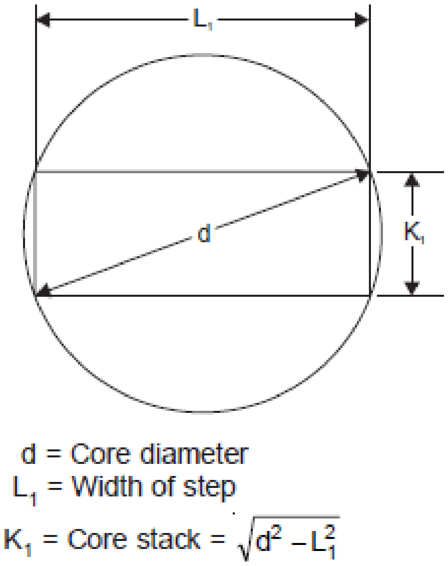


Figure 13: Transformer Core Steps and Stacks

When determining the step width, it is important to keep in mind that the steps must be spaced apart by at least 10-15 mm and in the proper order [23]. The designed transformer core thicknesses are arranged on 0.225 mm sheets. The core steps and stacks are found respectively, starting from Equation 3.16 to Equation 3.19.

$$K_1 = \sqrt{{d_{core}}^2 - {L_1}^2} \tag{3.16}$$

$$K_2 = \sqrt{{d_{core}}^2 - {L_2}^2} - K_1 \tag{3.17}$$

$$K_3 = \sqrt{{d_{core}}^2 - {L_3}^2} - (K_1 + K_2) \tag{3.18}$$

$$K_4 = \sqrt{{d_{core}}^2 - {L_4}^2} - (K_1 + K_2 + K_3) \tag{3.19}$$

3.3. MATHEMATICAL MODELING OF TRANSFORMERS WINDING

After the electrical design of the transformer core is modeled, it is time to model the windings of the transformer. The Multi-Objective Genetic Algorithm will be utilized in this study to optimize the conductors that will be employed in the LV and HV windings of the transformer. A two-dimensional rectangular conductor will be used on the LV side and a round conductor will be used on the HV side. The conductors to be used are shown in the Figure 14 and Figure 15.

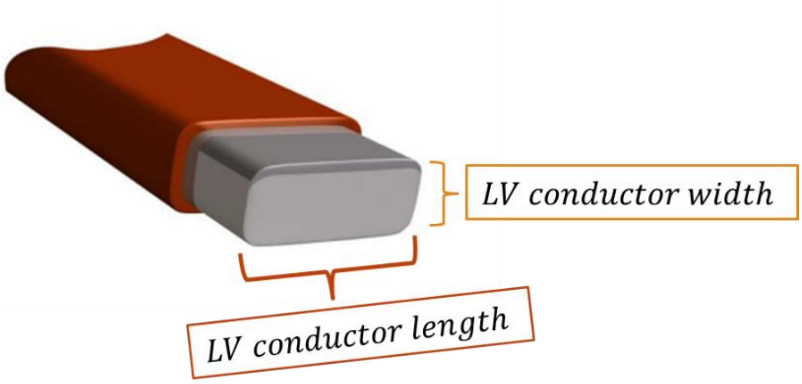


Figure 14: LV Conductor

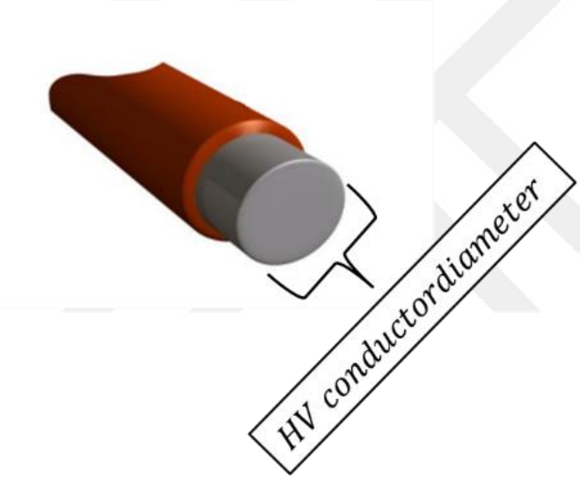


Figure 15: HV Conductor Diameter

The secondary side of area which is indicated in A_s calculated by Equation 3.20. Since a two-dimensional rectangular conductor is used on the secondary side of the transformer as shown in Figure 14, this is multiplied by the width and length of the conductor when calculating the area.

$$A_s = LV_{conductorlength} \times LV_{conductorwidth} \tag{3.20}$$

A round conductor is used on the primary side of the transformer as shown in Figure 15. The formula used to find the area of a circle is adapted to find the area of this conductor which is shown as A_p, and this is shown in Equation 3.21.

$$A_p = \pi \times \left(\frac{{HV_{conductordiameter}}^{2}}{4} \right) \tag{3.21}$$

Current densities that are j_1 and j_2 of these conductors are found according to Equation 3.22 and Equation 3.23 respectively.

$$j_1 = \frac{I_{HVll}}{A_p} \tag{3.22}$$

$$j_2 = \frac{I_{LVll}}{A_s} \tag{3.23}$$

Secondary winding inner and outer diameters are found according to Equation 3.24 and Equation 3.25. The distance between the LV inner diameter and the transformer core diameter is 5 mm. Primary winding inner and outer diameters are calculated in compliance with Equation 3.26 and Equation 3.27. The insulating gap (W_g) between the LV and HV is 15 mm. The values of t_{LV} and t_{HV} display the thickness of the LV and HV windings, respectively.

$$d_{LVinner} = d_{core} + 5\,mm \tag{3.24}$$

$$d_{LVouter} = d_{LVinner} + t_{LV} \tag{3.25}$$

$$d_{HVinner} = d_{LVouter} + W_g \tag{3.26}$$

$$d_{HVouter} = d_{HVinner} + t_{HV} \tag{3.27}$$

The thicknesses of primary and secondary windings are found by using the flowing Equation 3.28 and Equation 3.29;

$$\begin{aligned} &LV\ thickness\ (t_{LV}) \\ &\qquad = (LV\ floor\ number \times LV_{conductorwidth}) \\ &\qquad + (LV\ channel\ number\ \times LV\ channel\ thickness) \\ &\qquad + \big((LV\ floor\ number - 1) \times (LV\ floor\ insulation)\big) \end{aligned} \tag{3.28}$$

$$\begin{aligned} &HV\ thickness\ (t_{HV}) \\ &\qquad = (HV\ floor\ number \times (HV_{conductordiameter} \\ &\qquad + HV\ winding\ insulation) \\ &\qquad + (HV\ channel\ number\ \times HV\ channel\ thickness) \\ &\qquad + (HV\ floor\ insulation \\ &\qquad \times (HV\ floor\ number - HV\ channel\ number)) \end{aligned} \tag{3.29}$$

In Figures 16 and 17, the primary and secondary winding diameters are indicated.

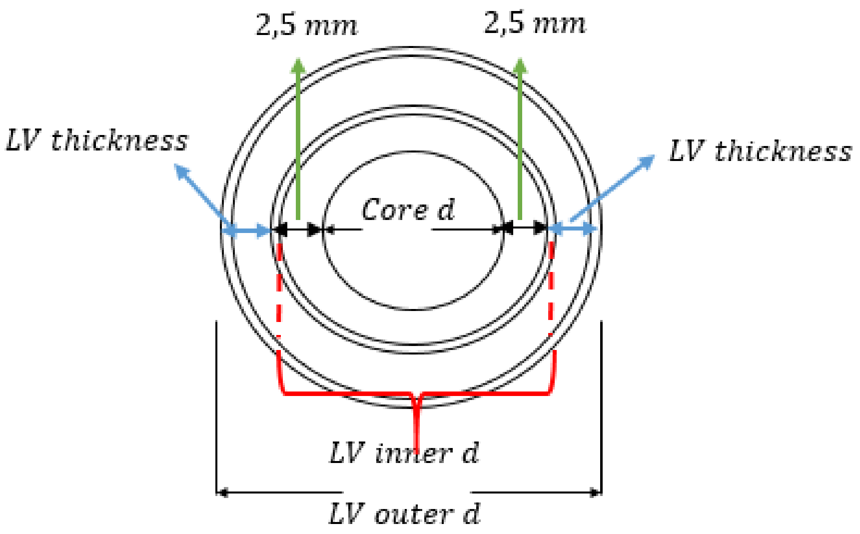


Figure 16: Secondary winding diameter

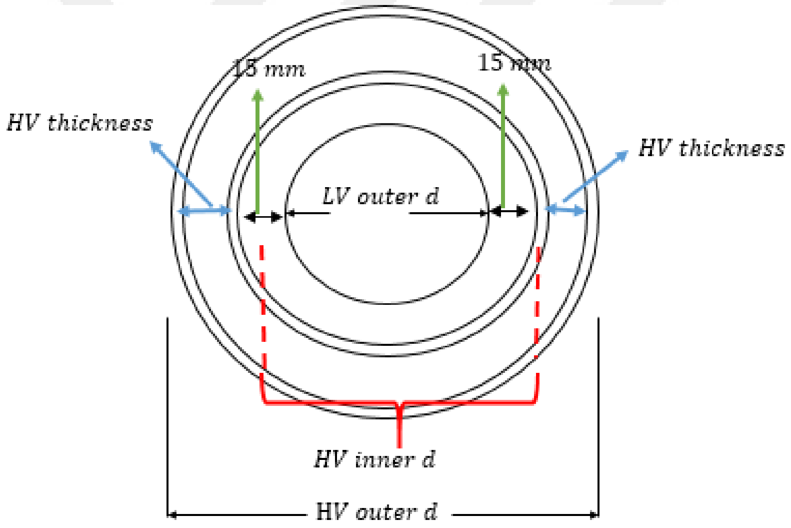


Figure 17: Secondary winding diameter

3.4. TANK DESIGN OF TRANSFORMERS

Using the established formulas, it is possible to calculate the mathematical modeling needed for the transformer's core and windings design. To determine the transformer tank size, width, length and height must be found. These are shown in Equation 3.30, Equation 3.31 and finally Equation 3.32.

$$Tank\ width = HV\ Winding\ outer\ diameter + (2 \times winding\ to\ tank\ short\ side\ clearance) \tag{3.30}$$

$$\begin{aligned} &Tank\ height \\ &= \ Core\ window\ height\ +\ 2\ \times core\ diameter \\ &+ Distance\ from\ the\ core\ surface\ to\ the\ tank\ cover \end{aligned} \tag{3.31}$$

$$\begin{aligned} &Tank\ length \\ &= 2\ \times Core\ window\ width\ + HV\ Winding\ outer\ diameter + 2 \\ &\times winding\ to\ tank\ short\ side\ clearance \end{aligned} \tag{3.32}$$

Tank dimensions with formulas shown are detailed in Figure 18.

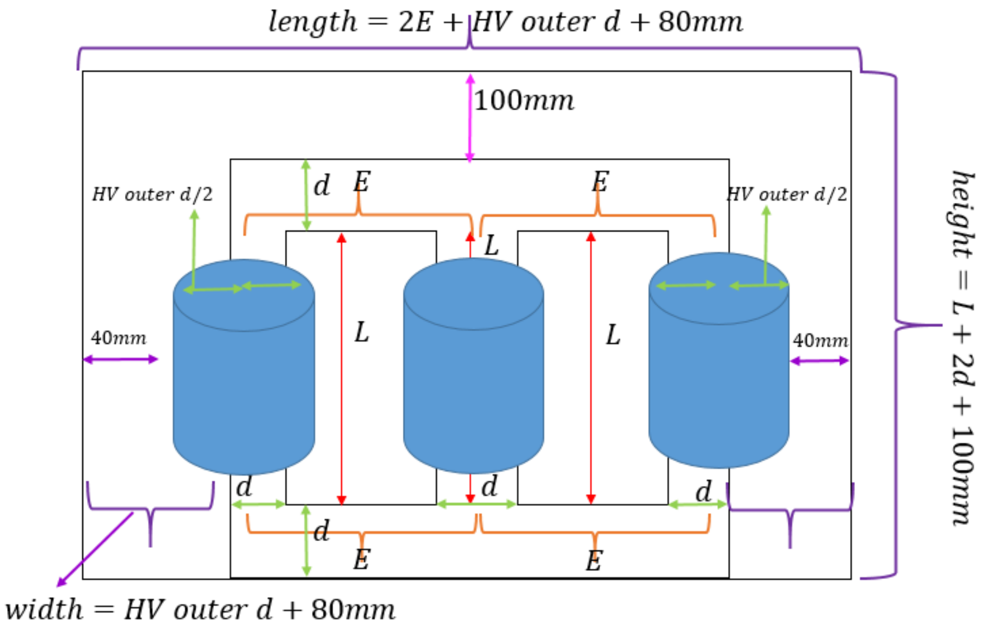


Figure 18: Transformer Tank Details

3.5. CALCULATION OF LOAD LOSSES

The losses in the load occur in the windings of the transformer. Current flows from both the primary and secondary of the transformer when a load is connected to the secondary. These losses are the result of current flowing through the windings. The terms copper losses and I^2R are other names for load losses. By knowing the weight of the conductor and the current density, the I^2R loss can be calculated. The method described in this section should only be used for rapid inspection or estimation; the calculation using the resistance value should be utilized for design [29]. Load loss is found by Equation 3.33:

$$P_K = K_{AL} \times j^2 \times W_{total\ winding} \tag{3.33}$$

j stands for the current density, K_{AL} is 12.61 for aluminum [30], and $W_{total\ winding}$ is the weight of the primary and secondary windings. The losses in the transformer's primary and secondary windings are estimated independently using the aforementioned formula. The overall load losses in the windings are then calculated by adding these two losses together.

3.6. CALCULATION OF SHORT CIRCUIT EMPEDANCE

The impedance value displayed by the transformer coils in the network center at the time of the short-circuit is known as the short-circuit impedance. When the secondary coil is short-circuited, it is the amount of voltage needed to keep the primary coil's current flowing at its rated rate. The short circuit power of the transformer facility is used to make the determination.

Reactive and resistive parts make up short circuit impedance. Alternating-current resistance which is indicated in U_R is found by Equation 3.35. Reactance which is shown in U_X is found by Equation 3.36. Short circuit impedance which is shown in U_K consists of the sum of resistive and reactive values as stated in Equation 3.34.

$$U_K = \sqrt{{U_X}^2 + {U_R}^2} \tag{3.34}$$

$$U_R = \frac{P_K \times 10^{-3}}{S} \times 100 \tag{3.35}$$

$$U_X = \frac{1.24 \times S \times D_m \times \left(\frac{t_{HV} + t_{LV}}{3} + W_g\right) \times K_R \times k_1 \times k_2}{3 \times \left({}^{E}/_{T}\right)^2 \times h_2 \times 10} \tag{3.36}$$

D_m is explained the mean diameter of LV outer diameter and HV inner diameter of winding and it is calculated as Equation 3.37.

$$D_m = \frac{d_{LVouter} + d_{HVinner}}{2} \tag{3.37}$$

K_R is mean that Rogowski's factor and it is explained by Equation 3.38.

$$K_R = \left[1 - \frac{t_{HV} + W_g + t_{LV}}{\pi \times \left(\frac{h_1 + h_2}{2}\right)}\right] \tag{3.38}$$

3.7. CALCULATION OF NO LOAD LOSSES

Iron losses and core losses are other names for no load losses. It happens as a result of the fluctuating flux in the transformer core. It is determined using Equation 3.39 as shown [29].

$$P_0 = W_{core} \times \left({}^{watt}/_{kg}\right) \times Building\ Factor \tag{3.39}$$

Where the W_{core} is defined as total weight of core, building factor is taken as 1.25 constant values , ${}^{watt}/_{kg}$ is material at working flux density. It is calculated by Equation 3.40.

$$\begin{aligned} {}^{watt}/_{kg} = \big(& 1.0948 \times {B_m}^6 - 5.7272 \times {B_m}^5 + 11.507 \times {B_m}^4 - 11.075 \times {B_m}^3 \\ & + 5.4336 \times {B_m}^2 - 1.0599 \times B_m + 0.069\big) \times 1.02 \end{aligned} \tag{3.40}$$

3.8. CALCULATION OF TRANSFORMERS WEIGHT

3.8.1. Transformers LV Winding Weight

The average secondary winding diameter ($D_{LV\ avg}$), circumference ($C_{LV\ avg}$), and wire length ($Wire\ L_{LV}$) must all be determined in order to determine the weight of the secondary coil of the transformer. The formulas are shown in Equation 3.41 to Equation 3.43.

$$D_{LV\ avg} = \frac{d_{LVinner} + d_{LVouter}}{2} \tag{3.41}$$

$$C_{LV\ avg} = 2 \times \pi \times D_{LV\ avg} \tag{3.42}$$

$$Wire\ L_{LV} = \frac{(C_{LV\ avg} \times N_{LV})}{1000} \times 3 \tag{3.43}$$

Using these three formulas, the weight of the secondary winding of the transformer was found as in Equation 3.44. The current density (j_{AL}) of the aluminum conductor is 2.7 kg/m^3.

$$W_{LV\ winding} = \frac{j_{AL} \times A_s \times\ Wire\ L_{LV}}{1000} \tag{3.44}$$

3.8.2. Transformers HV Winding Weight

The average primary winding diameter ($D_{HV\ avg}$), circumference ($C_{HV\ avg}$) and wire length ($Wire\ L_{HV}$) must all be determined in order to determine the weight of the primary coil of the transformer. The formulas required to find the HV winding weight are as shown in Equation 3.45, Equation 3.46 and Equation 3.47.

$$D_{HV\ avg} = \frac{d_{HVinner} + d_{HVouter}}{2} \tag{3.45}$$

$$C_{HV\ avg} = 2 \times \pi \times D_{HV\ avg} \tag{3.46}$$

$$Wire\ L_{HV} = \frac{(C_{HV\ avg} \times N_{HVmax})}{1000} \times 3 \tag{3.47}$$

Using Equation 3.45, Equation 3.46 and Equation 3.47, the primary winding weight of the transformer is specified in Equation 3.48.

$$W_{HV\ winding} = \frac{j_{AL} \times A_p \times \ Wire\ L_{HV}}{1000} \tag{3.48}$$

The primary and secondary winding weights are added to determine the transformer's overall winding weight. It is calculated by Equation 3.49.

$$W_{total\ winding} = W_{LV\ winding} + W_{HV\ winding} \tag{3.49}$$

3.8.3. Transformers Core Weight

The window width (E), length (L) and circumference (C_{core}) must be determined in order to find out the weight of the transformer's core. The transformer core specific weight (j_{core}) is 7.65 gr/cm^3. These are calculated by using Equation 3.50, Equation 3.51 and Equation 3.52 respectively.

$$E = d_{HVouter} + distance\ between\ phases \tag{3.50}$$

$$L = HV\ and\ LV\ winding\ height + lower\ yoke\ +\ upper\ yoke \tag{3.51}$$

$$C_{core} = (3 \times L) + (4 \times E) + (2 \times d_{core}) \tag{3.52}$$

Then, weight of transformer core is found by Equation 3.53.

$$W_{core} = \ j_{core} \times A_g \times C_{core} \tag{3.53}$$

3.8.4. Transformers Oil Weight

The internal volume of the tank is obtained first, and then the weight of the oil in the transformer is determined. Tank dimensions “3.4. Tank Design of Transformer” section. According to this, volume of transformer tank calculated by Equation 3.54.

$$V_{tank} = Tank\ length\ \times Tank\ width \times Tank\ height \tag{3.54}$$

The amount of oil per 1 L is 10 ^{6} mm^3. In this case, the volume of oil in the transformer tank is found as Equation 3.55.

$$V_{tank\ oil} = \frac{V_{tank}}{10^6} \tag{3.55}$$

The transformer core and windings make up the active component of transformers. By summing the volume of the core and windings individually, the volume of the active part may be calculated. The core volume is shown in Equation 3.56, while the volume of the windings is described by Equation 3.57.

$$V_{core} = \frac{W_{core}}{j_{core}} \tag{3.56}$$

$$V_{windings} = \frac{W_{LV\,winding} + W_{HV\,winding}}{j_{AL}} \tag{3.57}$$

By adding Equation 3.56 and Equation 3.57, the volume of the transformer active part is calculated as stated in Equation 3.58.

$$V_{active\,part} = V_{core} + V_{windings} \tag{3.58}$$

The volume of the active part is divided by the amount of oil per 1 L to find the volume of active part oil. The formula for the volume of the active part is specified in Equation 3.59.

$$V_{active\,part\,oil} = \frac{V_{active\,part}}{10^6} \tag{3.59}$$

Within the scope of this thesis, the corrugated wall oil of the transformer is accepted as a constant value. It is shown in Equation 3.60.

$$V_{corrugated\,wall\,oil} = 20\ L \tag{3.60}$$

The volume and weight of the oil in the transformer are found with the help of the following Equation 3.61 and Equation 3.62. The specific mass of the oil (j_{oil}) is gr/cm^3.

$$V_{transformer\,oil} = (V_{tank\,oil} + V_{corrugated\,wall\,oil}) - V_{active\,part\,oil} \tag{3.61}$$

$$W_{transformer\,oil} = V_{transformer\,oil} \times j_{oil} \tag{3.62}$$

The variable transformer parameters determined within the scope of the thesis will be found by the Multi-Objective Genetic Algorithm method, and then the design processes will be done. Therefore, the results of the formulas specified in the "Electrical Design of Oil Type Distribution Transformer” section will be included in Section 4.2 which is Optimization Result.

CHAPTER IV

NUMERICAL METHODOLOGY

Design optimization of transformers plays an important role due to competitive markets. Today, along with cost optimization, optimization studies are carried out for many parameters that will affect the design of the transformer such as weight, efficiency, performance or losses.

In the design optimization of transformers, choices were made considering the constraints of the technical specifications.

The purpose of this thesis is to demonstrate the Multi-Objective Genetic Algorithm technique, which employs MATLAB software, to reduce the manufacturing cost of the ideal 25 kVA distribution transformer. With the minimization of the cost, minimization has also occurred in system losses and weight statuses.

The optimization results were supported by the FEM method. It is designed in 3D by using transformer parameters obtained by optimization in ANSYS program. The FEM method was used to compute copper losses, iron losses, voltage and current values in the LV and HV windings, and the magnetic flux value of the transformer. Optimization results were verified by the FEM method.

4.1. MULTI-OBJECTIVE GENETIC ALGORITHM OPTIMIZATION TECHNIQUE

Based on certain limitations and the desired conditions, the objective function is minimized or maximized throughout the transformer design optimization process. Performance and cost of the transformer are difficult to balance in a satisfactory way. As a result, designers entered the field of artificial intelligence in order to address TDO issues [31].

An optimization method known as a genetic algorithm was created using the theory of evolution as inspiration. Using genetics and natural selection predictions, the

Genetic Algorithm is a search algorithm [32]. By imitating procedures like natural selection and genetic crossover, the Genetic Algorithm uses a population-based method to find the optimal solution to a problem. Genetic Algorithms are based on population, as opposed to conventional optimization algorithms, where each individual is parallel evolved and the final outcome is included in the last population [33].

The basic concepts that make up the genetic algorithm are gene, chromosome, population, crossover, selection and mutation. Genetic Algorithm parameters represent genes in biology, while clustered set of parameters make up chromosomes.

The gene is the part that determines the characteristics of an individual. Gene is a significant parameter on its own and is the structure that carries genetic information. Depending on the problem context for which the genetic algorithm is being used, genes can be characterized in many ways. The gene can also be expressed in letters such as a bit, bit sequence, A B, or in binary numbers, such as 1 0.

Genes come together to form chromosomes. Therefore, chromosomes contain all the information about the problem. Each individual in the genetic algorithm consists of populations represented as chromosomes.

In the Genetic Algorithm, a population consisting of a set of individuals is used. Each individual is the genetic sequence that represents the problem.

The goal of the Genetic Algorithm is to choose from a population of people the best suited individuals. This is accomplished by using a fitness function, which displays each person's performance. The fitness of the population is achieved with a minimum or maximum outcome within specified limits. The population is the set of potential solutions that the problem has chosen to explore. As a result, the size of populations changes depending on the nature of the issue. Individuals who are better suited to the issue can be found because of the genetic renewals that take place in the population. Selected members of the present population must be crossed and mutated in order to create a new community of populations. The notion states that theory the solution should be continued with suitable individuals. From these individuals, new people should be produced [34].

John Holland (1975) used GA for the first time as a consequence of extensive research. He came to the conclusion in his research that evolution and change had an impact on living things. These events led him to transfer the genetic evolution process to the computing environment. He conducted a study demonstrating that new people will be acquired as a result of genetic processes such as "mating, reproduction, change..." instead of enhancing the learning capacity of a single mechanical construction. He specified "Genetic Algorithm" as the name of the technique he created for this investigation [34]. David Goldberg who is John Holland’s student, realized the problem involving gas pipeline control in his thesis with a Genetic Algorithm.

Genetic Algorithm is obtained by selection, crossover and mutation. All three procedures depend on the suitability of the individuals.

- The process of selection involves choosing the best members of the population and passing them on to the following generation. The selection process is done by evaluating the individuals in the population according to their fitness functions. The selection includes the best solutions for the next generation of the fitness value defined for each individual.
- Mutation is a process by which the genes of individuals undergo a random change, which aims to expand the population's genetic diversity and allow individuals to develop unique traits.
- Crossover involves the combination of genes from two individuals to form a new individual. Random cuts are made between the genes of the selected individuals and the cut genes are exchanged with each other. This process allows the creation of new individuals. The process continues until the desired results are obtained.

At the end of the process, each individual has a cost function that gives the most appropriate solution for the identified problem. Individuals with a high value relative to the return value from the cost function are given the opportunity to multiply with other individuals in the population [34].

The actions listed below must be taken in order to identify the best answer to the issues identified with the assistance of the genetic algorithm:

- An accurate representation of individuals to use
- Preparing the problem in accordance with the purpose of the cost function
- Selection of genetic operators for the solution of the determined problem

The population-based feature of the Genetic Algorithm is well implemented in the Multi-Objective Genetic Algorithm.

A population-based strategy is used in the optimization algorithm known as the Multi-Objective Genetic Algorithm (MOGA), which is similar to Genetic Algorithms.

The genetic operators of selection, mutation, and crossover are combined with unique methods like Pareto sequencing and modified for optimization by the Multi-Objective Genetic Algorithm. It is used to solve problems with more than one objective function. This algorithm optimizes many different objective functions. In some cases, while the specified objective function is improved, the outcome of another determined objective function may deteriorate. Therefore, it tries to balance between these functions.

The Multi-Objective Genetic Algorithm's main objective is to produce a solution set (Pareto set) that simultaneously optimizes a number of objective functions chosen to solve the problem. The Pareto set is a solution set. The Multi-Objective Genetic Algorithm tries to find a solution set that contains as many Pareto fronts as possible. A Multi-Objective Genetic Algorithm is defined as the number of Pareto solutions. Pareto solutions; means more than one best solution.

In the Multi-Objective Genetic Algorithm, instead of a suitable solution, the appropriate solution set is mentioned. The solution that is suitable for a purpose determined in the solution set of multi-objective optimization problems may also be a bad solution according to the other purpose. The primary goal of the Multi-Objective Genetic Algorithm is to locate and approach the Pareto front. The Multi-Objective Genetic Algorithm selection scheme is shown in Figure 19.

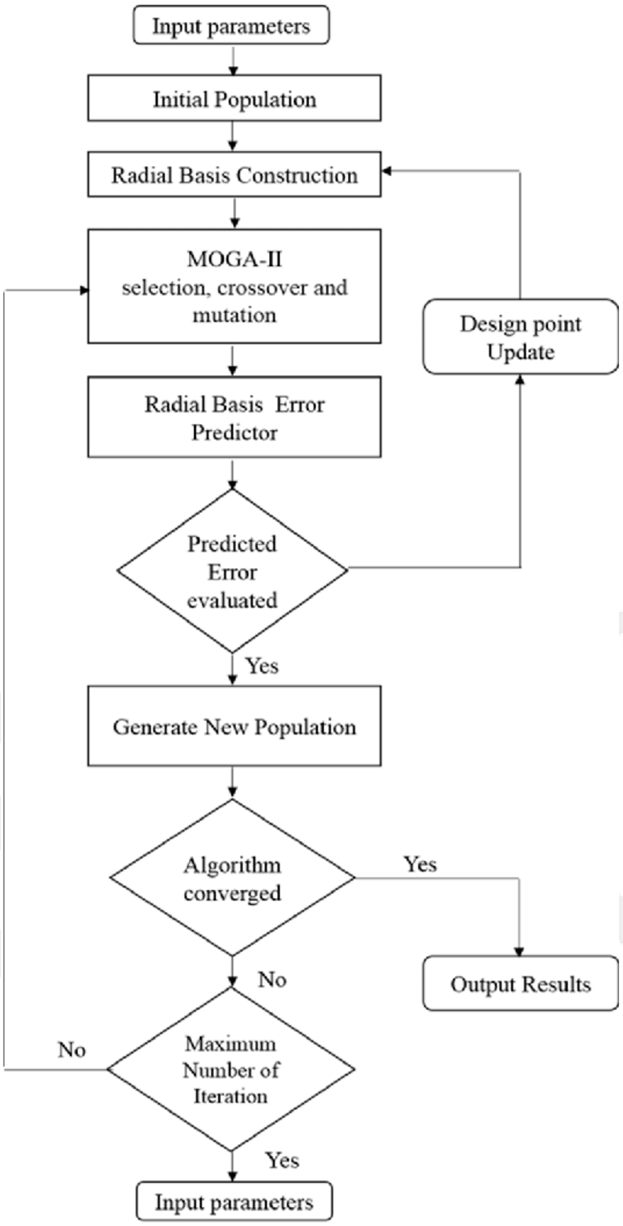


Figure 19: Genetic Algorithm Selection Phase

Initially, the population of combinations of genes representing the solution to the problem is randomly generated. A fitness value is assigned to each solution after it has been evaluated using a fitness function. The solution's quality is indicated by this fitness value. Solutions with high fitness values are chosen during the selection process. By simulating natural selection, the selection procedure enables the population to come to a better set of answers. The selected solutions are subjected to the crossover process. This process allows the creation of new solutions by changing some of the genes of the selected solutions. Mutation is applied to new solutions. Mutation occurs by randomly changing the genes of their new solution and provides diversity. The new population is formed by combining the old population and the new solutions. The fitness function is applied to this new population, which is then transmitted to the following generation. Generation; It is the new population obtained after selection, crossover and mutation processes are completed. For the optimization problem, the genetic algorithm can produce a finite amount of generations. The stopping criterion has been established, and the process is terminated when this criterion is satisfied. Changes in the fitness value, a specific number of generations, time restrictions, or the desired fitness value can all serve as ending criteria. By repeating these steps from the selection process, the population converges to a better solution set.

4.2. REASONS OF CHOOSING MULTI-OBJECTIVE GENETIC ALGORITHM

- Calculating derivatives or other auxiliary functions doesn't require any knowledge of derivatives or other related concepts [31 - 35].
- GA searches multiple points and examines solutions simultaneously. Thus, the chance of reaching the best result quickly without being stuck with the local best results is increased.
- It is possible to optimize multiple parameters by using GA for multiple purposes.

4.3. MULTI-OBJECTIVE GENETIC ALGORITHM DESIGN CONSTRAINTS

The Multi-Objective Genetic Algorithm will be used to optimize transformer design costs in the context of the thesis. The objective function of the transformer to be optimized is given Equation 4.1.

$$f_{obj} = (W_{core} \times 6\ \$) + \left(W_{windings} \times 3\ \$\right) + (W_{transformer\ oil} \times 2\ \$) \qquad (4.1)$$

Deciding on the optimization parameters is one of the most important considerations. Five variable design parameters were chosen. These parameters are K, LV conductor length, LV conductor width, LV layer number, and HV conductor diameter. According to the researches, the K constant value has been optimized in many studies. In addition, the transformer to be designed must be an integer or an even number, since the connection type on the LV side is zigzag. Therefore, the LV coefficient is one of the design parameters. Rectangular conductor is used on the LV side of the transformer in the design. Rectangular conductors are two-dimensional, have length and width. In this case, both the length and width of the conductor to be used should be optimized. Round conductor will be used on the HV side of the transformer. Round conductors are one-dimensional. Therefore, only the diameter of the HV conductor should be optimized.

The boundary conditions of the design parameters to be optimized are shown in the Table 3.

Table 3: Design Parameters Symbols, Lower and Upper Boundaries

Design Parameters	Symbol	Lower Bound	Upper Bound
K	X_1	0.25	0.55
LV conductor length (mm)	X_2	4	25
LV conductor width (mm)	X_3	2	5.5
LV layer number	X_4	3	6
HV conductor diameter (mm)	X_5	0.55	5

The transformer must comply with the specifications specified in the TEDAŞ MLZ.99.032.E specification. As a result, when designing, the boundary conditions specified in the specification should be taken into consideration. The oil and temperature rise points, load loss, no-load loss values shown in Table 1 show the limits of the designed transformer. Losses must remain equal to or below the specified values. The short-circuit impedance value must be 4.5%, 10% less than, or 10% more than, this number. Another boundary condition is the requirement that the design's maximum magnetic flux value be 1.8 Tesla. The transformer's design criteria are displayed in Table 4.

Table 4: Design Criteria of Transformer

Constraints	Boundary Condition
Short Circuit Impedance (u_k)	%4.5 ± 10
No Load Loss (P_0)	81W (max)
Load Loss (P_k)	660 W (max)
Magnetic Flux (B)	1.8 T

4.4. FINITE ELEMENT METHOD

One of the methods for numerical analysis is the finite element method (FEM). The Finite Element Method is a common tool in many engineering and scientific disciplines, including structural analysis, liquid and gas flow analysis, materials engineering, thermal analysis, electromagnetic field analysis, and many more. This method creates a mathematical model for understanding and analyzing the behavior of complex structures, making improvements to the design process, performing stress analysis, determining material properties, and developing new products.

FEM divides the analysis of large and complex systems into smaller and simpler finite elements. These elements are usually geometrically simple shapes such as triangles or quadrilaterals. Each element is defined using mathematical expressions and partial differential equations.

The FEM method began with the need for engineers in the aerospace industry to analyze the behavior of complex structures during World War II. In this period, names such as George R. Stibitz and Richard Courant worked on solving differential equations using numerical solutions. However, the modern version of FEM could not be developed in the 1940-1950s.

In the mid-1960s, FEM began to be widely used in engineering applications. Ray W. Clough, John O. Hallquist, Olgierd Zienkiewicz and others have made significant contributions to the development of FEM. In this period, FEM started to be used in different fields such as structural analysis, heat transfer, flow analysis and electromagnetic analysis.

Since the 1980s, the use of FEM has increased further with the development of computer technology. Computers with high processing power have made modeling and analysis of complex structures faster and more effective. In addition, the development and ease of use of FEM software has made it possible for engineers to use FEM more widely in their daily design and analysis processes.

The Finite Element Method (FEM) involves the following steps:

- The problem that will be analyzed must first be defined. This point in time, the geometry of the system is defined and the material properties, boundary conditions and physical event to be analyzed are determined.
- The area to be analyzed is divided into smaller elements. In this step, it is important to correctly divide the area to be analyzed. The size and number of elements can affect the accuracy of the analysis.
- Each element is modeled using mathematical expressions and equations. These expressions include material properties, geometry, and boundary conditions that represent the behavior of the elements. Connections, boundary conditions and forces between elements are also included.

- After modeling the elements, matrix and vector equation systems to be used in the analysis are created.
- The created equation system is solved by numerical methods. In this step, computer-based calculation methods are used. The equation system is solved using numerical analysis and linear algebra techniques.
- The outcomes are interpreted after the equation system has been solved. The results show the behavior of the analyzed system. The results can be used for design decisions or performance evaluation.

This thesis used the ANSYS/Maxwell program to conduct an electromagnetic analysis of an oil-type distribution transformer. ANSYS Maxwell is a software package for electromagnetic analysis. The behavior of electromagnetic fields is mathematically described by a set of differential equations known as Maxwell's equations. In the 19th century, James Clerk Maxwell developed the electromagnetic theory, which is represented as Maxwell's equations. The interaction and spread of electric and magnetic fields are explained by Maxwell's equations. Four fundamental equations make up the ANSYS/Maxwell equations used for electromagnetic analysis:

1. *Gauss's Law:* The relationship between the electric field and the charge density is explicated by Gauss's law. Its form is both integral and differential. It is shown in Equation 4.2.

$$\nabla . E = -\frac{\rho}{\varepsilon_0} \tag{4.2}$$

2. *Gauss's Law Magnetic:* Explains how the magnetic field and magnetic flux density are related. The magnetic monopole hypothesis is refuted by this Equation 4.3.

$$\nabla . B = 0 \tag{4.3}$$

3. *Faraday's Law:* Describes the process by which time-varying magnetic fields create an electric field. Equation 4.4 represents the fundamental model of electromagnetic induction.

$$\nabla \times E = -\frac{\varphi B}{\varphi t} \tag{4.4}$$

4. *Ampere's Law:* Explains how the magnetic field is affected by electric current. Equation 4.5 expresses the connection between the free currents and the rate of change of the magnetic field in differential form.

$$\nabla \times B = \mu_0 \left(J + \varepsilon_0 \frac{\varphi E}{\varphi t} \right) \tag{4.5}$$

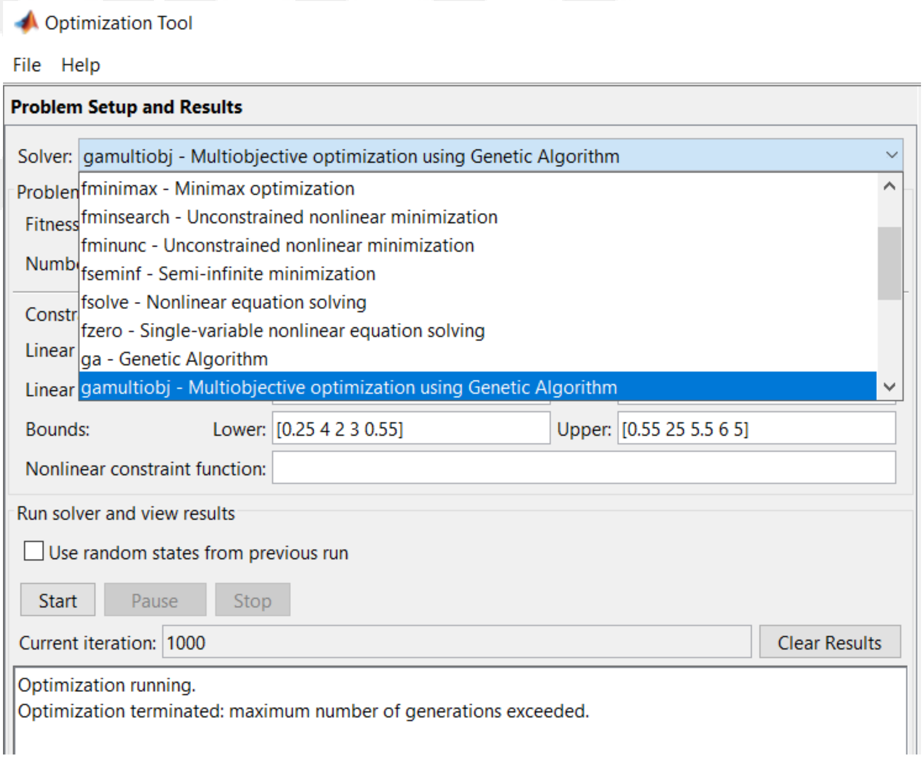
There are some universal constants that appear in these equations; The electric permittivity of empty space is ε_0, the magnetic permittivity of empty space μ_0. These four sets of equations mathematically describe the behavior of electromagnetic fields. ANSYS Maxwell solves these equations using numerical methods and enables electromagnetic field analysis. Maxwell's equations; It is used in many application areas such as magnetic field analysis, propagation of electromagnetic waves, electromagnetic induction and design of electromagnetic devices.

CHAPTER V

RESULTS

5.1. MULTI-OBJECTIVE OPTIMIZATION USING GENETIC ALGORITHM SET-UP

Using the Multi-Objective Genetic Algorithm method, the design parameters of the transformer developed for this thesis were optimized. This algorithm is provided with the MATLAB Tool Box.



Solver: gamultiobj - Multiobjective optimization using Genetic Algorithm

Bounds: Lower: [0.25 4 2 3 0.55] Upper: [0.55 25 5.5 6 5]

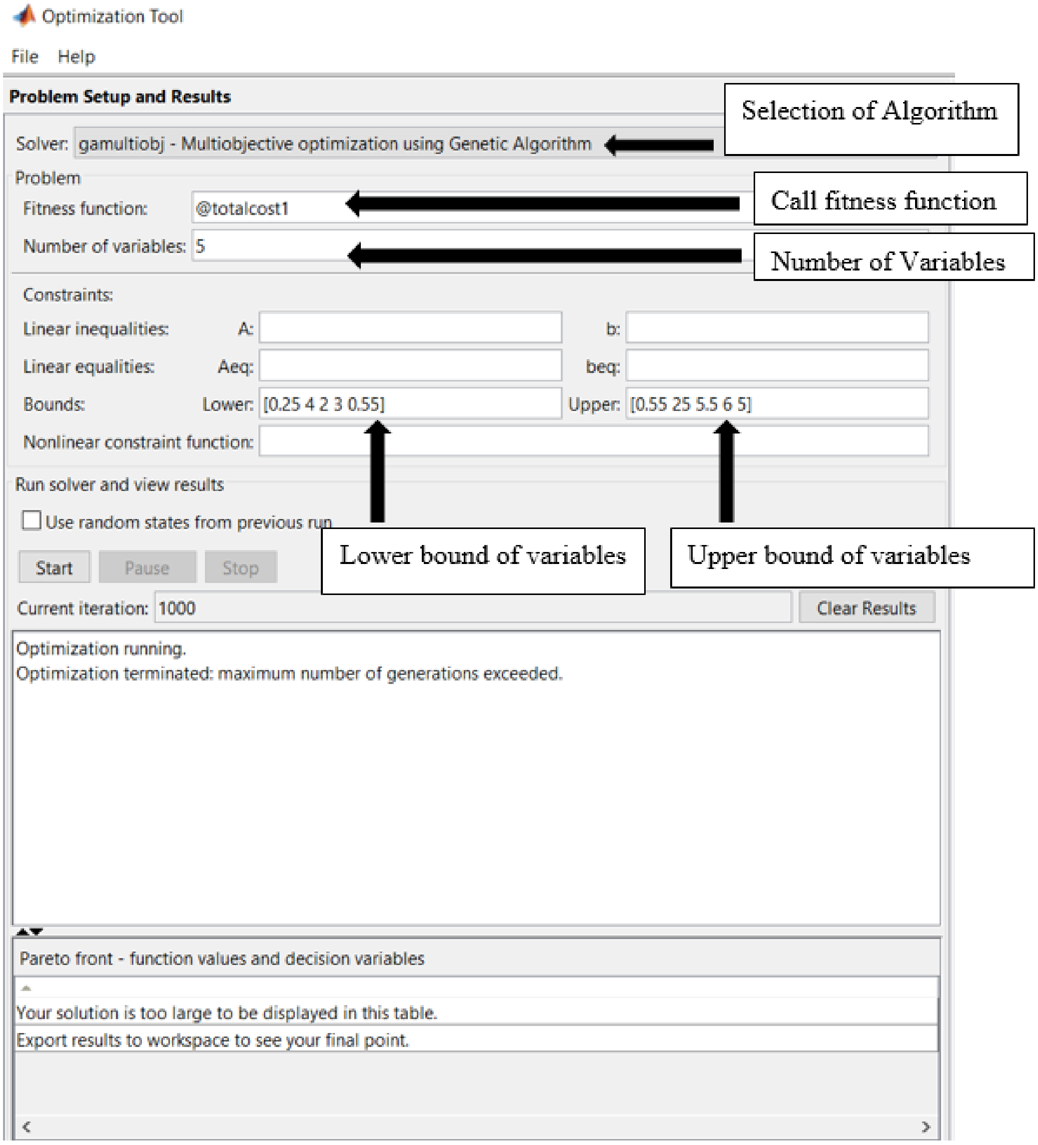
Nonlinear constraint function:

Current iteration: 1000

Optimization running.
Optimization terminated: maximum number of generations exceeded.

Figure 20: Solver Selection

There are methods for many different purposes in the Solver section. As shown in the Figure 20, the optimization method to be used for the objective function is selected in Solver Part. Since more than one variable will be used, the Multi-Objective Genetic Algorithm option is chosen.



Solver: gamultiobj - Multiobjective optimization using Genetic Algorithm

Fitness function: @totalcost1

Number of variables: 5

Bounds: Lower: [0.25 4 2 3 0.55] Upper: [0.55 25 5.5 6 5]

☐ Use random states from previous run

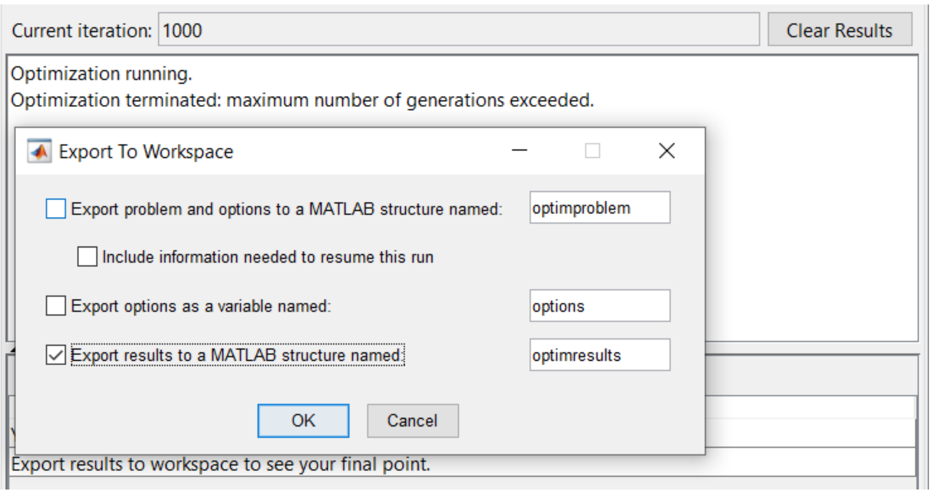
Current iteration: 1000

```
Optimization running.
Optimization terminated: maximum number of generations exceeded.
```

```
Your solution is too large to be displayed in this table.
Export results to workspace to see your final point.
```

Figure 21: Optimization Tool Detail #1

In the MATLAB program, transformer design formulas, boundary conditions and objective function are introduced in the m.file file named "totalcost1". In this thesis, five variable parameters will be optimized. Figure 21 shows the number of design parameters to be optimized and their lower and upper limit values.


Current iteration: 1000

Optimization running.
Optimization terminated: maximum number of generations exceeded.

Export To Workspace

☐ Export problem and options to a MATLAB structure named: optimproblem

☐ Include information needed to resume this run

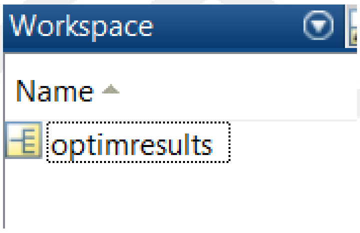
☐ Export options as a variable named: options

☑ Export results to a MATLAB structure named: optimresults

Export results to workspace to see your final point.

Figure 22: Optimization Tool Detail #2

The iteration number is selected as 1000 value as shown in Figure 22. Due to the high number of iterations, the optimization results are exported to the MATLAB workspace section which is shown in Figure 23. Thus, all the results were loaded into the MATLAB Workspace as a matrix.

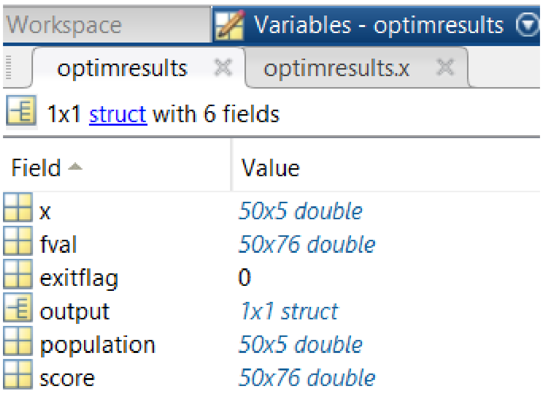

Workspace

Name

optimresults

Figure 23: Optimization Tool Workspace Detail #1

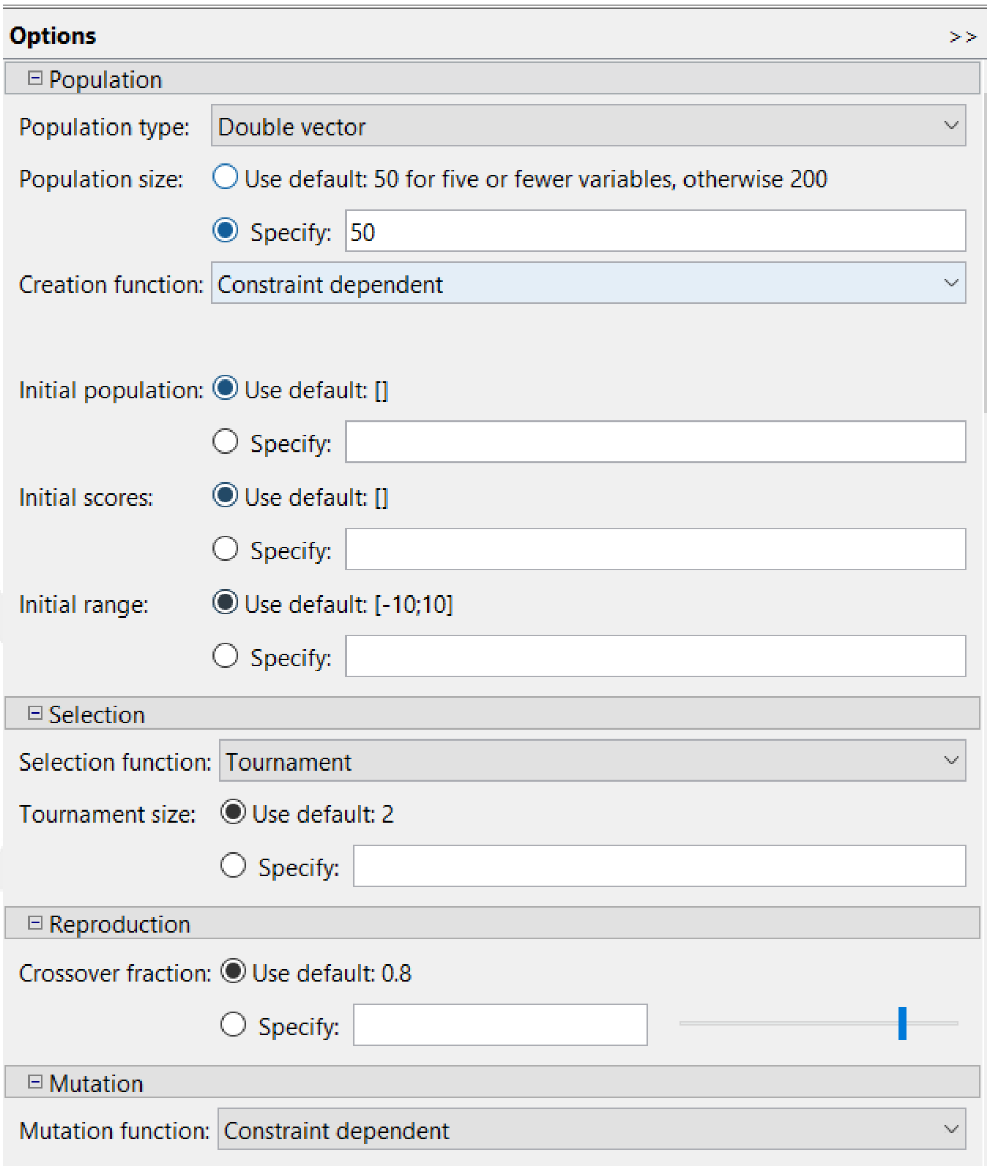
The results coming to the MATLAB workspace in matrix format are seen in Figure 24.



1x1 struct with 6 fields

Field	Value
x	50x5 double
fval	50x76 double
exitflag	0
output	1x1 struct
population	50x5 double
score	50x76 double

Figure 24: Optimization Tool Workspace Detail #2



Options >>

⊟ Population

Population type: Double vector

Population size: ○ Use default: 50 for five or fewer variables, otherwise 200

● Specify: 50

Creation function: Constraint dependent

Initial population: ● Use default: []

○ Specify:

Initial scores: ● Use default: []

○ Specify:

Initial range: ● Use default: [-10;10]

○ Specify:

⊟ Selection

Selection function: Tournament

Tournament size: ● Use default: 2

○ Specify:

⊟ Reproduction

Crossover fraction: ● Use default: 0.8

○ Specify:

⊟ Mutation

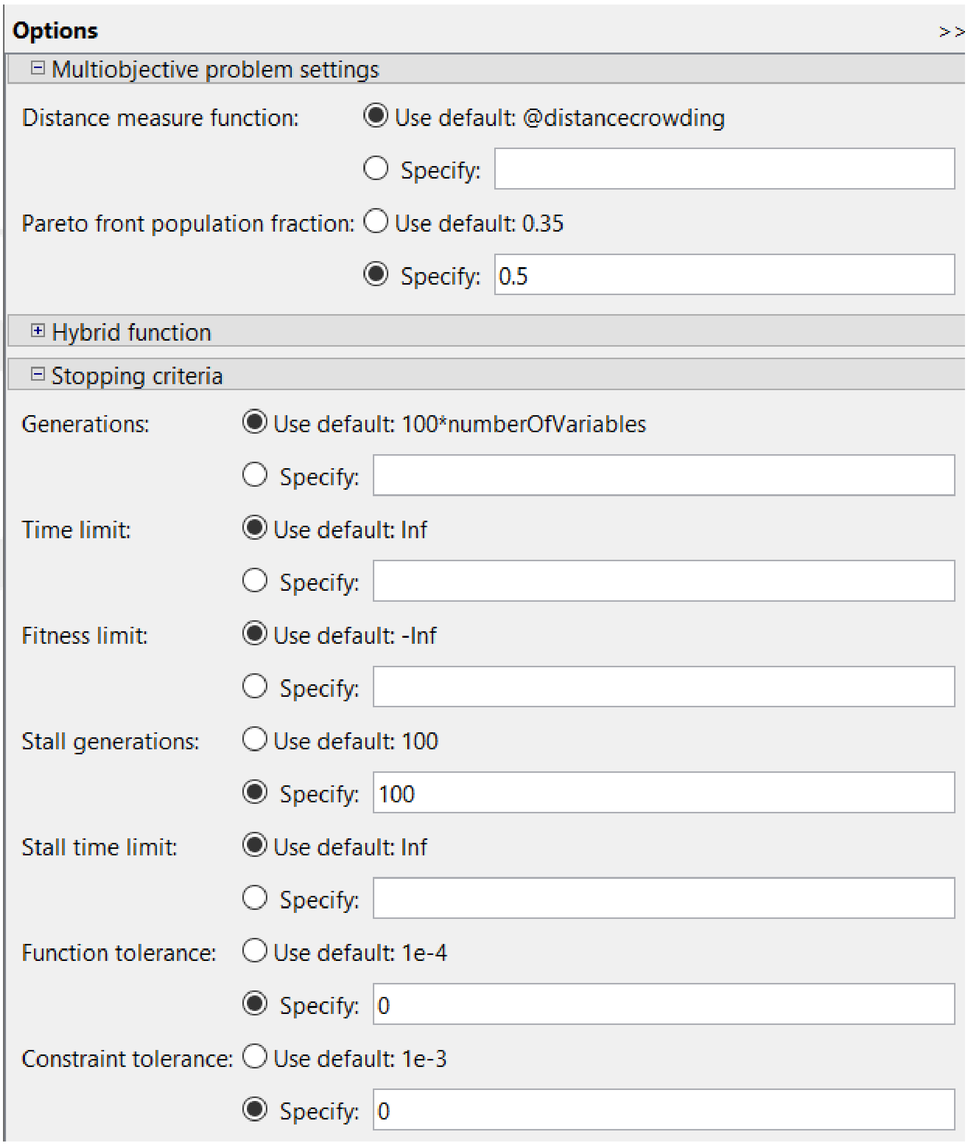
Mutation function: Constraint dependent

Figure 25: Optimization Tool Detail #3

On the right side of the MATLAB Tool Box which is shown in Figure 25, there is the "Options" section for the Multi-Objective Genetic Algorithm method. The number of population is determined by entering the number 50 in the population section. Thus, at the end of the iteration, a result matrix of 50x5 size was obtained. As can be seen from Figure 24, the result of the optimization is 50x5. Then, Creation function is selected “constraint dependent”.

Tournament selection is used in the "Selection" section. In this method, a group of individuals of a certain size is randomly selected. The best individual in the group is passed on to the next generation. With this method, the best individuals are protected. Tournament size is utilized as default that 2.

There are 5 options for the mutation function and 8 options for the crossover function. Based on the literature search and the results obtained for each option, the mutation "Constraint dependent"; crossover was selected as "Intermediate". Its ratio selects default value as 1.0.



Options

⊟ Multiobjective problem settings

Distance measure function: ● Use default: @distancecrowding ○ Specify:

Pareto front population fraction: ○ Use default: 0.35 ● Specify: 0.5

⊞ Hybrid function

⊟ Stopping criteria

Generations: ● Use default: 100*numberOfVariables ○ Specify:

Time limit: ● Use default: Inf ○ Specify:

Fitness limit: ● Use default: -Inf ○ Specify:

Stall generations: ○ Use default: 100 ● Specify: 100

Stall time limit: ● Use default: Inf ○ Specify:

Function tolerance: ○ Use default: 1e-4 ● Specify: 0

Constraint tolerance: ○ Use default: 1e-3 ● Specify: 0

Figure 26: Optimization Tool Detail #4

Crossover fraction 0.8 and Pareto front population fraction 0.5 were selected. It has been observed that better results are obtained at this value. However, if the pareto front population fraction is less than 0.5, the short circuit impedance exceeds the limit specified in Table 4. Generations of the stopping criteria is selected

"100*numberOfVariables". Then the generations parameter is 500. Function and Constraint Tolerances are selected zero. These steps are shown in Figure 26.

5.2. OPTIMIZATION RESULT

The lower and upper bounds stated in the "4.3. Multi-Objective Genetic Algorithm Design" section were used to optimize the Multi-Objective Genetic Algorithm for the transformer design parameters.

The parameters obtained as a result of the optimization have been replaced in the mathematical modeling formulas of the transformer in the "Electrical Design of Oil Type Distribution Transformer" section.

In the “5.1. Multi-Objective Optimization Using Genetic Algorithm Set-Up" section, the criteria used within the scope of Multi-Objective Genetic Algorithm optimization are given in detail in the MATLAB program. In this section, the results applied within the scope of the thesis are shown.

As a result of the Multi-Objective Genetic Algorithm, the K parameter, which is one of the design variables of the transformer, was obtained as 0.396967. Accordingly, $E/_T$ is 1.9838457, N_{LV} is 134, and N_{HV} is as in Table 5.

Table 5: HV taps and the corresponding turns numbers

Voltage (V)	Tap Number	Turn Numbers
28500	1	8268
30000	2	8704
31500	3	9139
33000	4	9574
34500	5	10009
36000	6	10444

A_g which is gross core area found as $54.19\ cm^2$. Then the core diameter d_{core} is 90 mm. Transformer core of steps width and core stack height is indicated in Table 6.

Table 6: Width of core steps and Core stack height

L	K
$L_1 = 80\ mm$	$K_1 = 41.23\ mm$
$L_2 = 70\ mm$	$K_2 = 15.33\ mm$

Table 6 Continued

$L_3 = 60\ mm$	$K_3 = 10.51\ mm$
$L_4 = 50\ mm$	$K_4 = 7.75\ mm$

Thus, transformer core geometry can be shown as in Figure 27.

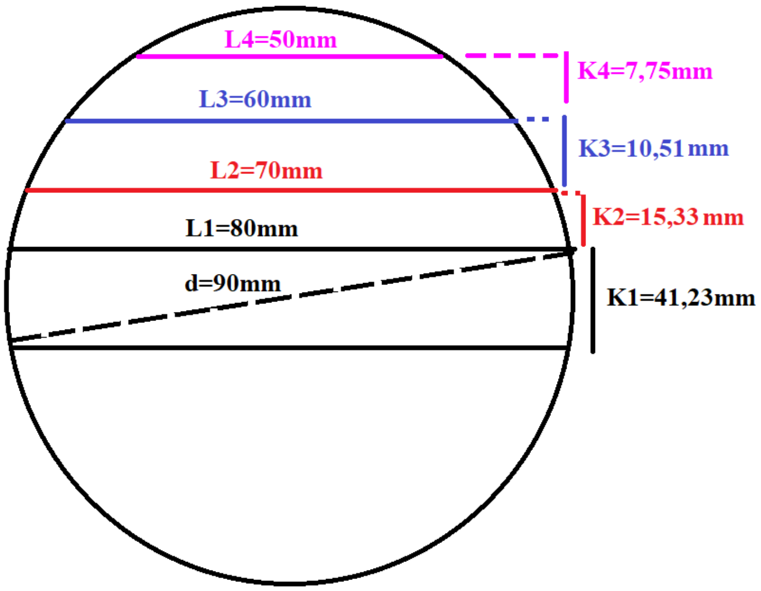


Figure 27: Transformer Core Geometry

By optimizing the parameters shown in Table 3, the HV and LV coil design parameters of the transformer are shown in Table 7.

Table 7: Design Parameters of Transformer Winding

Parameters	LV	HV
Number of turns per phase	134	8268-10444
Number of layers	4	28
Length of conductor, mm	7.8	-
Width of conductor, mm	2.7	0.61
Area of conductor, mm2	21.06	0.3
Current density, A/mm2	1.67	1.48
Inner diameter, mm	95	147
Insulation layer, mm	0.125	0.220
Radial Thickness, mm	11	27
Outer diameter	117	201
Winding Axial Height, mm	285	250

K_R is found as 0.939. Then the impedances are given in Table 8.

Table 8: Short circuit impedance values

Impedances	Values
$\%U_X$	3.74
$\%U_R$	2.61
$\%U_K$	4.57

After all these calculations, the results of the empirically designed transformer with the Multi-Objective Genetic Algorithm are compared in Table 9. Along with the decrease in cost with the Multi-Objective Genetic Algorithm method, there is a decrease in transformer winding weights.

Table 9: Experimental and Optimization Result

Parameters	Experimental Results	Optimization Results
K	0.36	0.396769
LV conductor length (mm)	8,9	7,8
LV conductor width (mm)	2,2	2,7
LV layer number	4	4
HV conductor diameter (mm)	0,7	0,61
Number of turns per phase for HV winding	148	134
Number of turns per phase for LV winding	9132-11535	8268-10444
LV Winding Inner diameter, mm	91	95
LV Winding Outer diameter, mm	117	117
HV Winding Inner diameter, mm	147	147
HV Winding Outer diameter, mm	209	201
LV Radial Thickness, mm	13	11
HV Radial Thickness, mm	31	27
LV winding weight, kg	8,4	7,77
HV winding weight, kg	20	13,619
Core weight, kg	81,989	78,338
Load Loss, Watt	660	654
No Load Loss, Watt	81	80
Transformer Cost, $	577,134	534,22

5.3. ANSYS/Maxwell RESULT

Within the scope of the thesis, the 3D model of the 25 kVA transformer was drawn in the ANSYS program. Transformer properties are detailed in Table 1 in "Chapter 3 - Electrical Design of Oil Type Distribution Transformer".

Figure 28 shows the ANSYS 3D model of the transformer core and windings is created.

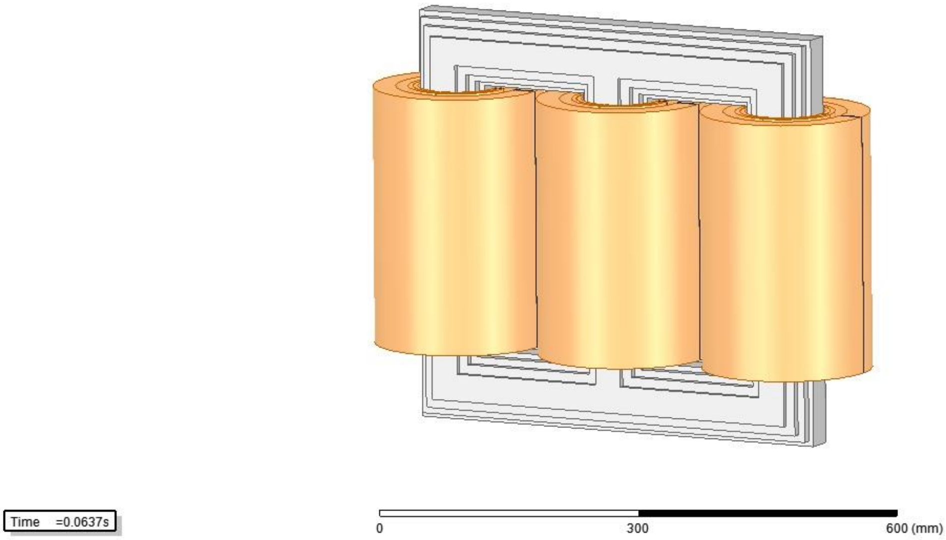


Figure 28: 25 kVA Transformer ANSYS/Maxwell 3D Model

Meshing is a tool for meshing geometries used in simulation analysis. There is a need for a mesh of elements that divide the drawn transformer geometry into smaller parts and represent each part. The meshing analysis of the transformer examined within the scope of the thesis can be seen in Figure 29.

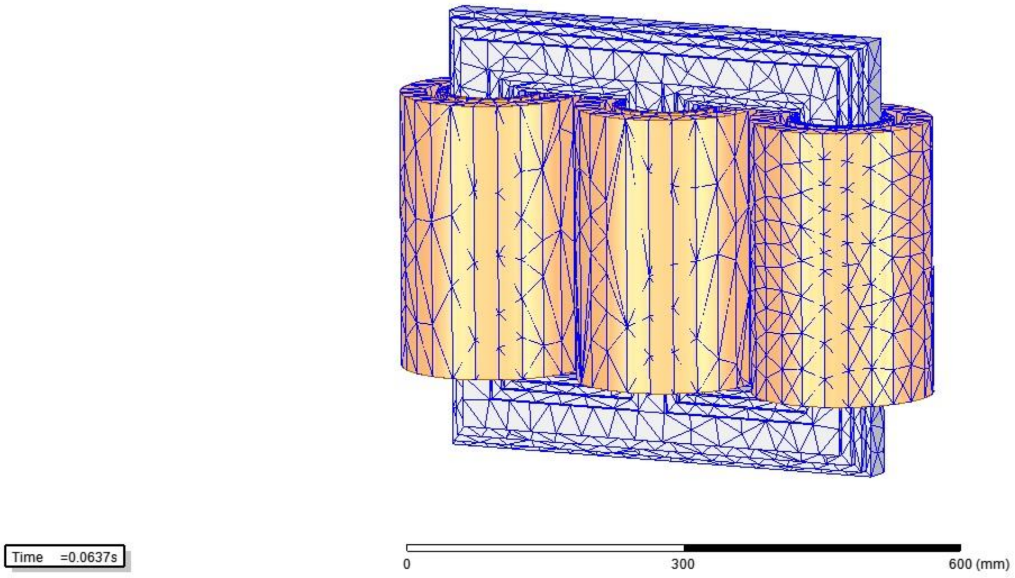


Figure 29: Meshing of Transformer

The magnetic flux in the regions inside the transformer has been detected. According to ANSYS/Maxwell results, it is a measure of 63 ms time. The magnetic flux is aimed to remain between 1.7-1.8 Tesla. It is shown in Figure 30. According to ANSYS results, it is seen that it does not exceed these values.

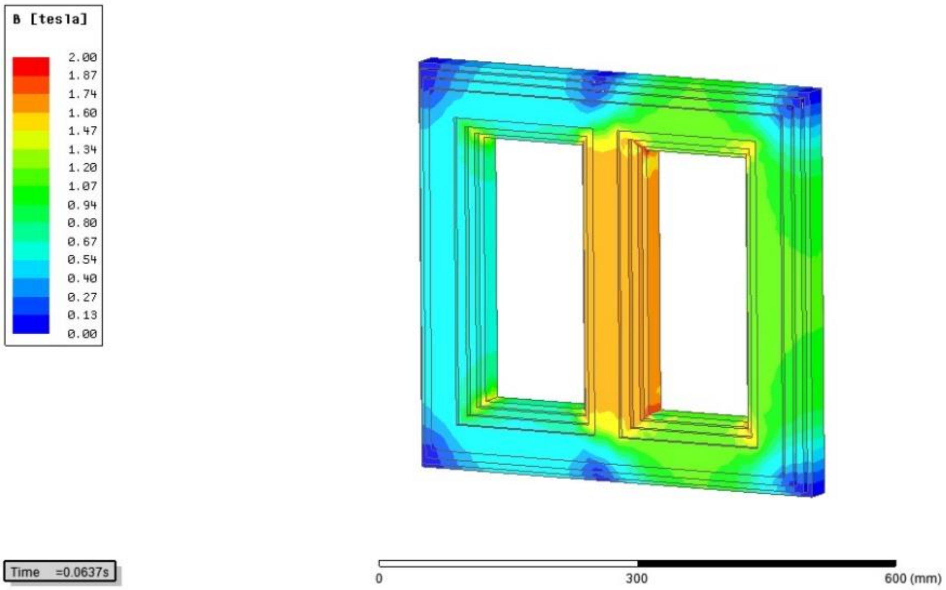


Figure 30: Transformer Flux Density in ANSYS/Maxwell

The simulation of line and phase current and voltage values of the transformer is as follows. The information given in Table 2 under the heading "3.1 - Mathematical Modeling of Transformer Connection" is verified.

The rated line voltage on the HV side of the transformer is 33 kV.

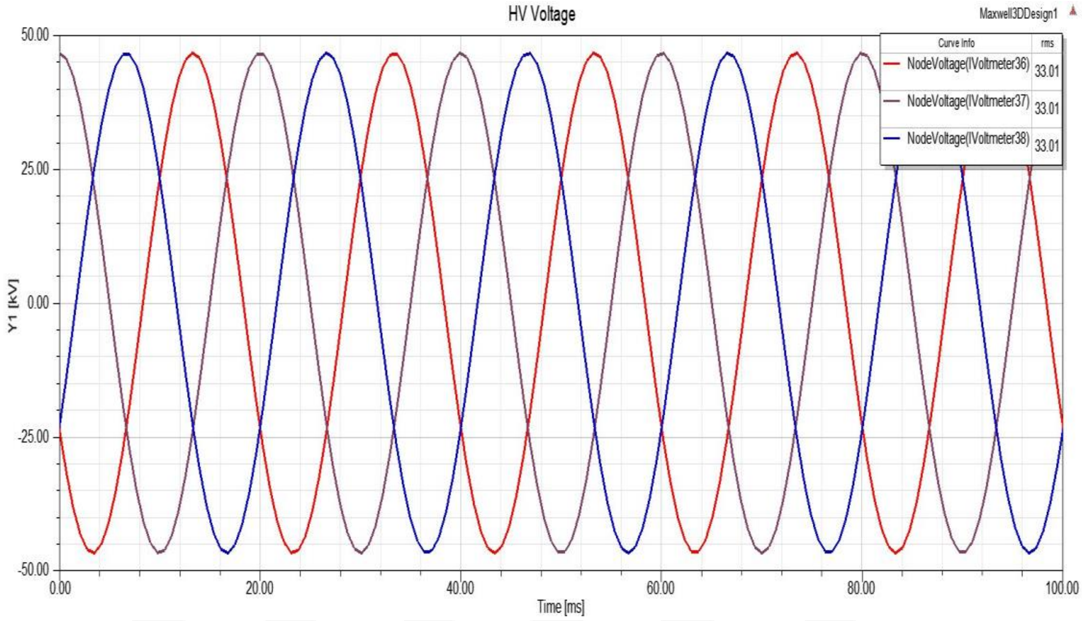


Figure 31: HV Line Voltage

The simulation result of the primary voltage of the 3-phase transformer shown in Figure 31 above appears. A more detailed representation of this image is as in Figure 32.

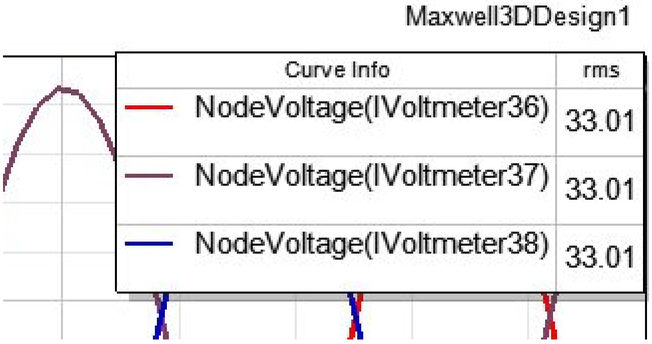


Figure 32: HV Line Voltage in Zoom

The transformer's Y connection is on the HV side. In star connection, current calculation is as in Equations 3.2 and Equation 3.3.

$$I_{HVll} = \frac{S \times 1000}{\sqrt{3} \times V_{HVll}} \tag{3.2}$$

$$I_{HVph} = I_{HVll} \tag{3.3}$$

According to the equations shown above, the rated line current in the HV winding of the transformer is found to be 0.437 A.

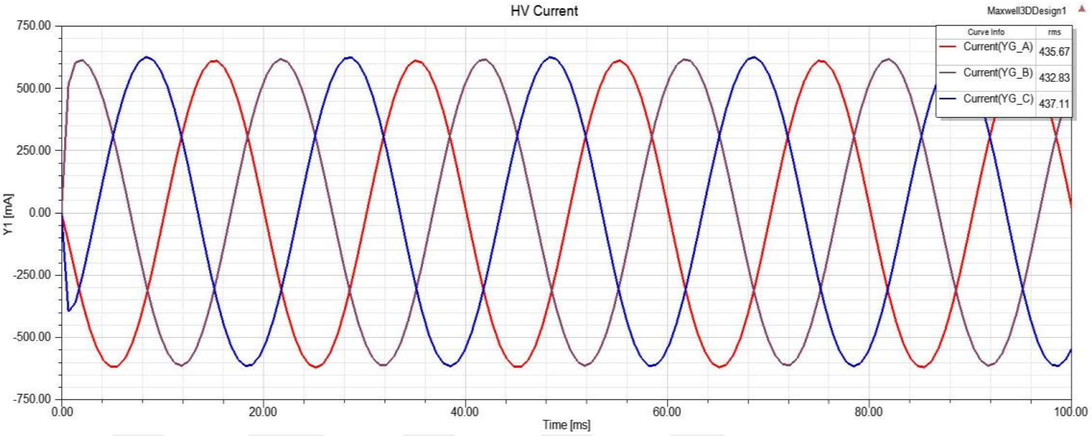


Figure 33: HV Line Current

The transformer high voltage line current is shown in Figure 33. A more detailed representation of this figure is as in Figure 34.

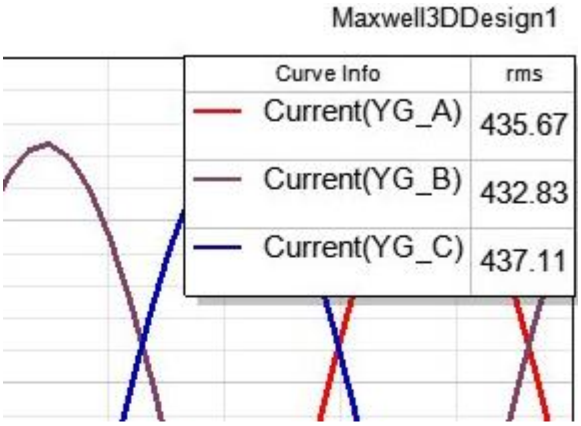


Figure 34: HV Line Current in Zoom

On the low voltage side of the transformer, the line voltage is 400 V. The connection type in this winding is Zig-Zag connection. As shown in Equation 3.6, the phase voltage of the LV winding is 230 V.

$$V_{LVll} = \sqrt{3} \times V_{LVph} \tag{3.6}$$

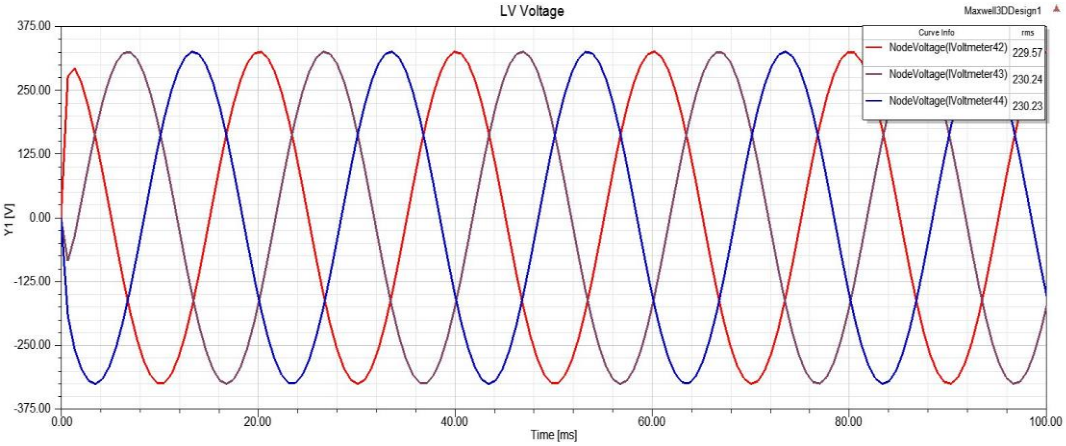


Figure 35: LV Phase Voltage

The transformer low voltage line current is shown in Figure 35. A more detailed representation of this figure is as in Figure 36.

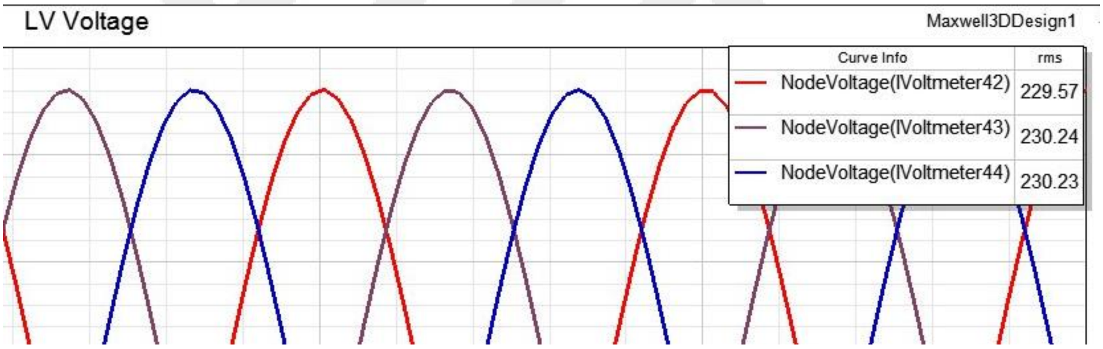


Figure 36: LV Line Voltage in Zoom

The current in the LV winding of the transformer is found as in the formulas in the HV winding. It is shown in Equations 3.4. Accordingly, the line current in the LV winding of the transformer was found to be 36.08 A. It has also been verified in the ANSYS simulation that is shown in Figure 37.

$$I_{LVll} = \frac{S \times 1000}{\sqrt{3} \times V_{LVll}} \tag{3.4}$$

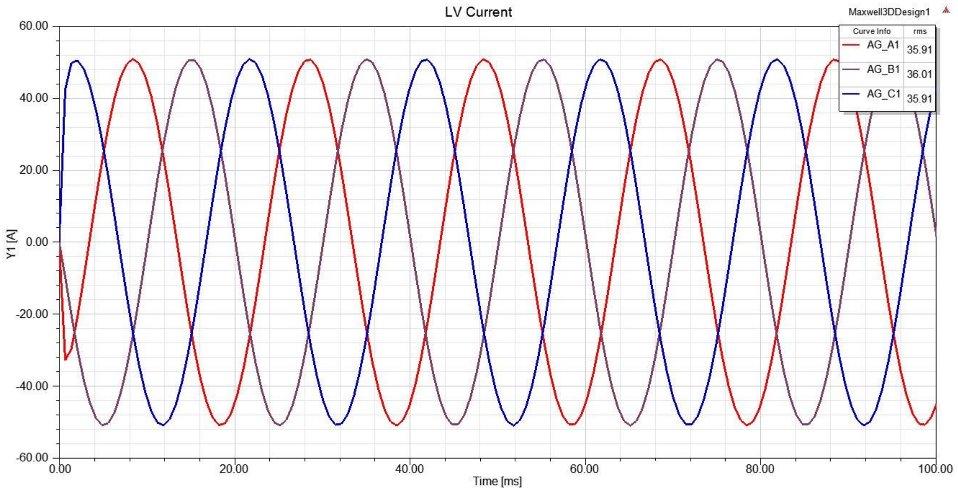


Figure 37: LV Line Current

The transformer low voltage line current is shown in Figure 37. A more detailed representation of this figure is as in Figure 38. As seen in Figure 37 and Figure 38, the current on the transformer LV side is approximately 36 A.

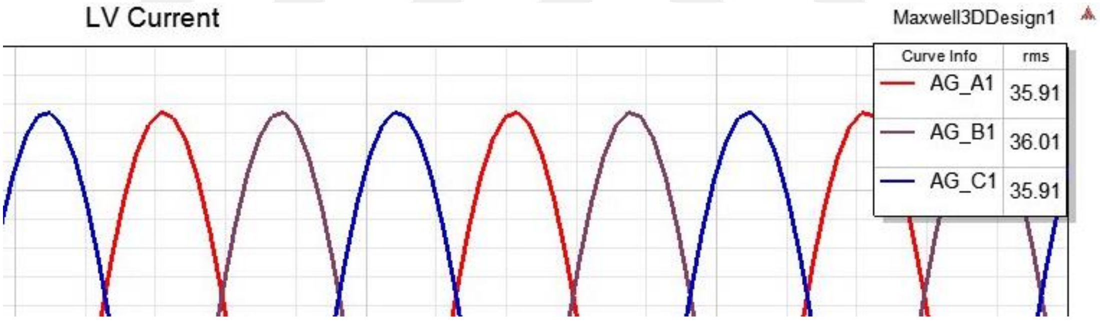


Figure 38: LV Line Current in Zoom

In the analyzes made in the ANSYS/Maxwell program, only the active part of the transformer is taken into account. These simulation results are valid for the core and windings; the tank connection is not included.

Iron and copper losses of the transformer obtained as a result of the optimized parameters by the Multi-Objective Genetic Algorithm method are shown in the Figure 39 and Figure 40.

Eddy Current Loss and Hysteresis Loss contribute to the transformer's no-load loss, as seen in Figure 39. The total of the hysteresis and eddy current losses is the no-load loss. As a result, the core loss is found to be 82.41W.

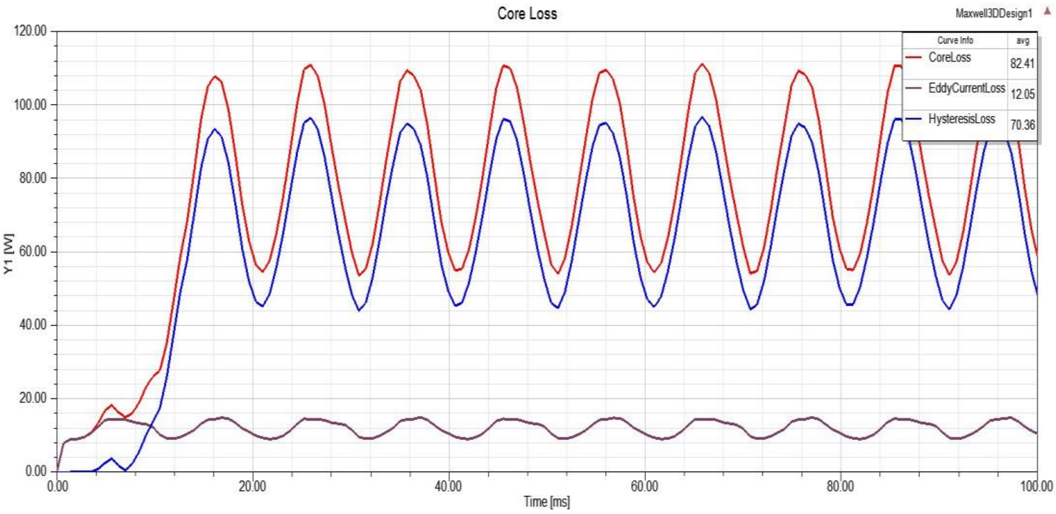


Figure 39: Transformer No-Load Loss

Figure 39 shows the simulation result of the no-load loss of the transformer consisting of Eddy Current Loss and Hysteresis loss. For a closer reading of this value, Figure 40 is used.

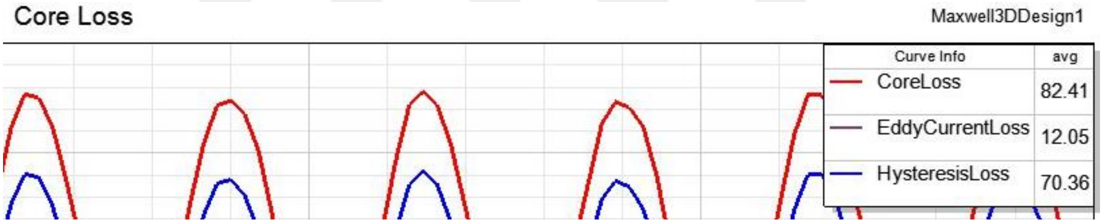


Figure 40: Transformer No-Load Loss in Detail

What is shown as "Stranded Loss" in Figure 41 is the transformer's loss at load. The load loss was found to be 621.70W.

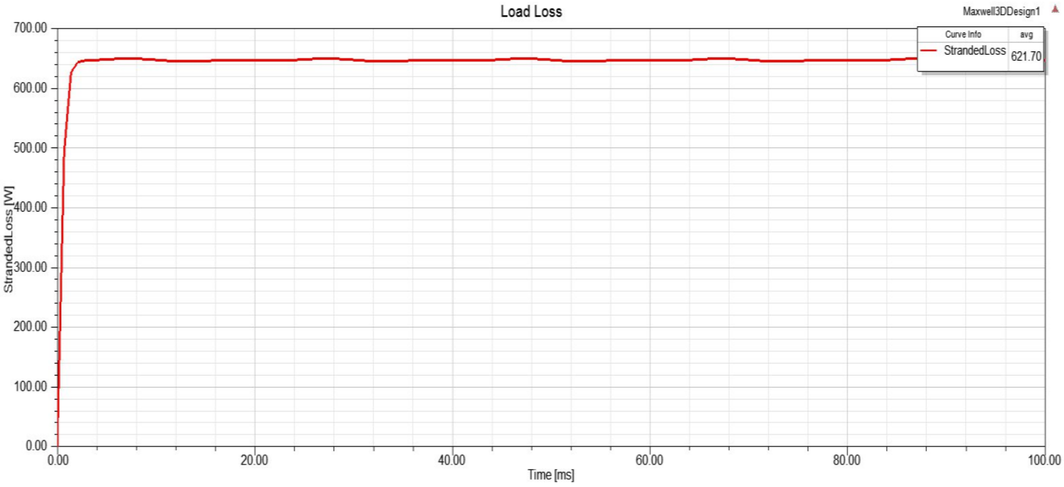


Figure 41: Transformer Load Loss

The simulation result of transformer load loss is indicated in Figure 41. In detail of this result is shown in Figure 42.

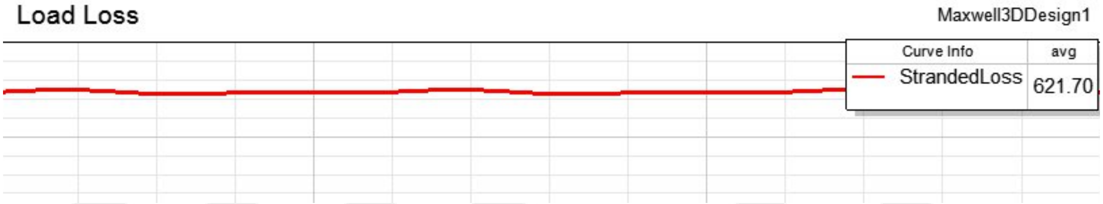


Figure 42: Transformer Load Loss in Detail

Table 10 displays the results from FEM and Multi-Objective Genetic Algorithm Optimization. The findings of the optimization, as shown in the table, are comparable to those obtained through FEM.

Table 10: FEM and Optimization Result

Result	Finite Element Method (FEM)	Multi-Objective Genetic Algorithm
LV Line Current, A	36.01	36.08
LV Phase Voltage, V	230.24	230.94
HV Line Current, A	0.43711	0.437
HV Line Voltage, kV	33.01	33
Load Loss, Watt	621.70	654
No Load Loss, Watt	82.41	80

CHAPTER VI

CONCLUSION

In this thesis, 5 of the design parameters of a 3-phase, Yzn11 connected, 25 kVA, 33/0.4 kV low power oil type distribution transformer was optimized by Multi-Objective Genetic Algorithm method using MATLAB code writing and MATLAB Optimization Tool Box. The effect of the design parameters obtained by the Multi-Objective Genetic Algorithm method on the transformer cost has been observed. It has been reached that there is a decrease in the requirements such as the weight and losses of the transformer, as well as the improvement in the cost.

The equations used in transformer design are introduced in MATLAB. In the MATLAB Optimization Tool Box, the information about the optimization is processed in the relevant sections. Optimization results were obtained by determining the number of iterations.

A manual code has been written to verify whether the results obtained as a result of the optimization give reasonable results. Verification was made in the written code using the empirical equation in the literature. In order to ensure that the obtained values give correct results when the iteration is over, magnetic flux value, the short-circuit impedance, np-load and load losses of the transformer were determined.

The length and diameter of the conductors of the transformer's coils, layer number of the secondary conductor of the transformer and the K value of the transformer are the parameters for which optimization is made.

When these parameters are changed, the effect on the cost of the transformer has been investigated.

In the design process, the importance of the necessary parameters of the transformer to obtain the optimal cost is included. It has been observed that the more parameters are optimized, the more suitable results are obtained for the specified boundary conditions. Optimum cost has been reached as a result of the parameters determined by considering various scenarios while designing.

The transformer, which was designed according to the values found in the optimization, was modeled in 3D in ANSYS Maxwell program. The results obtained by the analysis studies were also supported.

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